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Gasoline Content Regulation on Air Quality**

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CLEARING THE AIR? THE EFFECTS OF GASOLINE CONTENT REGULATION ON AIR QUALITY

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Abstract

This paper examines the effects of U.S. gasoline content regulations on ground-level ozone pollution. These regulations are costly and have been shown to fragment gasoline markets and raise prices paid by consumers. We provide the first comprehensive empirical estimates of the regulations' air quality benefits. We exploit the fact that gasoline regulations vary by time and place of introduction, using both difference-in-difference and regression discontinuity designs. We show that federal regulations targeting the emissions of volatile organic compounds (VOCs), one of the two main precursors to ozone, do not substantially improve air quality. This outcome is driven by the response of refiners to the regulation: minimizing the cost of abatement involves removing a type of VOC from gasoline that is not an important determinant of ozone pollution. In California, however, we show that precisely targeted regulations requiring the removal of VOCs particularly prone to forming ozone caused a significant improvement in air quality.

Keywords: Gasoline, Air Quality, Ozone, Refining
JEL Codes: Q53, Q58, L51, R19

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1. Introduction

Since the passage of the original Clean Air Act in 1963, U.S. state and federal governments have implemented numerous policies designed to reduce human exposure to ground-level ozone pollution. Ozone is an odorless, colorless gas that has been linked to several human health problems. Ozone can aggravate the symptoms of asthma, increase susceptibility to pneumonia and bronchitis, and cause airway irritation and pain during physical exertion. These effects are particularly pronounced amongst children and the elderly. Moreover, ozone is destructive to crops and natural vegetation.¹

While ozone is not emitted directly by any source, the two classes of chemicals that react in the atmosphere to produce ozone—volatile organic compounds (VOCs) and oxides of nitrogen (NO_x)—are pollutants produced in part through human activity. Ozone control programs have targeted a wide array of VOC and NO_x emissions sources, including motor vehicles, electricity generators, and large industrial emitters such as cement plants. Despite more than 40 years of regulatory effort, however, many areas of the U.S. continue to experience ambient air concentrations of ozone that exceed standards set by the Environmental Protection Agency (EPA).

This paper examines the effectiveness of one particular set of regulations targeting ozone: restrictions on the chemical composition of gasoline that are primarily intended to reduce VOC emissions from mobile sources. These regulations have recently come under scrutiny due to their cost and their adverse effects on gasoline markets. Gasoline content standards are not uniform across the country: the EPA regulates some states and counties more tightly than others, and some areas have implemented their own standards that are more stringent than those set by the EPA. The resulting “patchwork” of regulation has segmented the U.S. gasoline market so that gasoline transporters cannot arbitrage price differences across areas with different gasoline standards. Several recent papers—Brown *et al.* (2008), Chakravorty and Nauges (2008), and

¹ For evidence regarding ozone’s mortality, morbidity, and environmental impacts, see Bell *et al.* (2004), EPA (2006), Moretti and Neidell (2008), and Neidell (2004, 2009).

Muehlegger (2006)—have found that this market segmentation significantly increases both gasoline price levels and price volatility. Brown *et al.*, for example, find that federal reformulated gasoline increases prices by an average of 3 cents per gallon, and that increases are larger in areas whose gasoline markets became particularly isolated as a result of the regulations. The U.S. Congress, concerned about the price effects of segmented gasoline markets, inserted language into the Energy Policy Act of 2005 (section 1541(b)) that constrained the ability of the EPA to enact or approve new gasoline standards that could exacerbate segmentation.

Despite the considerable attention paid to the costs of gasoline content regulation, we are not aware of any study that comprehensively assesses the extent to which regulation has yielded benefits through reduced ozone pollution. While the EPA has conducted numerous road tests demonstrating that use of “cleaner” gasoline does reduce VOC emissions, an *ex post* evaluation of whether these reductions actually translate to lower levels of ground-level ozone has not been undertaken.

Our study relates to previous work in economics that seeks measure the air quality and health benefits of U.S. clean air regulations. Henderson (1996) examines the changes in counties’ ozone concentrations resulting from their designation as being in nonattainment of the EPA’s National Ambient Air Quality Standard for ozone. A nonattainment designation forces a county to undertake pollutant abatement actions, potentially including regulation of gasoline content. He finds that a nonattainment designation reduces summer daily maximum ozone concentrations by about 8%, though this result is not statistically significant in some specifications. Chay and Greenstone (2003, 2005) find a significant impact of total suspended particulate (TSP) nonattainment designation on TSP concentrations, infant mortality, and housing prices. Greenstone (2004), however, finds no effect of sulfur dioxide (SO₂) nonattainment on SO₂ concentrations.

We examine the effectiveness of gasoline content regulation using daily measurements of ambient ozone concentrations from hundreds of air quality monitors across the United States during 1989-2003. Our identification strategy takes advantage of the rich spatial and temporal

variation with which gasoline regulations were applied, as well as the discrete nature with which they phased-in. Unlike, for example, standards for vehicle emissions control equipment that only produce effects gradually through turnover in the vehicle fleet, the adoption of a gasoline content standard immediately affects all vehicles on the road. We therefore seek to identify step changes in ozone concentrations at the times and locations in which gasoline regulations came into effect. We use two methods: (1) a difference-in-difference (DD) estimator that also controls for time-varying observables in treated vs. control areas; and (2) a regression discontinuity (RD) design that examines changes in ozone concentrations immediately before and after gasoline regulations came into effect.

We find that the effectiveness of gasoline regulations varies substantially with the flexibility with which refiners are permitted to respond. A set of federal gasoline regulations that limits the total evaporation of VOCs from gasoline—without regard to which VOCs are most reactive in forming ozone—is estimated to have no economically or statistically significant effect on ground-level ozone concentrations. This result appears to be driven by the behavioral response of refiners to the VOC standard: they minimize their cost of compliance by reducing the concentration of a type of VOC that is only weakly related to ozone formation. Refiners do not reduce concentrations of highly reactive VOCs because doing so is expensive and the overall VOC standard provides no compensating incentive or mandate.

This outcome relates to other recent work demonstrating that the behavioral responses of firms and households can undermine the objectives of environmental regulation. Fowlie (2009) finds that the benefits of a major U.S. NO_x cap-and-trade program were substantially undercut by differences in compliance incentives between electric generators subject to traditional rate-of-return regulation and those in deregulated markets. NO_x abatement was concentrated in low marginal damage areas rather than dense urban centers in the Northeast. Davis (2008) examines the effectiveness of license plate-based driving restrictions in Mexico City that target the city's severe smog problem. He finds that the restrictions are ineffective because households

substituted into other polluting behaviors: they purchased more cars, and those cars had relatively high emissions intensities.

This paper goes beyond previous work in that we also examine the effectiveness of a set of regulations designed to overcome the behavioral response of the regulated agents. In 1996, California placed strict gasoline content limits on precisely those VOCs that are most important in forming ozone, thereby eliminating refiners' ability to avoid costly abatement of these compounds. As a result, California has enjoyed a significant improvement in air quality: we estimate that the introduction of California reformulated gasoline reduced ground-level ozone concentrations by 16% in the severely polluted Los Angeles – San Diego area. A conservative back of the envelope calculation indicates that the benefits from this air quality improvement outweigh the regulation's cost based on mortality impacts alone.

The remainder of the paper is organized as follows: section 2 provides a description of the gasoline reformulation policies examined in this paper. Section 3 describes the data we collected, and our identification strategy is given in section 4. Section 5 presents the estimation results. Section 6 discusses the role of refiners' behavior in explaining our findings, and section 7 concludes.

2. Regulatory Background

2.1 Ground-level ozone formation

The primary goal of gasoline content regulation is to reduce ambient concentrations of ground-level ozone by targeting emissions of its chemical precursors: VOCs and NO_x . The chemical reactions through which VOCs and NO_x form ozone are complex in several ways that are important to gasoline regulation and this study. First, ozone formation requires warm temperatures and sunlight; gasoline content regulations therefore tend to be particularly stringent during the summer. Second, the ozone production function exhibits Leontief-like properties in its inputs of VOCs and NO_x . That is, in areas in which VOC concentrations are relatively high,

ozone formation is “NO_x-limited” in that marginal reductions in VOC emissions will not affect ozone concentrations, but marginal reductions of NO_x emissions will. Conversely, areas with relatively high NO_x concentrations are said to be “VOC-limited.” Third, and finally, VOCs include a large number of chemical compounds across which the reactivity in forming ozone varies considerably: some compounds are nearly 80 times more reactive than others. The effectiveness of gasoline content regulations may therefore hinge on whether they target VOCs or NO_x in a way that matches the VOC or NO_x limitations of specific geographic areas, and whether they are effective in reducing emissions of those VOCs that are particularly reactive in forming ozone.

VOCs and NO_x are emitted by sources other than gasoline. Large NO_x emissions sources include electric generation plants, industrial boilers, and kilns. The use of solvents and paints contributes to VOC emissions, though the largest VOC sources are actually biogenic: deciduous trees are particularly significant contributors. It is because of these natural emissions that ozone formation in rural areas is generally NO_x-limited, while urban areas tend to be VOC-limited (Sillman 1999, Blanchard 2001).²

2.2 Reid vapor pressure (RVP) regulations

Gasoline regulations first targeted ground-level ozone pollution with the introduction of Reid vapor pressure (RVP) regulation in 1989. RVP, which is measured in pounds per square inch (psi), gauges the intensity with which VOCs are released from gasoline through evaporation. RVP regulation limits the RVP of gasoline sold during the summer months when hot, sunny weather is conducive to ozone formation, and reduces both on-road VOC emissions from vehicle exhaust and evaporative emissions that occur during vehicle fueling (the fumes you smell when fueling your vehicle are VOCs). Refiners meet the RVP limits by reducing the

² There are exceptions. Rural areas immediately downwind of an urban plume are sometimes VOC-limited. Urban areas in the heavily-wooded South, such as Atlanta, can sometimes be NO_x-limited.

concentration of “light” components—particularly butane—in the gasoline they sell (Lidderdale 1999).

RVP regulation was introduced in two phases. Under phase I, which covered 1989 through 1991, each of the contiguous 48 states was assigned an RVP limit during the summer months. The limit varied by state according to EPA modeling of where VOC emission reductions were most needed, and took on a value of 10.5, 9.5, or 9.0 psi, with lower numbers indicating a tighter standard. The summer compliance period was June 1 – September 15 for retail gasoline stations and May 1 – September 15 for refiners and wholesale distribution terminals. RVP limits in some states were more stringent in July and August than in June and September, and Texas and Illinois had within-state differences in their limits. Table 1 provides state-level detail of the RVP phase I program.³

RVP Phase II began in 1992 and required all counties in the United States to meet a summer RVP limit of at most 9.0 psi, which had been the most stringent limit under phase I. Moreover, RVP II mandated a tighter 7.8 psi summer RVP limit in ozone nonattainment areas in southern states. This tight limit reduces VOC emissions from gasoline by at least 15% relative to the 9.0 psi limit (EPA 1993). In addition, some areas implemented even stricter limits, as low as 7.0 psi, as part of their plans to meet the EPA’s ozone standard, and the entire state of California adopted an RVP standard of 7.8 psi. RVP phase II regulations remain active today, though in some areas they have been superceded by RFG or CARB standards, discussed below. RVP phase II details are provided in table 2. Figure 1 summarizes the timing with which RVP and subsequent regulations came into effect, and figure 2 provides a map of affected areas.

2.3 Reformulated gasoline (RFG) regulations

Federal reformulated gasoline (RFG) was mandated by the Clean Air Act Amendments of 1990, and the EPA began to enforce RFG regulations in 1995. RFG is federally mandated in

³ Details of the RVP phase I program, as well as RVP phase II and the RFG program, were extracted from the Code of Federal Regulations (40 CFR Part 80).

areas designated to be in severe nonattainment of the EPA's ozone standard. Marginal, moderate, and serious nonattainment areas, which are not as polluted as severe areas but nonetheless fail to meet the EPA's ozone standard, may opt-in to federal RFG as part of their plans to reach attainment. A detailed listing of where and when RFG has been implemented is provided in table 3.

RFG was imposed in two phases: phase I came into force in 1995 and phase II in 2000. Like RVP regulations, RFG targets ground-level ozone; however, RFG regulations are tighter than those of RVP and involve both content criteria and performance standards. Under phase I, RFG must contain no more than 1% benzene, a toxic carcinogen that is also a VOC, and must contain at least 2% oxygen via use of an oxygenate such as MTBE or ethanol.⁴ Phase I RFG must also reduce both VOC and toxic air pollutant (TAP) emissions by 15% relative to conventional gasoline. TAPs consist of five chemical compounds, including benzene, that are known carcinogens and are also VOCs.⁵ In addition, the NO_x emissions of phase I RFG must not exceed those of conventional gasoline. The benzene, TAP, and NO_x standards are year-round, while the VOC standard applies only during the summer ozone season of June 1 – September 15. Phase II RFG tightened the seasonal VOC emission reduction standard to 25% while also tightening the TAP standard to 20%. In addition, phase II introduced a NO_x reduction requirement of 5.5% that applies year-round.

California and Arizona have implemented their own reformulated gasoline programs that are more stringent than federal RFG. Beginning in March 1996, California Air Resources Board (CARB) gasoline was required throughout the entire state of California, including rural parts of the state that were in attainment of the EPA's ozone standard. Like federal RFG, CARB gasoline caps the benzene content of gasoline at 1% by volume. CARB gasoline targets VOC emissions

⁴ Oxygenates are used to reduce carbon monoxide (CO) emissions, particularly in the winter. In addition to oxygenate requirements through RFG, some non-RFG areas with CO pollution problems have their own oxygenate programs. The effectiveness of oxygenates in reducing ambient CO concentrations is not examined in this study.

⁵ The TAPs are benzene, 1,3-butadiene, polycyclic organic matter, formaldehyde, and acetaldehyde. Of these, only benzene naturally occurs in gasoline; the others are combustion products. Benzene exhaust and non-exhaust (evaporative) emissions are estimated by the EPA to comprise 70-75% of all toxics emissions from gasoline. All five toxics are VOCs, though benzene is not strongly reactive in forming ozone.

more stringently than RFG, applying both a seasonal 7.0 psi RVP limit and year-round content criteria that limit concentrations of olefins (6% by volume) and aromatic hydrocarbons (25% by volume). Both of these classes of VOCs are highly reactive in forming ozone—CARB (2007) estimates that they are three to ten times more reactive than butane, the compound that refiners remove from gasoline to meet federal RVP standards. In addition, CARB gasoline mandates an 80% reduction in sulfur content to reduce emissions of both sulfur dioxide and NO_x.⁶ These standards are collectively more stringent than those of federal phase II RFG. Finally, Arizona's Cleaner Burning Gasoline (AZCBG) specifies that gasoline sold in the Phoenix area must meet federal RFG phase II specifications in the summer and CARB specifications in the winter.

3. Data

Air quality monitor data

We obtained data on ambient air concentrations of ozone from the EPA's Air Quality Standards database for 1989-2003.⁷ This database reports hourly readings from the EPA's network of air quality monitors. We use these data to construct two measures of ozone concentrations at the monitor-day level: the daily maximum concentration and the daily 8 hour maximum. This latter measure is constructed by calculating the average ozone concentration within all 8 hour periods of each day, and then taking the maximum of these averages. We choose these two measures because the EPA's ozone standards have been built around them. The effective standard until June 2004 was a daily maximum ozone concentration of 0.12 parts per million (ppm); this was replaced by an 8 hour standard of 0.08 ppm. These standards reflect what the EPA believes are the maximum allowable ozone concentrations that protect public health.

⁶ We do not examine the impact of CARB's sulfur standards on sulfur dioxide concentrations in this study. The removal of sulfur affects NO_x emissions because sulfur inhibits vehicles' on-board NO_x emission control equipment.

⁷ Data are available beyond 2003; however, both federal and California gasoline regulations began to restrict the sulfur content of gasoline in 2004. These new sulfur standards could affect NO_x emissions and confound our analysis of RVP, RFG, and CARB regulations; we therefore do not use data from this period in our analysis. The effectiveness of these sulfur programs on urban air concentrations of ozone, NO_x, and sulfur dioxide remains a topic for future research.

We follow EPA data standards by disqualifying all monitor-days for which observations are not recorded for at least 9 hours between 9am and 9pm. We also disqualify monitor-years for which more than 25% of the days during the summer ozone season (1 June – 31 August) report no observation. Finally, we drop from the dataset monitors located in a county that is adjacent to a county treated with a more stringent regulation. Conversations with EPA staff have indicated that federal RFG is sometimes sold in non-RFG counties that border RFG areas to reduce fuel distribution costs; thus, such counties may not be true controls. Dropping these monitors reduces the dataset by 9.8%, and does not substantially affect the estimated results.

Table 4 describes the sample of monitors used in this study. We possess measured ozone concentrations for a total of 1,144,026 monitor-days. The number of monitors increases over our sample frame from 720 to 945, indicating that the monitoring network grows at a rate of 2.0% per year. Roughly 80% of the monitors are located in rural and suburban settings, with the remaining 20% located in urban areas.⁸ The “total counties” column of table 4 indicates that the set of monitored counties grew by 1.3% per year, demonstrating that the growth in monitors came from both adding previously unmonitored counties as well as increasing the number of monitors in previously monitored counties.

The right-most four columns of table 4 display the number of monitored counties, by year, for each of four types of content regulation: RVP phase I (counties with RVP limits of 9.5 and 10.5 psi), RVP phase II (limits of 7.8 psi and below), federal RFG, and CARB. Counties not enumerated in any of the four columns have an RVP limit of 9.0 psi under either RVP phase I or phase II. RVP phase II is seen to begin in 1992 with the introduction of stringent RVP limits in southern ozone nonattainment areas. In 1995, approximately 30 of the monitored counties that had been observing these strict limits adopted RFG. While these counties still technically participate in the RVP program, the RVP requirements are superceded by the RFG standards.

⁸ The urban, suburban, and rural designations are provided by the EPA. We have spot checked 100 monitors based on their latitude and longitude data in Google Earth and confirmed this location classification based on our judgment.

1995 also saw about 80 monitored counties that had been observing an RVP standard of 9.0 psi adopt RFG.

Table 4 also demonstrates the introduction of CARB reformulated gasoline throughout the entire state of California in 1996. 6 counties in the Los Angeles-San Diego area that had been observing federal RFG switched to the CARB formulation, and the remainder of the state switched from the RVP 7.8 psi standard to CARB. Over 1996-2003, we observe monitors in 48 to 50 of these counties, out of 58 California counties in total.

Weather data

We control for weather in our analysis because ozone concentrations increase with temperature and sunlight. We acquired weather data measurements from the National Climatic Data Center's Cooperative Station Data (NOAA, 2008), which provide daily minimum and maximum temperatures, rain, and snowfall at more than 20,000 weather stations across the United States.⁹ These weather stations are not typically located adjacent to a pollution monitor and many have missing observations. To obtain a daily weather observation at each pollution monitor, we use the following algorithm. First, we calculate the Vincenty distance of each pollution monitor to all weather stations. We then identify the ten closest weather stations to each pollution monitor, provided that each is less than 50 miles from the monitor and the elevation difference between the monitor and the station is less than 500 vertical feet. Of these stations, we identify the "primary station" as the closest station for which 50% of the pollution monitor's daily readings can be matched to the station's weather data. We then match the four climate variables for this station to the time series of ozone measurements.

Following these steps, 10.2% of the daily ozone measurements are not matched to a full set of weather variables from a primary station. We fill in these missing values by first regressing, for observations in which the primary weather station was active, the relevant

⁹ Modeled weather data at an even finer spatial scale are available from the PRISM group, but only at a monthly frequency.

weather variable for the primary station onto the same variable for the remaining nine closest stations. We use the predicted values from that regression to replace missing values. Following this step, primary station observations are still missing whenever one of the remaining nine closest stations is also missing an observation. To estimate the remaining missing values, we repeat the above step with the 8 closest stations, then the 7 closest, etc. At the end of this procedure, less than 0.1% of the remaining ozone monitor observations are still missing a matching climate observation. We drop these observations from our analysis.

To check the performance of our algorithm, we conduct the following experiment. First, we select the set of data points for which the primary weather station has an observation. We then randomly set 10% of the temperature data for this station to missing. After applying the algorithm described above to this sample, we compare the predicted temperature data to the observations we had set aside. Even for observations in which a single additional weather station was used to predict a missing temperature, the correlation coefficient between actual and predicted temperatures exceeds 0.95. Plotting the actual and predicted series against each other provides an almost perfect fit. We therefore feel confident that our algorithm provides us with a close representation of the true data generating process for missing weather observations.

Plots of air quality and temperature data

Figure 3 plots the daily maximum ozone concentrations in our sample, averaged across June, July, and August of each year. The data are grouped by the type of regulation employed by each county. The solid thin line plots concentrations for “control” counties that have a standard 9.0 psi summer RVP limit under RVP phase II. The dashed thin line tracks mean concentrations for counties which adopted an RVP standard of 7.8 psi or lower under RVP phase II, but were never treated with RFG or CARB. The solid thick line corresponds to counties treated with RFG but not CARB, and the dashed thick line represents CARB counties.

The ozone levels across the four county types reflect the fact that gasoline regulations targeted counties with air pollution problems. RVP counties have slightly higher ozone

concentrations than control counties, and RFG and CARB counties have concentrations that are substantially higher. The stringent RVP standards of 7.8 psi or lower came into effect in 1992; however, the raw data in the graph show no indication that ozone concentrations decreased in RVP counties at this time. Federal RFG began in 1995 and CARB began in 1996; the effects of these regulations cannot be clearly discerned from the graph alone. For example, while California experienced a large decrease in ozone concentrations during our sample period, it is not clear without further analysis whether these reductions were due to gasoline regulations or other factors.

Figure 4 plots the average daily maximum temperature by year for the same summer months as figure 3, broken out by the same types of counties. A comparison of these two graphs shows the strong correlation between temperature and ambient ozone concentrations. In particular, hot summers in RFG counties (1995, 1999, and 2002) and California (1994 and 1996) are associated with high ozone concentrations. This strong correlation underscores the need to control for weather in the formal empirical analysis.

4. Empirical Strategy

Our goal is to identify the extent to which each gasoline program affects ambient ozone concentrations. Specifically, we aim to distinguish the effects of the following types of content regulation:

1. Summer RVP of 9.0 psi (some counties, 1989-1991; most ozone attainment counties, 1992 onward)
2. Summer RVP of 9.5 psi or 10.5 psi (many counties, 1989-1991)
3. Summer RVP of 7.8 psi or below (southern ozone nonattainment counties and northern opt-in counties, 1992 onward)

4. Federal RFG (severe ozone nonattainment and opt-in counties, 1995 onward)¹⁰
5. CARB (all California counties, 1996 onward)

Throughout our empirical discussion, we treat regulation 1, summer RVP of 9.0 psi, as a “baseline” against which the other four regulations are compared. We assess the impacts of these regulations using both a difference-in-difference (DD) method and a regression discontinuity (RD) design.

4.1 Difference-in-difference (DD)

In the DD approach, identification of the regulations’ effects comes from the year-to-year change in air quality following the introduction of a particular regulation in treated areas, compared to the contemporaneous change in control areas. We restrict our sample to the summer months of June through August, when ozone levels are at their seasonal peak and the effectiveness of gasoline regulations is most crucial. Moreover, RVP regulations are in effect only during the summer months, as are the VOC control components of RFG and CARB regulations.

We apply the DD method using a sample of observations at the monitor-day level and use both each monitor’s daily maximum reading and its daily 8 hour maximum reading as dependent variables. Our most basic DD model is given by equation (1) below, in which y_{it} denotes the value of one of these two variables as recorded at monitor i on date t . \mathbf{Treat}_{ct} is a vector of four variables indicating whether the county c in which monitor i is located is subject to one of the four possible regulatory treatments at time t (excluding the baseline RVP standard of 9.0 psi). α is a four-element vector of parameters whose estimation is of primary interest.

$$\ln(y_{it}) = \alpha \cdot \mathbf{Treat}_{ct} + \mu_i + \eta_{ry} + \varepsilon_{it} \quad (1)$$

¹⁰ We have carried out analyses that attempt to distinguish the effect of RFG phase II in 2000 from that of phase I. These regressions indicate no evidence of an incremental effect of RFG II and, for brevity, are omitted here.

Equation (1) includes a set of monitor fixed effects, denoted by μ_i , that control for unobservables that cause some locations to, on average, have higher ozone concentrations than others. These fixed effects prevent the estimates of the treatment effects, α , from being biased upward by the fact that treated counties generally have higher levels of ozone pollution, both before and after treatment, than do control counties. Also included in (1) are fixed effects η_{ry} for the interaction of the four U.S. census regions r with each year y . These interactions control for unobserved year-to-year shocks that are common to both treated and untreated monitors within each census region. Finally, ε_{it} represents an unobserved disturbance.

The identification assumption underlying (1) is that county-specific unobserved factors affecting ozone concentrations are constant over time. Formally, identification of α requires that $E[\mathbf{Treat}_{ct} \cdot \varepsilon_{it} \mid \mu_i, \eta_{ry}] = 0$. This assumption may not hold, however, if air quality in treated counties has a long-term trend that differs from the trend in control counties. Treated counties are generally those that are in non-attainment for ozone and may experience forces that cause their ozone concentrations to increase or decrease over time relative to control counties. Economic activity may grow more quickly in treated areas, which tend to be relatively urban, putting upward pressure on ozone. However, these areas may also be undertaking pollution abatement actions that could result in a downward trend, relative to control counties. In either case, such a differential trend in treated vs. control counties will bias the estimate of α : the first case will create upward bias, while the second will create downward bias.

To control for factors that affect treated and control counties differentially over time, we augment (1) with additional variables to form specification (2) below:

$$\ln(y_{it}) = \alpha \cdot \mathbf{Treat}_{ct} + \beta \cdot \mathbf{W}_{it} + \gamma_r \cdot \mathbf{D}_{rt} + \delta \cdot I_{ct} + \theta \cdot \mathbf{Trend}_{rct} + \mu_i + \eta_{ry} + \varepsilon_{it} \quad (2)$$

In (2), the variables \mathbf{W}_{it} control for monitor-specific weather shocks and include a flexible polynomial in temperature and precipitation, as well as interactions of these variables with day-

of-year and day-of-week.¹¹ \mathbf{D}_t denotes a vector consisting of six dummy variables for day-of-week and a day-of-year variable. The coefficients γ_r on \mathbf{D}_t are census region-specific. I_{ct} denotes county-level total annual personal income (BEA, 2008). Finally, the set of variables denoted by $Trend_{rct}$ are linear time trends that are specific to treated and control counties within each census region. That is, counties that are treated with RFG in census region 1 are given a trend that is distinct from region 1 counties that are treated with RVP or not treated at all.¹² These trends are included in the specification to attempt to distinguish the impacts of gasoline regulations from long-run trends driven by unobservables.¹³

The identification assumption of the augmented DD model (2) is that unobserved factors are not correlated with treatment, conditional on the covariates; that is, $E[Treat_{ct} \cdot \varepsilon_{it} \mid \mathbf{W}_{it}, \mathbf{D}_t, I_{ct}, Trend_{rct}, \mu_i, \eta_{ry}] = 0$. This identification assumption, while more relaxed than that of (1), may nonetheless be invalid if unobserved factors exist that affect ozone concentrations in a way that is non-linear over time and not captured by any of \mathbf{W}_{it} , \mathbf{D}_t , or I_{ct} .

For inference, we allow the unobserved disturbance ε_{it} to be correlated across all observations within the same state and year. The standard errors we report therefore use a robust variance estimator that is clustered on each state-year combination (Arellano 1987, Wooldridge 2003).¹⁴

¹¹ Specifically, \mathbf{W}_{it} includes cubic polynomials in maximum and minimum temperature (T_{max} and T_{min}), the interaction of T_{max} and T_{min} , quadratics in rainfall and snowfall, the interaction of rainfall with T_{max} , one-day lags of T_{max} and T_{min} , T_{max} interacted with lagged T_{max} , and T_{max} interacted with lagged T_{min} . \mathbf{W}_{it} also interacts all of these variables with a day-of-year variable to allow weather effects to vary over the summer, and interacts T_{max} , T_{min} , rainfall, and snowfall with day-of-week dummies to allow for variations in ozone formation on weekdays and weekends.

¹² Moreover, counties that are initially treated with RVP and then subsequently treated with RFG receive a time trend that is distinct from those of counties that were treated with only one of RVP or RFG. CARB counties, as well as counties in the Los Angeles area that had federal RFG in 1995 and CARB from 1996 onwards, also receive their own trends.

¹³ We have also attempted to control for unobserved time-varying factors by estimating a version of (2) that includes dummy variables for each county's attainment status for ozone and five other "criteria" pollutants: particulate matter, NO_x , sulfur dioxide, carbon monoxide, and lead. Including these variables has only a negligible impact on the estimated treatment effects, reflecting the fact that very few treated counties change their ozone attainment status during the sample period.

¹⁴ We investigated whether within-monitor, cross-year correlation is important by regressing the residuals from equation (2) on the within-year residuals and a set of residuals lagged by approximately one year. When this set of one year lagged residuals includes only the 365 day lag, the point estimate of this lag is only 0.003 and is not statistically significant. When additional lags ranging from 365 to 390 days are also included, some are statistically

4.2 Regression discontinuity (RD) design

In the RD approach, identification of the regulations' effects comes from the change in ozone concentration within a narrow window around the phase-in of each regulation. We are able to focus on a short time period because: (1) imposition of a gasoline standard affects all cars simultaneously, implying that the standard will cause a step change in emissions almost immediately after implementation; and (2) ozone decomposes overnight, meaning that daily maximum ozone concentrations will respond quickly to changes in emissions. This approach permits an identification assumption that is more relaxed than that of the DD model. While identification of the DD equation (2) requires that unobserved variables affecting ozone concentrations do so only through a linear time trend, the RD model permits unobserved factors to act non-linearly over time, so long as they are not discontinuous when gasoline regulations phase-in (Hahn, Todd, and Van der Klaauw 2001).¹⁵

Our implementation of the RD design is similar to that of Davis (2008). We estimate equation (3) below, which is more flexible than the DD model (2) in a number of ways. In (3), the treatment effects α_i and the coefficients β_i on the weather variables are monitor-specific.¹⁶ In addition, the linear time trend in (2) is replaced in (3) with $f_i(\text{Date}_i)$, a fifth-order Chebychev polynomial in time that is also monitor-specific.¹⁷ We therefore estimate (3) one monitor at a time. This monitor-specific approach permits considerable flexibility in the manner in which

significant, but the magnitudes of the point estimates are always lower than 0.07. We therefore believe that clustering on state-year yields an accurate estimate of our estimates' standard errors. We repeated this exercise for our RD estimates and obtained similar results.

¹⁵ The discontinuity in our approach is across time, rather than a more traditional cross-sectional discontinuity at a treatment threshold. We do not use a cross-sectional threshold, such as the ozone concentration that triggers a non-attainment designation by the EPA, because such an approach would not address the factors we seek to control for in the RD: other regulatory actions that are brought about by a non-attainment designation. Moreover, this approach would be of no help in evaluating the impact of CARB regulation, which affected every county in California regardless of its pre-treatment ozone level.

¹⁶ In the RD model (3) we expand the number of weather variables by interacting them with seasonal dummies, and we also include stand-alone month dummies.

¹⁷ We have also used a sixth-order and eighth-order polynomial; doing so does not substantially affect the results presented here. Shortening the sample window from 1989-2003 to 1989-2000 also does not substantially alter the results.

both observed and unobserved factors can influence ozone concentrations while simultaneously allowing us to evaluate spatial heterogeneity in the treatment effects.

$$\ln(y_{it}) = \alpha_i \cdot \mathbf{Treat}_{ct} + \beta_i \cdot \mathbf{W}_{it} + f_i(\mathbf{Date}_t) + \mu_i + \varepsilon_{it} \quad (3)$$

We estimate (3) using data from all seasons of the year so that observations near the regulatory transitions that occur in the spring and fall are included in the sample. We restrict the sample to monitors that deliver valid daily readings for more than 75% of each calendar quarter for 75% of all possible quarters. This sample therefore represents a set of monitors that consistently record concentrations year-round and is smaller than the set of summer monitors used in the DD analysis.¹⁸

To identify the effects of RVP phase II and federal RFG, we focus on counties that only experienced a single change in regulation over the 1989-2003 sample frame. For example, to evaluate the effect of an RVP phase II limit of 7.8 psi or lower, we use the set of counties that received RVP II in 1992 and were not treated with RFG or CARB in a later year.¹⁹ We further ensure that there are a sufficient number of pre-treatment observations by enforcing that all monitors be active for 75% of the days in 75% of the quarters prior to treatment. Both RVP phase II and RFG regulations are modeled so that they are in effect only during the summer VOC control periods. In an RVP county, for instance, the element of \mathbf{Treat}_{ct} corresponding to RVP phase II takes on a value of one if retail gasoline stations in county c are required to stock and sell RVP-limited gasoline on date t .

The regulatory discontinuity at the start and end of each summer's VOC control period is not sharp. Gasoline at retail stations and in the gas tanks of vehicles does completely turn over in a single day. We therefore assume that the treatment's phase-in is linear between the date that refiners are required to produce the regulated gasoline and the date that gas stations are required

¹⁸ When the DD specification (2) is estimated using the same sample of monitors used to estimate the RD specification (3), results are similar to the DD results shown in table 6.

¹⁹ Similarly, we only estimate the effect of RFG using counties that were not previously treated with an RVP phase II limit of 7.8 psi or lower. The implication of this choice is that our RFG RD results only reflect counties in the northern half of the U.S.

to stock and sell it—a 30 day period. At the end of the summer VOC control season we allow a 30 day linear phase-out as conventional gasoline returns to retail stations and into vehicles' gas tanks.

In our RD estimation of the effect of CARB regulation, we model CARB as a year-round treatment that becomes effective on the date of its introduction: 1 March, 1996. While CARB does include a seasonal RVP limit, CARB's restrictions on the content of olefins and aromatic hydrocarbons—both highly reactive in forming ozone—are year-round.²⁰ We allow for a linear ramp in the element of $Treat_{ct}$ corresponding to CARB over the 30 days prior to 1 March, 1996.

Our RD estimation of CARB's effectiveness is complicated by the facts that the entire state of California was subject to an RVP standard of 7.8 psi beginning in 1992 and that six counties in the Los Angeles and San Diego areas were also treated with federal RFG in 1995. In estimating (3), we therefore include in our regressions all elements of $Treat_{ct}$ that are applicable to each county. For example, in modeling ozone concentrations in Los Angeles, we control for potential impacts from RVP during the summers of 1992-1994 and RFG during the summer of 1995.

In all RD specifications, we allow each monitor's time-varying unobserved disturbance ε_{it} to be correlated across all observations within each year-season. Thus, we estimate standard errors of our parameter estimates using a clustered robust variance estimator (Arellano 1987, Wooldridge 2003).

²⁰ Even though ground-level ozone concentrations are relatively low in the winter, CARB enforces its olefin and aromatic hydrocarbon content limits in all months of the year because these compounds are toxic and therefore cause health problems independently of their ability to form ozone (CARB, 2009).

5. Results

5.1 Difference-in-difference (DD) results

Plots of yearly residuals

Figure 5 depicts the time path of ozone concentrations in counties under different forms of regulation while removing the noise associated with weather shocks. Each panel plots the residuals of a regression of daily maximum ozone concentrations on the weather, day-of-week, and day-of-year variables W_{it} and D_{it} , as well as monitor fixed effects. These residuals are averaged across monitors and dates within each year and regulation type, and offer insight into the estimates of the DD model.

Panel (a) compares the ozone residuals in counties treated with a stringent RVP phase II standard of 7.8 psi or lower (and never treated with RFG or CARB) to baseline counties with an RVP limit of 9.0 psi. These two sets of residuals track each other very closely throughout the sample period: they are typically no farther apart than 0.001 ppm, relative to average concentrations of about 0.06 ppm. The introduction of 7.8 psi RVP gasoline, which occurred in 1992 in most treated counties, does not appear to have substantially affected summertime ozone concentrations.

Panel (b) suggests that the introduction of federal RFG in 1995 may have caused modest reductions in ozone pollution. Prior to 1995, the residual ozone concentrations for RFG counties are higher than those of baseline counties, whereas this pattern is reversed from 1995 onwards. It is possible, however, that this shift may have been part of a trend in which ozone concentrations in RFG counties, relative to baseline counties, gradually decreased over 1992-1996. Similarly, panel (c) indicates a substantial decrease in ozone concentrations in California counties around the time when CARB gasoline was introduced in 1996. Again, it is difficult to discern from this graph alone whether this decrease can be attributed to CARB gasoline or to other factors acting over a multi-year time span. The interpretation of panel (c) is also made difficult by the fact that

the heavily monitored counties in the Los Angeles and San Diego areas were treated with federal RFG in 1995 before adopting CARB standards.

DD Estimation results

The DD estimates of the effect of gasoline content regulations on summer ozone concentrations are given in table 5. The top four rows indicate the estimated effect of RVP phase I (RVPs of 9.5 and 10.5 psi), RVP phase II (RVPs of 7.8 psi and lower), federal RFG, and CARB standards on the logarithm of ozone concentration, all relative to the baseline RVP standard of 9.0 psi. Column I displays the results of estimating specification (1), which includes monitor fixed effects μ_i and region-year effects η_{ry} but no additional controls, and uses the logarithm of the daily maximum ozone concentration as the dependent variable. Neither RVP phase I nor RVP phase II is estimated to have a significant impact on ozone. While both point estimates do have the correct sign (the high phase I RVPs increase ozone relative to the baseline, while the low phase II RVPs decrease it), they are small in magnitude and statistically insignificant. We estimate that imposition of federal RFG is associated with a modest decline in $\log(\text{ozone})$ of -0.029, statistically significant at the 1% level. Only CARB gasoline is estimated to have a large impact on ozone concentrations: the implementation of CARB standards is associated with a decrease in $\log(\text{ozone})$ of -0.095 (equivalent to a 9.1% decrease in absolute ozone concentration) that is statistically significant at the 1% level.

Columns II through IV of table 5 progressively add control variables to the specification, moving from an estimate of equation (1) in column I to equation (2) in column IV. The estimated regulatory effects do not change qualitatively over these specifications. Column II includes variables for weather (W_{it}) as well as day-of-week and day-of-year (D_t). These variables have little effect on the point estimates, though the standard errors decrease slightly and the regression's R^2 increases substantially from 0.02 to 0.26. Nearly all of this increase is due to the inclusion of the weather variables.

Column III controls for county-level annual personal income, causing modest declines in the estimated effects of RVP II, RFG, and CARB regulations. Increases in income are therefore associated with decreases in ozone, consistent with increases in pollution abatement in high-growth counties. Finally, the addition of the time trends in column IV causes a modest decrease in the magnitude of the estimated effect of CARB while increasing the magnitude of RFG's effect, underscoring the importance of controlling for time-varying unobservables.

Columns V through VIII of table 5 repeat the specifications in columns I through IV, but use the logarithm of the daily 8 hour ozone concentration as the dependent variable rather than the daily maximum. These estimated effects vary little from those presented in columns I through IV.

Table 6 presents results that are broken out by whether each monitor is in an urban, suburban, or rural area. The specification used in columns II, IV, and VI is exactly that given by (2), while columns I, III, and V do not include the time trends. Again, little evidence is found of an impact of RVP regulations on ozone concentrations, with the exception of a weak, marginally significant effect in suburban areas when time trends are included. The effects of RFG are strongest in suburban areas; in urban and rural areas RFG is estimated to only have a marginally statistically significant effect, reducing ozone concentrations by 0.4-3.1% depending on the specification. CARB gasoline has significant effects in both urban and suburban areas of about 7% and 10%, respectively. CARB's effectiveness in rural areas is weaker: it is estimated to significantly decrease ozone concentrations by 4% in specification V, but the inclusion of time trends in specification VI yields a small, insignificant effect of 1.7%.

The diminished effectiveness of both federal RFG and CARB gasoline in rural areas likely reflects the Leontief nature of the ozone production function. Because rural areas tend to be NO_x-limited, gasoline regulations, which primarily affect VOC emissions, may be relatively ineffective in these regions.

Table 7 presents results obtained by estimating the same pooled specifications presented in table 5, but using a dataset consisting of only those monitors that report observations during

every year of the 1989-2003 sample period. These results generally report treatment effects that are more negative than those reported in table 5, indicating that the full-time monitors located in treated areas experienced a decrease in ozone concentrations relative to part-time monitors. This outcome could result from the placement of new monitors in areas that are experiencing increases in ozone pollution.

Point estimates for the effect of CARB gasoline on $\log(\text{ozone})$ in table 7 range from -0.118 to -0.148, and estimates for RFG range from -0.018 to -0.055. The effect of RVP phase II is now statistically significant in column IV, in which time trends are included, with an estimated magnitude of -0.025. However, the effects of RVP phase I standards weaker than the 9.0 psi baseline are also estimated to be negative in this specification, with a magnitude of -0.019 that is not statistically significant. Thus, the estimated effect of a stringent RVP phase II standard is not significantly different from that of a lax RVP phase I standard, suggesting again that RVP regulations are not effective in reducing ozone concentrations.

Overall, the results presented in this section provide evidence that CARB gasoline substantially decreases ozone concentrations and that federal RFG may have a modest impact. RVP regulations, however, are not estimated to significantly reduce ozone pollution. The magnitudes of the estimated effects, however, are somewhat sensitive to the inclusion of time trends and the choice of monitors to include in the sample. The regression discontinuity design addresses these issues by allowing for time-varying unobservables and substantial monitor-level heterogeneity.

5.2 Regression discontinuity results: RVP and RFG

The treatment effects we estimate using the RD design are monitor-specific. Figure 6 plots daily ozone concentrations for monitors that are characteristic of our results for RVP phase II and RFG gasoline. The points plotted in each panel are the residuals of a monitor-level regression of $\log(\text{ozone})$ on the weather and seasonality variables W_{it} . The fitted lines are the predicted values of a regression of these residuals on the relevant treatment dummies and a fifth-

order polynomial on date. These plots therefore illustrate our RD specification for RVP and RFG: an abrupt change in the seasonality of the residuals and the fitted line in the year a regulation becomes active is indicative of a significant effect of the regulation on ground-level ozone pollution.

Panel (a) depicts the RD result for pollution monitor 1001 in East Baton Rouge, Louisiana, which was treated with an RVP phase II standard of 7.8 psi in 1992. A shift in neither the residuals nor the fitted line is apparent in 1992. Accordingly, the RD estimate of the effect of RVP on $\log(\text{ozone})$ for this monitor is -0.001 and statistically insignificant.

The blue dotted line in Figure 8 displays a kernel-smoothed cross-monitor distribution of the RD estimates of RVP phase II's effect on the logarithm of ozone concentration. This plot also displays our estimated effects for RFG (black dashed) and CARB (red solid). East Baton Rouge lies at the mean of the RVP distribution, which includes results from 46 monitors. The appendix lists the county-specific RD estimates that make up this distribution, as well as the distributions of RFG's and CARB's impacts. On average, we find that imposition of RVP does not cause a significant reduction in ozone concentrations, consistent with the DD results discussed above.

The distribution of the RFG estimates depicted in figure 8 is shifted slightly to the left relative to that of RVP. Its mean is -0.038, smaller in magnitude than most of the DD estimates of RFG's impact. This distribution includes results from 27 monitors, of which 8 are found to have reductions in ozone that are statistically significant at the 5% level. These monitors are almost all located on the eastern seaboard between Wilmington, Delaware and Long Island, New York (monitor-specific point estimates may be found in the appendix). In most locations, however, the estimates of the RD specifications suggest that federal RFG regulation did not substantially reduce ozone concentrations.

The estimated RFG impact of -0.031 at monitor 4002 in Hampshire County, Massachusetts is at the median of the estimated distribution of RFG's effects. Residual ozone concentrations and a fitted line for this monitor are shown in panel (b) of figure 6. The fitted line

shows a slight drop in summertime daily maximum ozone concentrations following the imposition of RFG in 1995, consistent with a small but statistically insignificant estimated treatment effect. In contrast, the residual ozone concentrations at monitor 1001 in Camden County, New Jersey, displayed in panel (c), exhibit substantial seasonality following the introduction of RFG. From 1995 onwards, the residuals are lower in the summer than during the winter, consistent with a significant impact from RFG regulation. Camden County may be benefiting from RFG-driven reductions in VOC emissions from Philadelphia, Pennsylvania, which is located upwind, just to the west.

5.3 Regression discontinuity results: CARB

Figure 7 illustrates our RD strategy for identifying the impact of CARB regulation. As with figure 6, the points plotted in each panel are residual ozone concentrations recorded at the indicated pollution monitor. Because California was treated not only with CARB in 1996, but also RVP (7.8 psi) in 1992 and RFG in 1995 (in the Los Angeles and San Diego area), the fitted line includes treatment dummies for all three types of regulation. Panel (a) depicts residual ozone concentrations at monitor 1201 in northern, coastal Los Angeles County, California, while panel (b) displays the residuals for monitor 1701, located in the interior of Los Angeles county just east (and downwind) of the intersection of the San Bernardino Freeway (I-10) with the Orange Freeway (SR-57). These two locations are indicated on a map of the Los Angeles area in figure 9, panel (a).

While the coastal monitor in panel (a) of figure 7 indicates little evidence of an impact of CARB on ozone, the residual concentrations shown for the inland monitor 1701 in panel (b) reveal an abrupt, substantial reduction in ozone concentrations in early 1996. These plots reflect our RD estimates of CARB's effect at each monitor. For the coastal monitor, our point estimate is that CARB reduced ozone concentrations by 10.2%; however, this result is not statistically distinct from zero (the t-statistic is -0.986). At the inland monitoring location, in contrast, we

find that CARB reduced ozone concentrations by 35.2%, statistically significant at the 1% level.²¹

The impact of CARB gasoline on ozone is therefore spatially heterogeneous. The spatial distribution of our monitor-specific estimates is indicated on the maps of Los Angeles and California in figure 9, panels (a) and (b), respectively. Specific point estimates and standard errors for each monitor are given in the appendix. Nearly all of the statistically and economically significant effects are found in the inland Los Angeles and San Diego areas that feature high temperatures, dense populations, high baseline ozone levels, and VOC-limited ozone formation conditions. Areas of the state that do not possess all of these features, such as the San Francisco Bay area or the rural Central Valley, do not appear to benefit substantially from CARB regulation. This pattern of outcomes is consistent with the science of ozone formation. Reductions in the content of ozone-forming VOCs in gasoline will be most effective in areas where gasoline-emitted VOCs drive substantial ozone formation: these areas will be hot, densely populated, and VOC-limited.

The kernel density plot of figure 8 indicates that the distribution of CARB's effect on ozone is shifted to the left relative to that of RFG or RVP: the mean estimated effect of CARB on $\log(\text{ozone})$ is -0.060. Moreover, the CARB distribution features a large left tail of substantial, statistically significant impacts that is not present in the other distributions. This difference is not solely due to the fact that California is different from the states and counties for which we evaluated RVP and RFG. Also plotted in figure 8 are the results from estimating the impact of

²¹ The fitted line in panel (b) also suggests that RVP and RFG led to substantial increases in ozone concentrations at the inland Los Angeles location. We suspect, however, that this result is actually driven by the likelihood that CARB's effect on ozone is greater in the summer than in the winter. This enhanced summer effect may arise because the rate of release of VOCs from gasoline is larger when temperatures are higher and/or because ozone levels are elevated in the summer. Thus, following the imposition of CARB in 1996, the seasonal ozone pattern shifts so that the summer peak is mitigated. Our RD design does not accommodate such a shift; thus, the larger seasonal amplitude prior to 1996 is picked up by the RVP and RFG treatment variables.

We have investigated RD specifications that allow for both a year-round and a seasonal impact of CARB. However, these specifications produce unstable results: the estimated effects are highly variant both spatially and with regard to changes in the specification.

RVP on ozone concentrations in California.²² This distribution is centered near zero and is a close match to the distribution of RVP estimates obtained from monitors in other states (if anything, it is shifted slightly to the right). This last result indicates that RVP regulation was ineffective at the same locations for which CARB regulation significantly reduced ozone concentrations.²³

Overall, the estimates obtained from the RD strategy reaffirm the findings from the DD model and indicate the presence of spatially heterogeneous effects. We find evidence that the introduction of federal RFG in 1995 led to modest decreases in ground-level ozone in New Jersey and New York, but not elsewhere. In California, the adoption of CARB standards in 1996 caused a large, significant decrease in ozone concentrations in the densely populated and heavily polluted southern part of the state. However, we find no evidence that federal RVP standards are effective in reducing ozone pollution, even in California.

6. The importance of refiners' behavioral response

The likely explanation for the failure of RVP regulations to reduce ambient ozone concentrations centers on the flexibility that RVP regulations grant to refiners in meeting RVP's VOC reduction standards. VOCs include a large number of compounds, and while RVP standards cap the overall rate of VOC emissions from gasoline, they allow refiners to choose which particular VOCs to remove.

Refiners meet RVP requirements primarily by removing the VOC butane from their gasoline, as noted by EPA rulemaking.²⁴ Butane is a light, highly volatile compound that refiners typically blend into conventional gasoline to increase its octane rating. Reducing the amount of

²² We evaluated the effect of RVP on ozone in California by estimating equation (3) using data from only 1989-1994, thereby avoiding data from time periods when RFG or CARB were in effect.

²³ Moreover, the spatial distribution of the estimated RVP effects in California is not systematic, as is the case with the CARB impacts. That is, the negative part of the distribution is not concentrated in the Los Angeles and San Diego areas, as would be expected if RVP were effective in reducing ozone concentrations.

²⁴ See in particular the final RVP rule in 40 CFR Part 80 (also in the federal register at 54 FR 11868) and the EPA's regulatory impact analysis for RFG (1993).

butane that is blended is the most cost-effective avenue available to refiners to meet RVP standards. However, butane is not highly reactive in forming ozone (CARB, 2007). Thus, even though gasoline that meets RVP standards emits a substantially lower volume of VOCs than does conventional gasoline, this emissions reduction does not translate into reductions in ground-level ozone.²⁵

Evidence from both the butane market and air quality measurements indicates that RVP regulations substantially reduced the use of butane in summer gasoline. Lidderdale (1999) evaluates the impact of RVP on refining operations and finds that refiners' summer blending of butane substantially decreased following the imposition of RVP standards. In figure 10, we replicate one of Lidderdale's graphs using data from the Energy Information Administration on refinery net production of butane. This plot indicates that butane production becomes highly seasonal beginning in 1989, when RVP standards are first implemented, and that this seasonality is accentuated following the imposition of RVP phase II in 1992. Under RVP, refinery net production of butane is high in the summer, meaning that refiners produce butane as a refinery output rather than blend it into gasoline. The negative net production of butane in the winter indicates that the butane produced in the summer is stored and then blended back into gasoline during the winter when RVP standards are not in effect.

The decrease in summer gasoline's butane content is also observable in ambient air quality measurements. Lee *et al.* (2006) measure air concentrations of a variety of anthropogenic VOCs in Massachusetts over 1992-1996. They find that, unlike other VOCs, summer concentrations of butane dip during the summer. Figure 11 is a reproduction from their paper and clearly indicates that, while the concentrations of pentane and hexane—VOCs similar to butane—peak during the summer, summer concentrations of butane are low relative to its

²⁵ This explanation behind RVP's ineffectiveness prompts the question of why RVP regulations, as well as the VOC reduction mandates of federal RFG, do not distinguish between high and low-reactivity VOCs. According to the final Regulatory Impact Analysis for RFG (EPA 1993), the EPA claims that the Clean Air Act Amendments (CAAA) of 1990 forbid it from using reactivity-weighting when setting VOC emission reduction standards, since the law states that these standards must be set on a "mass basis." The Regulatory Impact Analysis further notes that, while early versions of the CAAAs did not include this "mass basis" statement, the wording was added during the meetings of a conference committee to reconcile differences between the House and Senate versions of the bill.

concentrations during the winter. The authors attribute this result to the RVP standards in place in Massachusetts during the years these measurements were taken.

In contrast to RVP, CARB regulations (and to a lesser extent federal RFG) include restrictions on specific VOCs that are highly reactive in forming ozone. CARB gasoline imposes content limits on classes of compounds called olefins and aromatic hydrocarbons that are three to ten times more reactive than butanes. CARB therefore denies refiners the flexibility to choose which VOCs to remove from gasoline, and forces them to target components that can significantly impact ozone formation, even though these components are more expensive to remove. Thus, we observe substantial air quality improvements following the imposition of CARB gasoline.

The primary feature of federal RFG regulation is its limit on overall VOC emissions, without regard to ozone reactivity. However, the RFG standard does impose a limit on the emissions of toxic air pollutants, some of which are highly reactive VOCs. Thus, we find some evidence that RFG is associated with modest reductions in ozone concentrations. This impact could be described as incidental, however, given that the primary objective of toxic pollutant abatement is to reduce the air concentrations of these carcinogenic chemicals themselves rather than ozone (EPA 1993).

7. Conclusions

This paper examines the effectiveness of three types of gasoline content regulations: federal Reid vapor pressure (RVP) standards, federal reformulated gasoline (RFG), and California reformulated gasoline (CARB). Using ground-level ozone concentration data from the EPA's monitoring network, we find that the imposition of CARB standards substantially reduces ozone pollution, particularly in areas with the most severe *ex ante* ozone problems. We also find some modest evidence that RFG regulations are effective in reducing ozone concentrations. There is no evidence, however, that the RVP regulations are effective. This last result should be

of particular concern to regulators because RVP standards are applied throughout the U.S. and have been shown to adversely affect gasoline markets and prices. The cost imposed on consumers by RVP regulation is substantial: given U.S. non-California 2008 summer gasoline consumption of 47 billion gallons and a \$0.01 - \$0.015 per gallon RVP price effect estimated in Brown *et al.* (2008), RVP regulations increase U.S. annual gasoline expenditures by \$524 - \$784 million.²⁶

RVP's ineffectiveness, in spite of its costs, can be explained by the cost-minimizing response of refiners to the regulation. Because RVP standards grant refiners broad leeway in deciding which specific VOCs to remove from their gasoline, they are able to reduce the content of a particular VOC, butane, that is relatively cheap to remove but is not prone to forming ozone. Refiners do not reduce emissions of VOCs that are highly reactive in ozone formation, driving RVP's ineffectiveness. In contrast, CARB gasoline, and to a lesser extent federal RFG, mandates reductions in concentrations of highly reactive VOCs and yields substantial reductions in ground-level ozone pollution. These outcomes highlight the need for environmental regulations to anticipate and mitigate the behavioral responses of the regulated agents.

The air quality improvement driven by CARB gasoline is substantial in the densely populated southern part of the state. The introduction of CARB in 1996 reduced ozone concentrations by more than 20% at some monitoring locations. Our regression discontinuity estimates indicate that the average ozone reduction across monitors in the severe ozone non-attainment area consisting of Los Angeles, Orange, Riverside, San Bernardino, San Diego, and Ventura counties is 15.6%. Other California counties that are cooler or less densely populated, however, generally do not experience large reductions in ozone pollution following the

²⁶ The \$0.01 - \$0.015 per gallon effect estimated in Brown *et al.* (2008) applies specifically to the price differential between RVP 7.8 psi gasoline and RVP 9.0 psi gasoline. The above calculation assumes that relaxing the summer VOC emission standards of RFG and relaxing the federal "baseline" 9.0 psi standard would have similar price effects. The 47 billion gallon consumption figure was sourced from the EIA (http://tonto.eia.doe.gov/dnav/pet/pet_cons_psup_dc_nus_mbb1_a.htm), using data for May, June, July, August, and half of September.

imposition of CARB. Fortunately, these counties are those for which ozone levels are typically below unhealthy levels.²⁷

Using our estimated ozone reductions for California, a “back of the envelope” calculation indicates that the benefits of CARB gasoline significantly outweigh its costs. Using Bell, McDermott, and Zeger’s (2004) estimates of ozone’s mortality impacts, our RD estimates translate into 660 saved lives in California each year.²⁸ Further, given California’s 2008 gasoline consumption of about 14.8 billion gallons each year and estimates that CARB increases gasoline’s production cost by 8-11 cents per gallon,²⁹ CARB imposes a cost of approximately \$1.2-\$1.6 billion per year. These figures translate into a cost of \$1.8-\$2.4 million per life saved. This range is significantly lower than the EPA’s official value of a statistical life of \$6.45 million (2005 US\$). If we were to factor ozone’s morbidity and environmental impacts into this calculation, CARB gasoline’s benefit to cost ratio would be pushed even further upwards.

If carried out on a county-by-county basis, our simple cost-benefit analysis would of course suggest that CARB should be required in only a select group of counties. However, a comprehensive policy analysis of spatial gasoline regulation must recognize the possibility that fine-tuned regulatory targeting may further segment the gasoline market, potentially increasing gasoline price levels and volatility. Further, CARB (and RFG) may convey health benefits through reductions in emissions of toxic air pollutants. These benefits are not evaluated in this paper and may be significant even in areas for which we do not observe substantial decreases in ozone levels. A full assessment the trade-offs involved in optimizing regional gasoline regulations is beyond the scope of this paper; however, the air quality benefits that we estimate here should serve as useful inputs to future research in this direction.

²⁷ These heterogeneous effects were of course estimated using changes in ozone concentrations at the time of CARB’s introduction: March 1996. Our estimates may not accurately reflect CARB’s *current* impact on ozone to the extent that ozone precursor emissions have changed since 1996.

²⁸ We calculate this impact by first averaging our monitor-level results to the county-level and assuming no effect in non-monitored counties. We then use Bell, McDermott, and Zeger’s (2004) formula, in combination with data on population and pre-CARB ozone levels, to compute county-level estimates of lives saved.

²⁹ The estimated cost range comes from the summation of the 3 cents per gallon estimated price effect of RFG from Brown *et al.* (2008) with a 5 to 8 cents per gallon estimated incremental cost of CARB (CARB, 2008).

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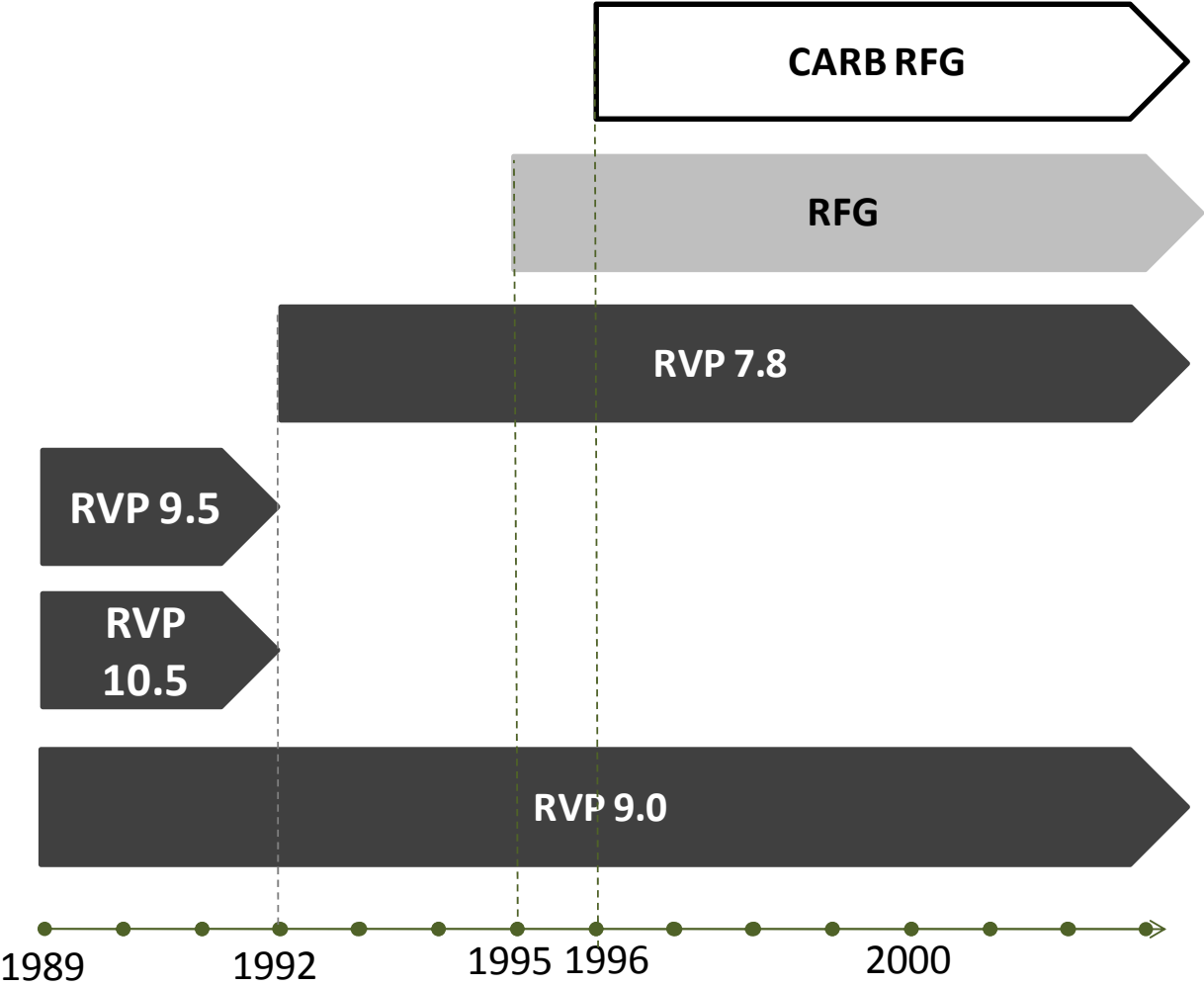
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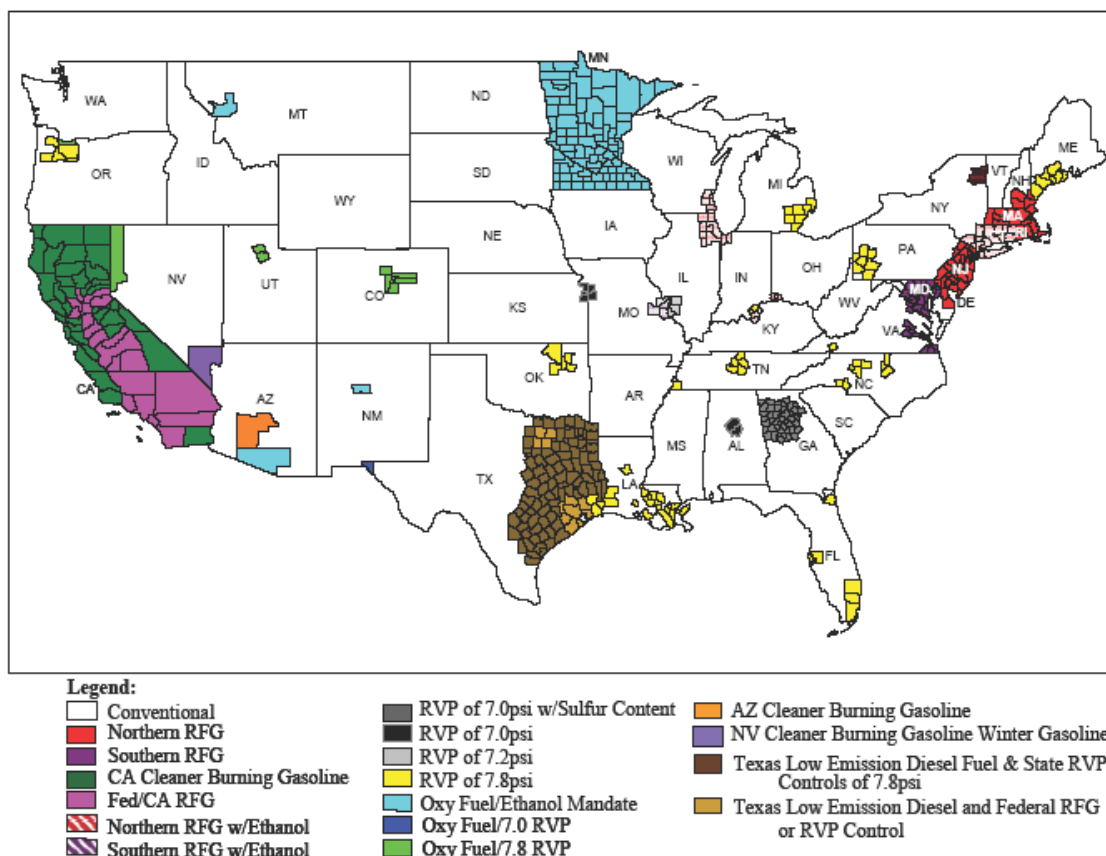
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Figure 1: Regulatory timeline



Notes: RVP: Reid vapor pressure regulation (the number refers to the vapor pressure limit)
RFG: Federal reformulated gasoline
CARB RFG: California Air Resources Board reformulated gasoline

Figure 2: Map of RVP phase II and RFG regulations as of 2006



Source: EPA (Dec., 2006)

Notes: Unshaded “conventional” gasoline areas are subject to the summertime RVP phase II standard of 9.0 psi.

Shaded areas in Minnesota, Colorado, Utah, and Montana have oxygenated gasoline for control of carbon monoxide pollution, but do not have RVP or RFG.

Figure 3: Mean summer ozone concentrations

Broken out by regulation type

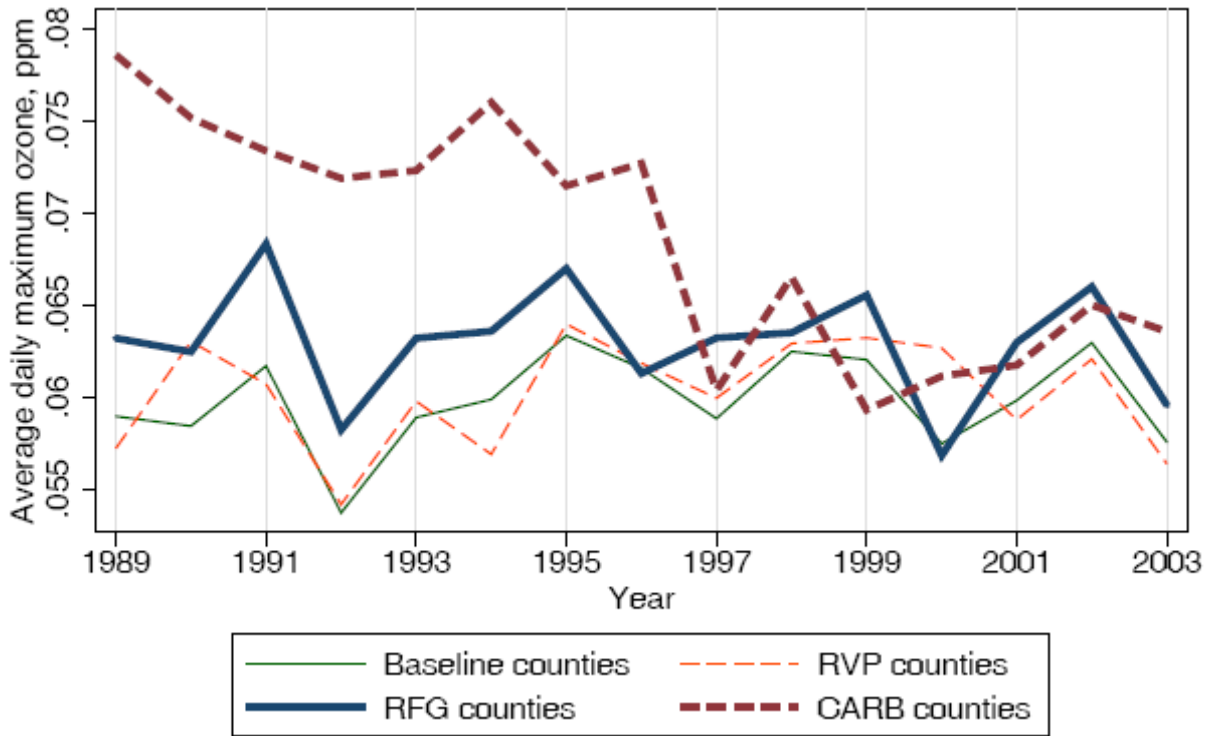


Figure 4: Mean summer daily temperature maxima

Broken out by regulation type

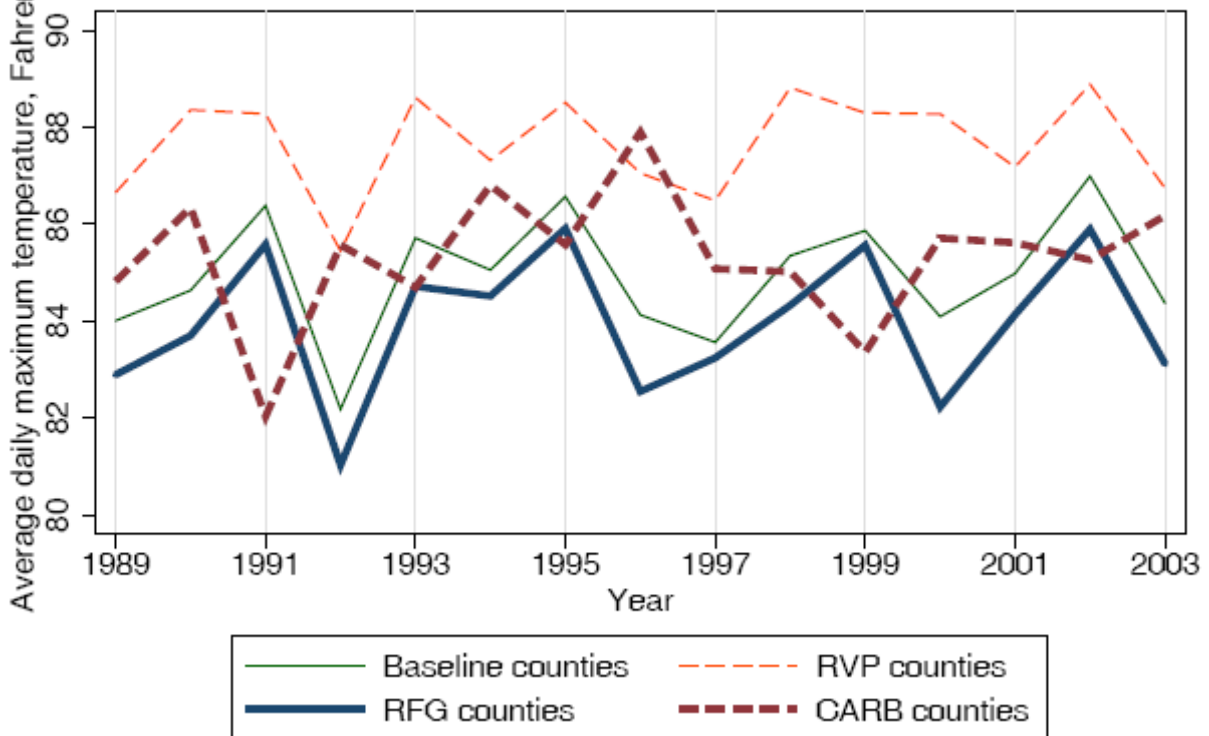
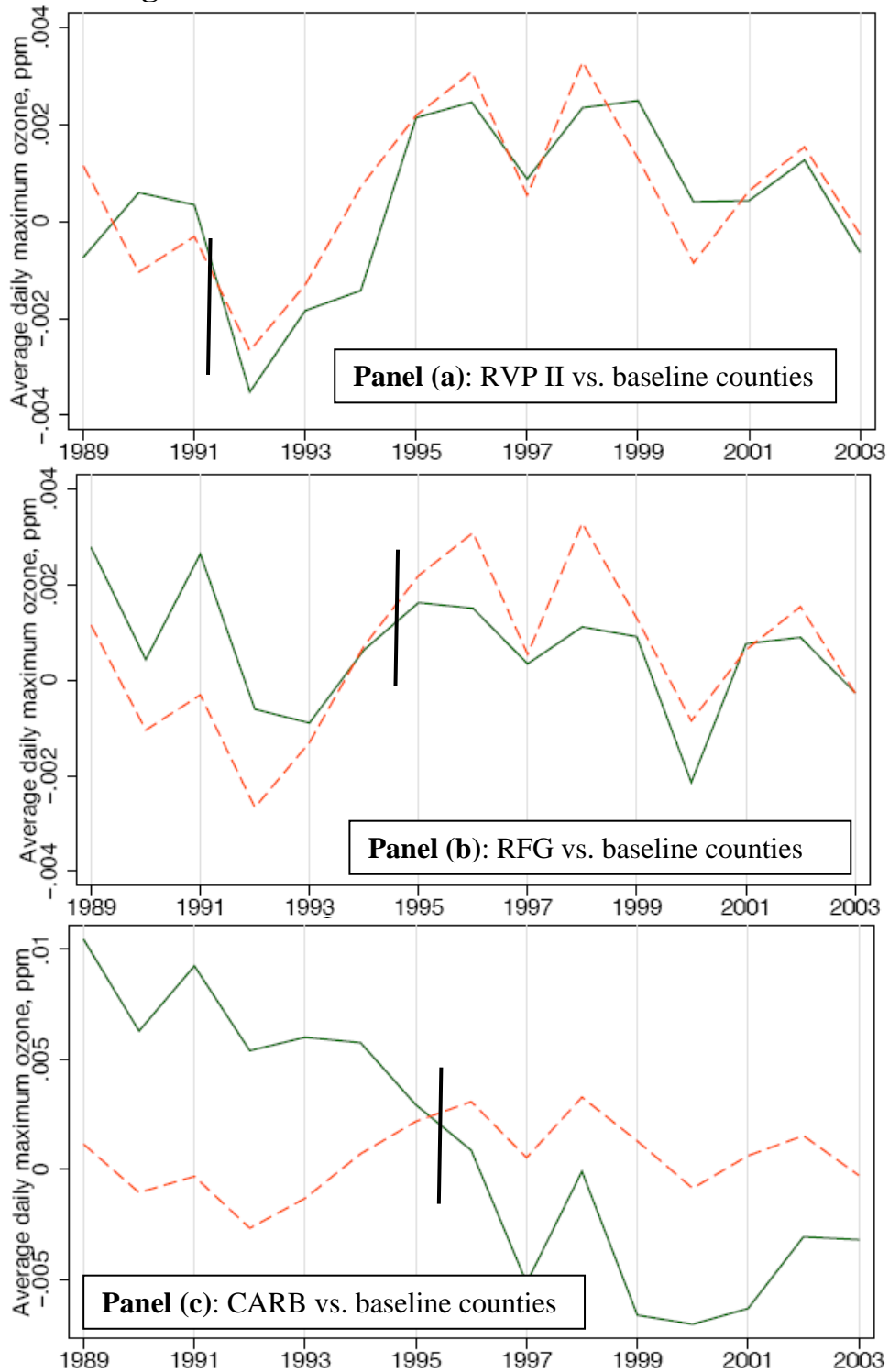
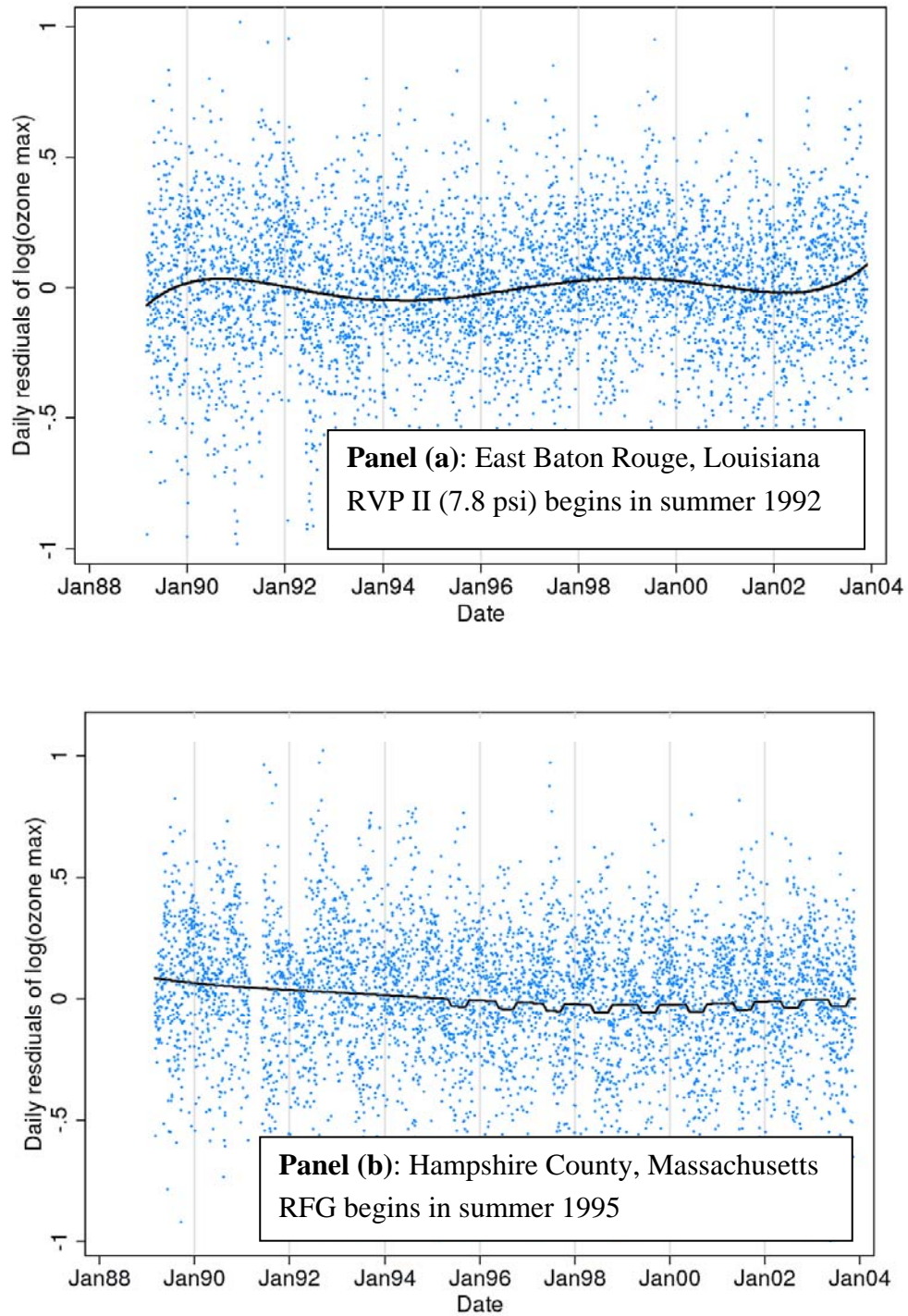


Figure 5: Mean summer ozone concentrations



Notes: Values plotted are averaged residuals of a regression of daily maximum ozone on weather variables W_{it} and D_{it} described in section 4.1 and monitor fixed effects. Solid lines are TREATED counties; dashed lines are BASELINE counties. Vertical bars indicate the first implementation of the indicated regulation. Data include only those monitors recording data in every summer.

Figure 6: Daily maximum ozone concentrations



Notes: Values plotted are averaged residuals of a regression of daily maximum ozone on weather and seasonality variables W_{it} described in section 4.2. Fitted lines are the predicted values obtained after regressing the residuals on regulation dummies and a fifth-order polynomial on date.

Figure 6, continued: Daily maximum ozone concentrations

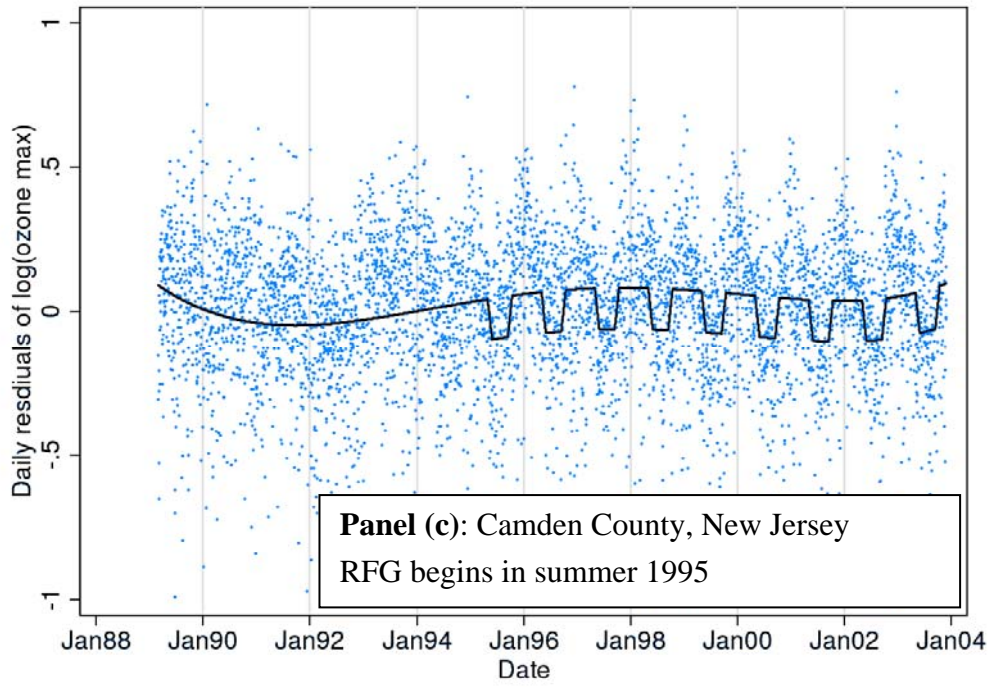
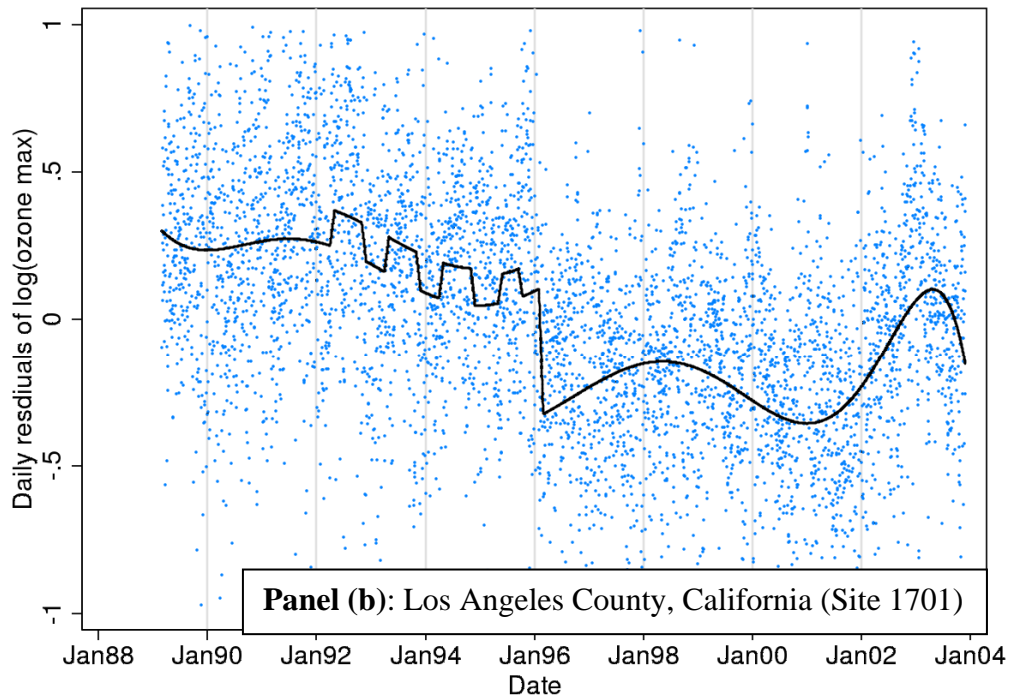
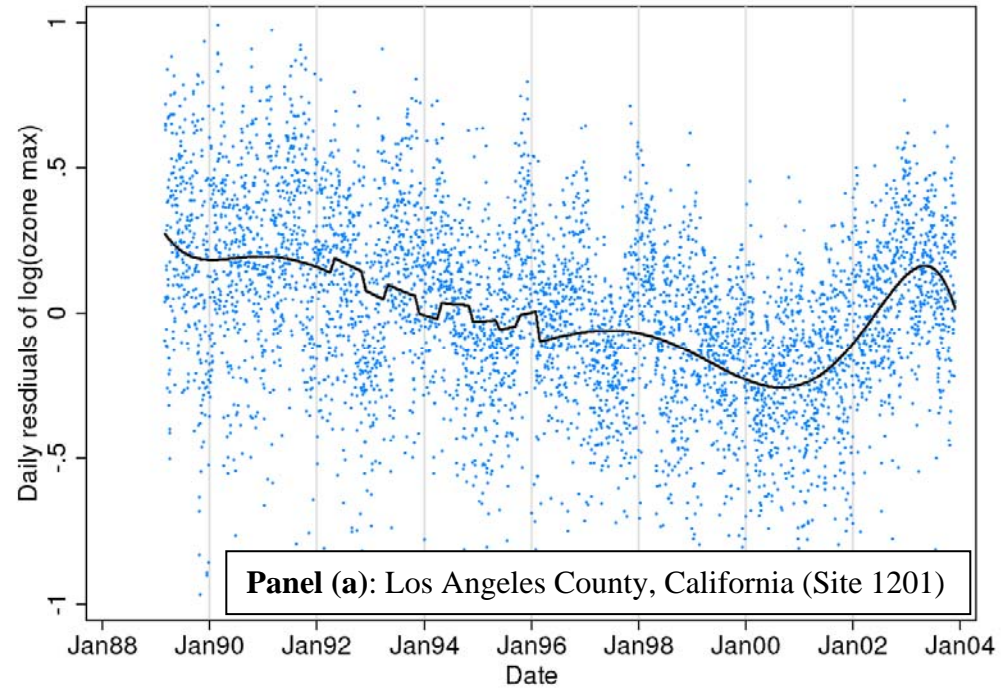
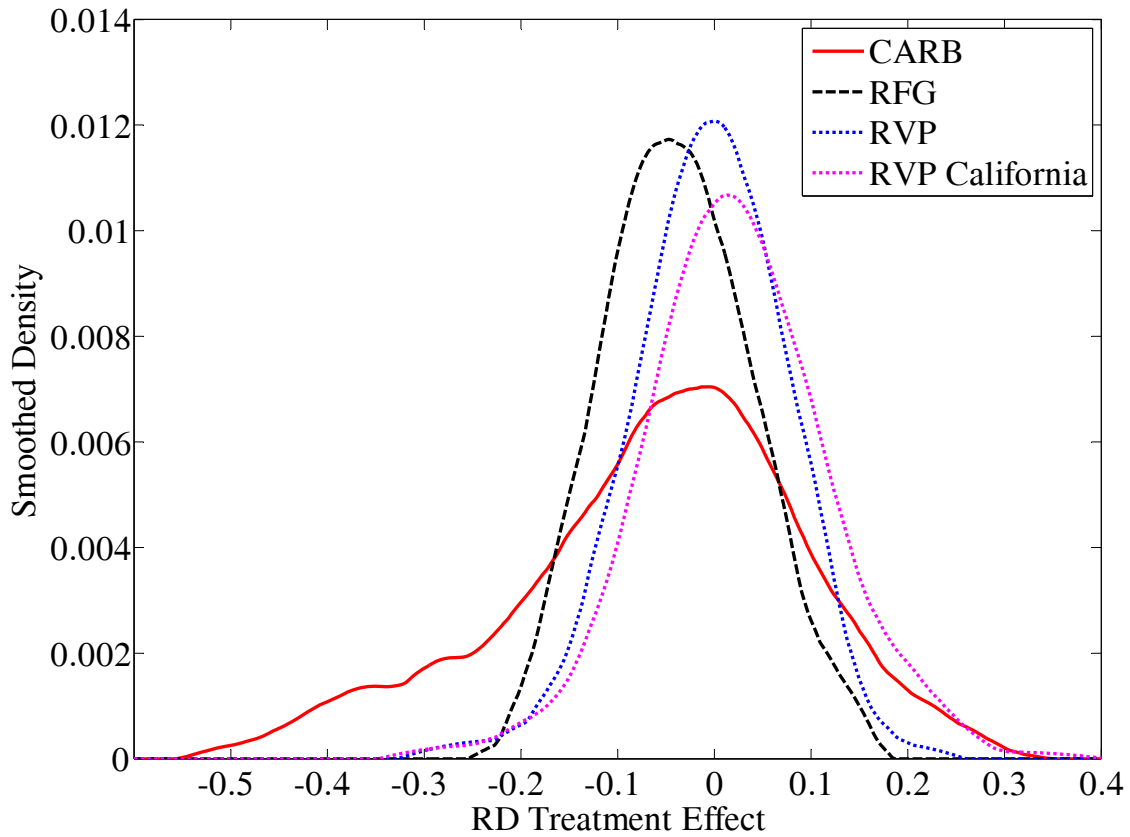


Figure 7: Daily maximum ozone concentrations



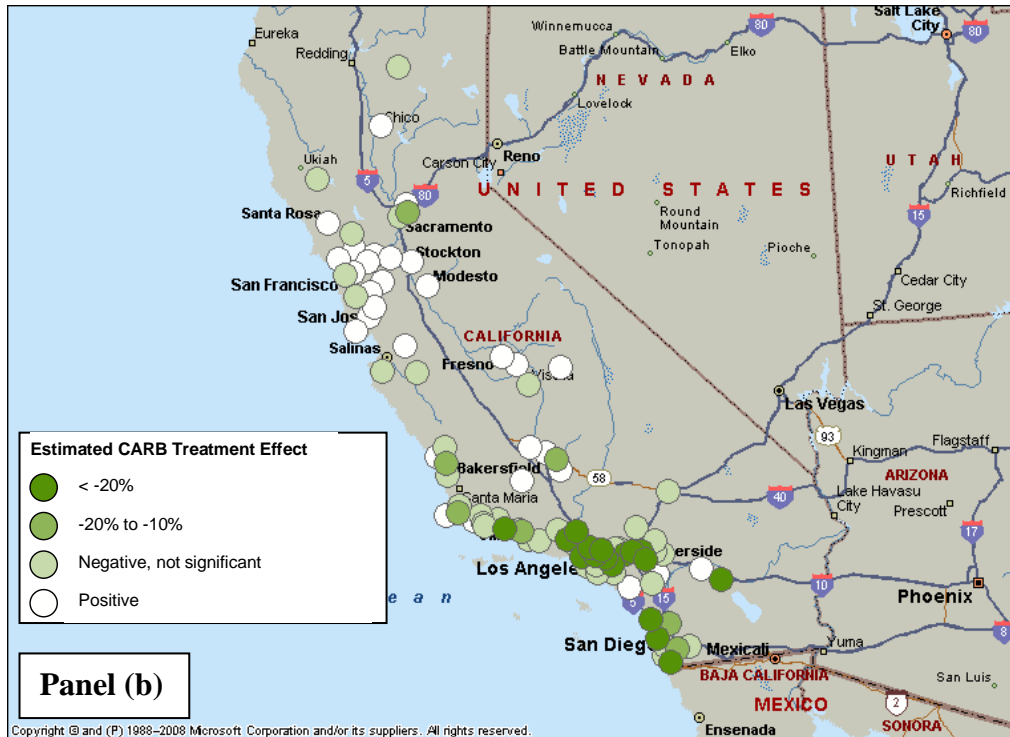
Notes: Values plotted are averaged residuals of a regression of daily maximum ozone on weather and seasonality variables W_{it} described in section 4.2. Fitted lines are the predicted values obtained after regressing the residuals on regulation dummies and a fifth-order polynomial on date. Regulations include RVP (summer 1992-1994), RFG (summer 1995), and CARB (March 1996-)

Figure 8: Distribution of Estimated RD Treatment Effects by Policy Type



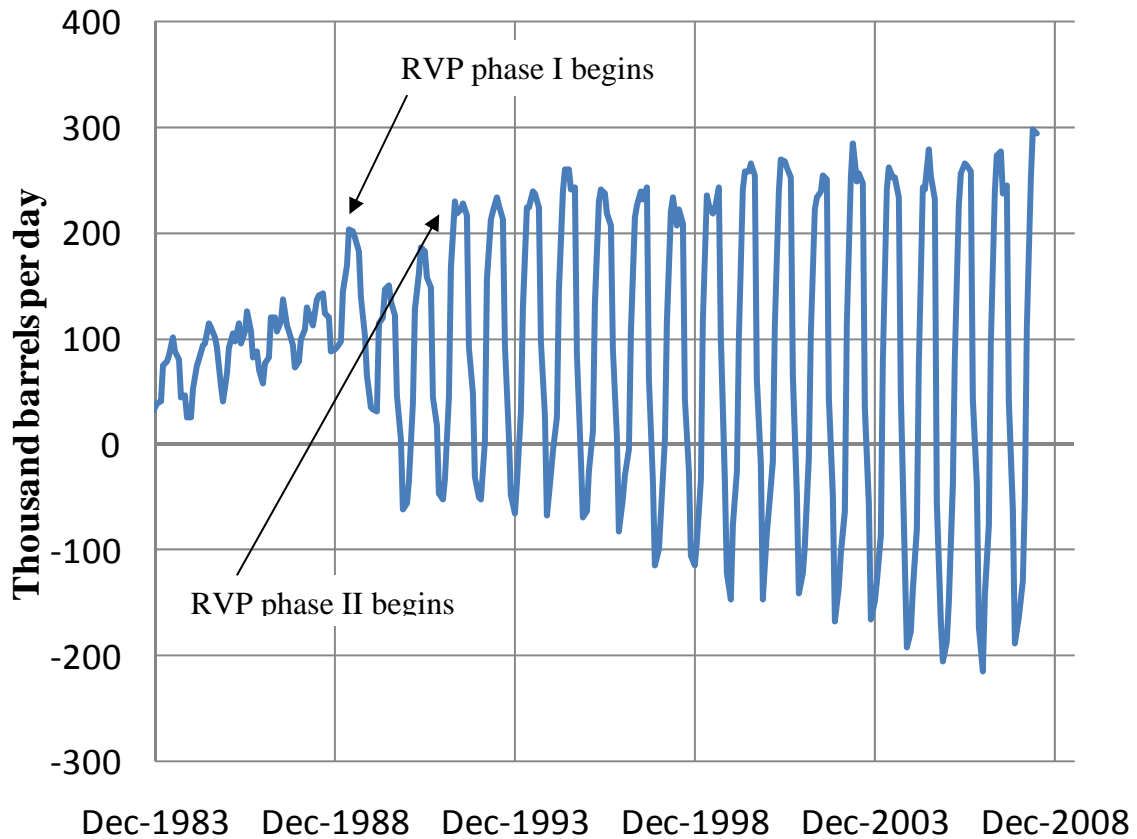
Notes: The figure displays the smoothed cross-monitor distribution of estimated treatment effects from equation (3). The smoother uses an Epanechnikov kernel with a bandwidth of 0.05.

Figure 9: Maps of Estimated CARB RD Treatment Effects



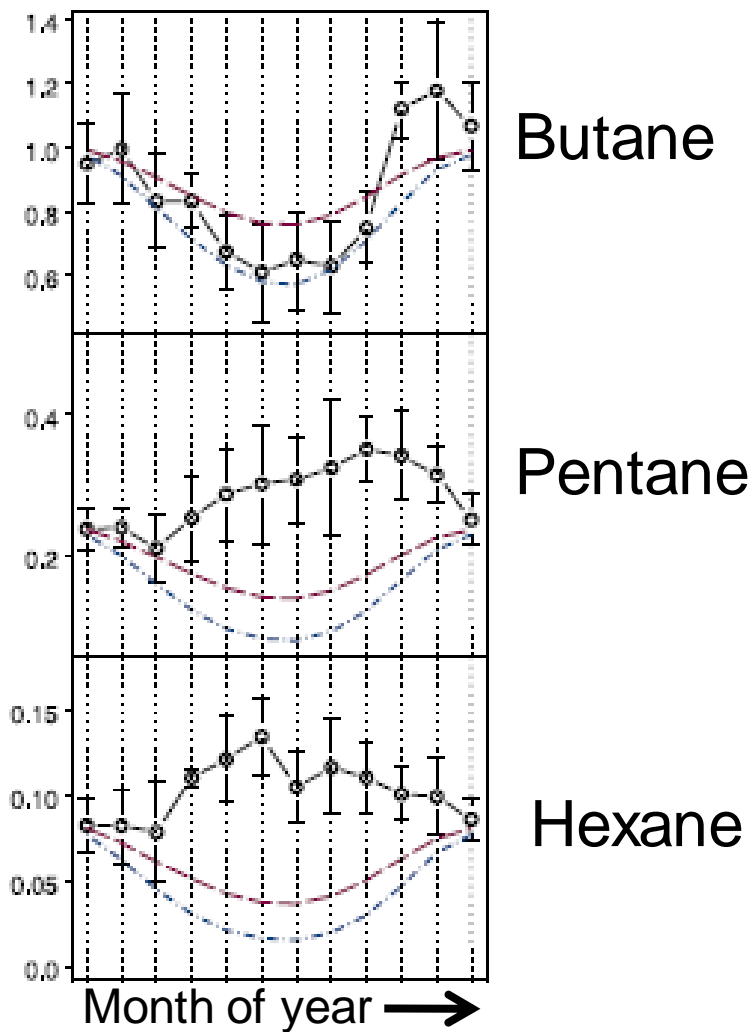
Notes: The maps display the coefficient estimates from equation (3) for CARB gasoline using all available monitors with valid data for the entire sample period.

Figure 10: Refinery net production of butane



Notes: Positive values indicate that the quantity of butane refiners produce from crude oil exceeds the quantity blended into gasoline. Negative values indicate that refiners are blending more butane into gasoline than they produce from crude; that is, they are withdrawing butane from storage.

Figure 11: Ambient VOC concentrations in Massachusetts, 1992-1996



Source: Reproduced from Lee *et al.* (2006)

Notes: The solid lines with markers represent the ratios of butane, pentane, and hexane concentrations relative to concentrations of acetylene. Relative measurements are used because acetylene is believed to be emitted at a constant rate across the year, and seasonal fluctuations in its concentration will be entirely due to atmospheric mixing effects that would similarly affect butane, pentane, and hexane.

Table 1: Reid vapor pressure (RVP) phase I regulatory details

RVP level (psi)¹	States
10.5	DE, DC, FL, ID, IL (northern), IN, IA, KY, ME, MD, MI, MN, MT, NE, NH, ND, OH, OR, PA, SD, VT, WA, WA, WV, WI, WY
10.5 Jun/Sep; 9.5 Jul/Aug	AL, AR, GA, IL (southern), KS, LA, MS, MO, NC, SC, TN
9.5	CA, CO, NV, OK, TX (eastern, except Dallas area), UT
9.5 Sep, 9.0 Jun-Aug	AZ, NM, TX (western)
9.0 ²	CT, MA, NJ, NY, TX (Dallas area), RI

¹The RVP control season for retail gasoline distribution stations is June 1 - September 15. Refiners and wholesale terminals must comply by May 1. RVP phase I covers the summers of 1989-1991.

²These areas had been assigned higher RVP limits by the EPA's RVP rule, but elected to observe a tighter limit as part of their State Implementation Plans to achieve the ozone air quality standard

Table 2: Reid vapor pressure (RVP) phase II regulatory details

Area	Number of Counties	RVP First Year	RVP Last Year	VOC Control Period ¹		RVP level (psi)
				Seasonal Start Date	Seasonal End Date	
<i>Federally mandated</i>						
Birmingham, AL	2	1992	1997 ²	01 Jun	15 Sep	7.8
Phoenix, AZ	1	1992	1997 ³	01 Jun	15 Sep	7.8
Denver, CO	6	1992		01 Jun	15 Sep	7.8
Washington, DC-MD-VA ⁴	17	1992	1994 ⁵	01 Jun	15 Sep	7.8
Ft. Lauderdale-Miami, FL	6	1992		01 Jun	15 Sep	7.8
Atlanta, GA	13	1992	1998 ²	01 Jun	15 Sep	7.8
Kansas City, KS	2	1992	1996 ²	01 Jun	15 Sep	7.8
Baton Rouge-New Orleans, LA	17	1992		01 Jun	15 Sep	7.8
Baltimore, MD ⁴	6	1992	1994 ⁵	01 Jun	15 Sep	7.8
Kansas City, MO	3	1992	1996 ²	01 Jun	15 Sep	7.8
St. Louis, MO ⁴	5	1992	1998 ⁵	01 Jun	15 Sep	7.8
Greensboro-Raleigh, NC	9	1992		01 Jun	15 Sep	7.8
Reno-Sparks, NV	1	1992		01 Jun	15 Sep	7.8
Portland, OR	5	1992		01 Jun	15 Sep	7.8
Knoxville, TN	1	1992	1993 ⁶	01 Jun	15 Sep	7.8
Memphis & Nashville, TN	6	1992		01 Jun	15 Sep	7.8
Beaumont, TX	3	1992		01 Jun	15 Sep	7.8
Dallas & Houston, TX	12	1992	1994 ⁵	01 Jun	15 Sep	7.8
El Paso, TX	1	1992	1995 ²	01 Jun	15 Sep	7.8
Victoria, TX	1	1992	1999 ²	01 Jun	15 Sep	7.8
Salt Lake City, UT	2	1992		01 Jun	15 Sep	7.8
Norfolk, VA ⁴	11	1992	1994 ⁵	01 Jun	15 Sep	7.8
Richmond, VA ⁴	7	1992	1994 ⁵	01 Jun	15 Sep	7.8
White Top Mountain, VA	1	1992		01 Jun	15 Sep	7.8
All other areas		1992		01 Jun	15 Sep	9.0
<i>State Implementation Plans</i>						
Los Angeles-San Diego, CA	6	1992	1994 ⁵	01 May	31 Oct	7.8
Rest of state, CA	52	1992	1995 ⁷	varies ⁸	varies ⁸	7.8
Atlanta plus 12 addl. counties, GA	25	1999	2002	01 Jun	15 Sep	7.0 ⁹
Atlanta plus 32 addl. counties, GA	45	2003		01 Jun	15 Sep	7.0 ⁹
East St. Louis-Wood River, IL	3	1995		01 Jun	15 Sep	7.2
Jeffersonville, IN	2	1996		01 Jun	15 Sep	7.8
Kansas City, KS	2	1997	2000 ²	01 Jun	15 Sep	7.2
Kansas City, KS	2	2001		01 Jun	15 Sep	7.0
Bangor-Portland, ME	7	1999		01 May	15 Sep	7.8
Detroit, MI	7	1996		01 Jun ¹⁰	15 Sep	7.8
Kansas City, MO	3	1997	2000 ²	01 Jun	15 Sep	7.2
Kansas City, MO	3	2001		01 Jun	15 Sep	7.0
Pittsburgh, PA	7	1998		01 Jun	15 Sep	7.8
Eastern TX (excl. Dallas & Houston)	95	2000		01 May	01 Oct	7.8
El Paso, TX	1	1996		01 Jun	15 Sep	7.0

¹Indicated control period represents compliance date for retail gasoline distribution stations. Refiners and wholesale terminals must comply one month prior to indicated date.

²Adopted more stringent RVP program in the following summer as part of a State Implementation Plan (also indicated further below in table).

³Phoenix adopted RFG on 4 August, 1997.

⁴Baltimore, Washington DC, St. Louis, and several cities in Virginia are not parts of counties, and are treated as if they are separate counties in this table and the analysis.

⁵Adopted RFG in the following summer.

⁶Designated attainment following summer 1993

⁷Adopted CARB in the following summer.

⁸Seasonal start and end dates are county-specific.

⁹GA gasoline also restricts sulfur content

Table 3: Reformulated gasoline (RFG) regulatory details

Area	Number of Counties	RFG First Year	RFG Last Year	VOC Control Period ¹	
				Seasonal Start Date	Seasonal End Date
<i>Federally mandated</i>					
Los Angeles-San Diego, CA	6	1995	1996 ²	01 Jun	15 Sep
Hartford, CT	6	1995		01 Jun	15 Sep
Chicago-Gary, IL-IN ³	10	1995		01 Jun	15 Sep
Baltimore, MD ⁴	6	1995		01 Jun	15 Sep
New York, NY-CT-NJ	25	1995		01 Jun	15 Sep
Philadelphia, PA-DE-MD-NJ	14	1995		01 Jun	15 Sep
Houston, TX	8	1995		01 Jun	15 Sep
Milwaukee, WI	6	1995		01 Jun	15 Sep
<i>Opt-in</i>					
Phoenix, AZ	1	1997 ⁵	1998 ⁵	01 Jun	30 Sep
Rest of state, CT	6	1995		01 Jun	15 Sep
Washington, DC-MD-VA ⁴	17	1995		01 Jun	15 Sep
Rest of state, DE	entire state	1995		01 Jun	15 Sep
Cincinnati-Hamilton, KY	3	1995		01 Jun	15 Sep
Louisville, KY	3	1995		01 Jun	15 Sep
Entire state, MA	14	1995		01 Jun	15 Sep
Bangor-Portland, ME	7	1995	1998 ⁶	01 Jun	15 Sep
St. Louis, MO ⁴	5	1999		01 Jun	15 Sep
Boston-Lawrence-Worcester, NH	4	1995		01 Jun	15 Sep
Rest of state, NJ	3	1995		01 Jun	15 Sep
Essex, NY	2	1995		01 Jun	15 Sep
Entire state, RI	5	1995		01 Jun	15 Sep
Dallas-Ft. Worth, TX	4	1995		01 Jun	15 Sep
Norfolk, VA ⁴	11	1995		01 Jun	15 Sep
Richmond, VA ⁴	7	1995		01 Jun	15 Sep
<i>State-specific reformulations</i>					
Phoenix, AZ (AZCBG)	1	1998		01 Jun	30 Sep
Entire state, CA (CARB)	58	1996		varies ⁷	varies ⁷

¹Indicated control period represents compliance date for gasoline distribution stations. Refiners and wholesale terminals must comply one month prior to indicated date.

²LA-San Diego area converted from federal RFG to CARB gasoline in March 1996 (concurrent with the conversion from federal RVP to CARB in the rest of CA). CARB regulations exceed federal RFG requirements.

³Chicago-area RFG is blended with 100% ethanol. RFG blendstock has a very low RVP of 5.5 psi.

⁴Baltimore, Washington DC, St. Louis, and several cities in Virginia are not parts of counties, and are treated as if they are separate counties in this table and the analysis.

⁵Phoenix (Maricopa County) adopted RFG on 04 Aug, 1997, and converted from federal RFG to Arizona Cleaner-Buring Gasoline (AZCBG) on 10 June, 1998.

⁶ME opted-out of RFG in March 1999 and adopted an RVP of 7.8 psi.

⁷Seasonal start and end dates are county-specific.

Table 4: Summary Statistics on Monitors and Regulation for the Summer Ozone Season (June-August)

Year	Observations (Count)	Total monitors (Counts of active monitors)	Urban	Suburban	Rural	Total counties (Counts of counties subject to each regulation)	RVPI*	RVPII**	RF95	CARB
1989	63,076	720	153	323	244	418	371	0	0	0
1990	66,108	751	157	326	268	436	381	0	0	0
1991	69,164	782	151	334	297	451	395	0	0	0
1992	69,848	789	155	334	300	452	0	132	0	0
1993	72,606	815	167	347	301	469	0	140	0	0
1994	74,440	835	163	356	316	473	0	140	0	0
1995	77,007	865	170	365	330	477	0	111	111	0
1996	76,463	854	165	359	330	471	0	76	106	48
1997	78,283	873	166	371	336	478	0	76	108	48
1998	79,544	889	165	380	344	487	0	82	108	49
1999	80,750	899	168	387	344	485	0	87	108	49
2000	82,466	915	178	391	346	489	0	97	107	49
2001	83,781	929	178	396	355	490	0	97	108	47
2002	85,230	943	177	405	361	495	0	100	109	49
2003	85,260	945	180	403	362	498	0	101	108	50
Total	1,144,026									
Average		854	166	365	322	471				

Data used in the construction of this table are monitor-days for which at least 9 hours were recorded between 9am and 9pm, and monitor-years for which valid monitor-days were recorded for at least 75% of the days between 1 June and 31 August.

This table only uses data for the months June, July and August, which constitute the main ozone season.

Counties not counted in a RVPI, RVPII, RFG, or CARB column are subject to an RVP standard of 9.0 psi.

*The RVPI column lists, for 1989-1991, the number of counties with a 9.5 or 10.5 psi RVP requirement.

**The RVPII column lists, for 1992 onwards, the number of counties subject to an RVP of 7.8 psi or lower.

Table 5: Difference-in-difference estimation results

Regressand	Dependent var: ln(daily maximum ozone concentration)				Dependent var: ln(daily max 8 hour concentration)			
	I	II	III	IV	V	VI	VII	VIII
RVP Phase I: 9.5 or 10.5 psi	0.016 (0.016)	0.013 (0.015)	0.015 (0.016)	0.001 (0.016)	0.018 (0.017)	0.015 (0.017)	0.016 (0.017)	-0.001 (0.018)
RVP Phase II: 7.8 psi or lower	-0.007 (0.008)	-0.011 (0.007)	-0.007 (0.007)	-0.012 (0.009)	-0.005 (0.008)	-0.009 (0.007)	-0.006 (0.008)	-0.013 (0.009)
Federal RFG	-0.029 (0.009)***	-0.030 (0.007)***	-0.016 (0.008)**	-0.036 (0.011)***	-0.028 (0.009)***	-0.028 (0.008)***	-0.018 (0.008)**	-0.041 (0.012)***
CARB Gasoline	-0.095 (0.013)**	-0.090 (0.011)***	-0.077 (0.011)***	-0.065 (0.019)***	-0.090 (0.013)***	-0.086 (0.012)***	-0.077 (0.012)***	-0.065 (0.019)***
County income (\$ billion)	-	-	-1.379 (0.285)***	-0.225 (0.245)	-	-	-1.012 (0.278)***	-0.027 (0.253)
Monitor FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region - Year FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region - DOW FEs	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Region FE - DOY interaction	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Weather controls	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Income	No	No	Yes	Yes	No	No	Yes	Yes
Regulation - region trends	No	No	No	Yes	No	No	No	Yes
Observations	1144026	1144026	1144026	1144026	1144026	1144026	1144026	1144026
R-squared (within-monitor)	0.02	0.26	0.26	0.26	0.03	0.26	0.26	0.26

Values shows are the coefficients of OLS regressions of the indicated dependent variable on the regressands.

Standard errors clustered by state-year are in parentheses

All regulatory effects are relative to the omitted baseline of a 9.0 psi RVP standard

Sample uses data from June-August each year

* significant at 10%; ** significant at 5%; *** significant at 1%

Table 6: Difference-in-difference estimation results: urban vs. suburban vs. rural

Regressand	Dependent var: ln(daily maximum ozone concentration)					
	Urban		Suburban		Rural	
	I	II	III	IV	V	VI
RVP Phase I: 9.5 or 10.5 psi	0.020 (0.021)	0.007 (0.021)	0.024 (0.018)	-0.001 (0.016)	0.011 (0.018)	0.001 (0.022)
RVP Phase II: 7.8 psi or lower	0.002 (0.014)	0.002 (0.014)	-0.011 (0.009)	-0.020 (0.011)*	-0.006 (0.009)	-0.011 (0.011)
Federal RFG	-0.004 (0.013)	-0.032 (0.015)**	-0.025 (0.009)***	-0.049 (0.014)***	-0.018 (0.011)	-0.027 (0.013)**
CARB Gasoline	-0.071 (0.016)***	-0.072 (0.025)***	-0.113 (0.014)***	-0.102 (0.022)***	-0.040 (0.013)***	-0.017 (0.024)
County income (\$ billion)	-1.236 (0.397)***	0.470 (0.428)	-1.614 (0.268)***	-0.727 (0.219)***	-1.145 (0.629)*	0.051 (0.841)
Monitor FEs	Yes	Yes	Yes	Yes	Yes	Yes
Region - Year FEs	Yes	Yes	Yes	Yes	Yes	Yes
Region - DOW FEs	Yes	Yes	Yes	Yes	Yes	Yes
Region FE - DOY interaction	Yes	Yes	Yes	Yes	Yes	Yes
Weather controls	Yes	Yes	Yes	Yes	Yes	Yes
Income	Yes	Yes	Yes	Yes	Yes	Yes
Regulation - region trends	No	Yes	No	Yes	No	Yes
Observations	222982	222982	490539	490539	430505	430505
R-squared (within-monitor)	0.28	0.29	0.27	0.28	0.24	0.24

Values shows are the coefficients of OLS regressions of the indicated dependent variable on the regressands.

Standard errors clustered by state-year are in parentheses

All regulatory effects are relative to the omitted baseline of a 9.0 psi RVP standard

Sample uses data from June-August each year

* significant at 10%; ** significant at 5%; *** significant at 1%

Table 7: Difference-in-difference estimation results: monitors recording data in every year

Regressand	Dependent var: ln(daily maximum ozone concentration)				Dependent var: ln(daily max 8 hour concentration)			
	I	II	III	IV	V	VI	VII	VIII
RVP Phase I: 9.5 or 10.5 psi	-0.009 (0.015)	-0.005 (0.015)	-0.005 (0.016)	-0.019 (0.016)	-0.007 (0.016)	-0.003 (0.017)	-0.003 (0.017)	-0.023 (0.017)
RVP Phase II: 7.8 psi or lower	-0.009 (0.009)	-0.014 (0.008)*	-0.009 (0.008)	-0.025 (0.010)**	-0.009 (0.009)	-0.013 (0.009)	-0.009 (0.009)	-0.028 (0.011)***
Federal RFG	-0.031 (0.010)***	-0.034 (0.008)***	-0.018 (0.009)**	-0.055 (0.013)***	-0.031 (0.010)***	-0.034 (0.009)***	-0.021 (0.009)**	-0.061 (0.014)***
CARB Gasoline	-0.148 (0.014)**	-0.144 (0.013)***	-0.118 (0.013)***	-0.134 (0.023)***	-0.139 (0.014)***	-0.137 (0.014)***	-0.116 (0.014)***	-0.132 (0.023)***
County income (\$ billion)	-	-	-1.851 (0.326)***	-0.289 (0.265)	-	-	-1.486 (0.312)***	-0.082 (0.284)
Monitor FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region - Year FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region - DOW FEs	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Region FE - DOY interaction	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Weather controls	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Income	No	No	Yes	Yes	No	No	Yes	Yes
Regulation - region trends	No	No	No	Yes	No	No	No	Yes
Observations	455084	455084	455084	455084	455084	455084	455084	455084
R-squared (within-monitor)	0.03	0.28	0.28	0.28	0.03	0.27	0.27	0.28

Values shows are the coefficients of OLS regressions of the indicated dependent variable on the regressands.

Standard errors clustered by state-year are in parentheses

All regulatory effects are relative to the omitted baseline of a 9.0 psi RVP standard

Sample uses data from June-August each year

* significant at 10%; ** significant at 5%; *** significant at 1%

Appendix: Monitor-specific regression discontinuity estimation results for RVP and RFG

State	County	Monitor ID	Effect on log(ozone max)	Standard error	State	County	Monitor ID	Effect on log(ozone max)	Standard error
RVP Gasoline					RFG Gasoline				
Colorado	Adams	3001	0.047	(0.057)	Delaware	New Castle	1003	-0.110	(0.057) *
Colorado	Arapahoe	2	0.093	(0.075) **	Illinois	Cook	50	-0.002	(0.051)
Colorado	Denver	14	0.077	(0.064) *	Illinois	Cook	64	-0.074	(0.053)
Colorado	Jefferson	2	0.037	(0.098)	Illinois	Cook	7002	0.059	(0.029) **
Florida	Broward	2003	-0.034	(0.048)	Illinois	DuPage	6001	0.018	(0.026)
Florida	Broward	8002	-0.117	(0.059) ***	Illinois	Kane	5	0.072	(0.028) **
Florida	Duval	77	0.030	(0.044)	Illinois	Lake	1002	-0.003	(0.034)
Florida	Hillsborough	81	0.037	(0.065)	Illinois	Lake	3001	-0.021	(0.036)
Florida	Hillsborough	1035	-0.024	(0.092)	Illinois	Will	1008	0.055	(0.030) *
Florida	Miami-Dade	21	-0.114	(0.057) ***	Massachusetts	Hampden	8	-0.015	(0.041)
Florida	Miami-Dade	27	-0.080	(0.060) **	Massachusetts	Hampshire	4002	-0.030	(0.029)
Florida	Miami-Dade	29	0.018	(0.061)	New Jersey	Atlantic	5	-0.108	(0.030) ***
Florida	Miami-Dade	30	-0.083	(0.060) *	New Jersey	Camden	3	-0.022	(0.034)
Florida	Palm Beach	2004	-0.216	(0.065) *	New Jersey	Camden	1001	-0.143	(0.030) ***
Florida	Pinellas	4	-0.025	(0.092)	New Jersey	Cumberland	7	-0.114	(0.025) ***
Florida	Pinellas	18	-0.044	(0.083)	New Jersey	Gloucester	2	-0.091	(0.030) ***
Florida	Pinellas	5002	-0.084	(0.089) **	New Jersey	Hudson	6	-0.022	(0.029)
Illinois	Madison	8	0.039	(0.115)	New Jersey	Hunterdon	1	-0.012	(0.033)
Illinois	Madison	1009	0.011	(0.133)	New Jersey	Mercer	5	-0.115	(0.040) ***
Illinois	Madison	2007	0.016	(0.116)	New Jersey	Monmouth	5	-0.023	(0.028)
Illinois	Madison	3007	0.012	(0.109)	New Jersey	Morris	3001	-0.057	(0.032) *
Illinois	Saint Clair	10	0.058	(0.153) *	New York	Dutchess	7	-0.043	(0.033)
Louisiana	Beauregard	2	0.018	(0.086)	New York	Essex	2	-0.071	(0.026) ***
Louisiana	Calcasieu	2	-0.042	(0.127)	New York	Essex	3	-0.087	(0.024) ***
Louisiana	East Baton Rouge	3	0.025	(0.071)	New York	New York	63	-0.068	(0.049)
Louisiana	East Baton Rouge	1001	-0.001	(0.127)	New York	Suffolk	2	-0.077	(0.033) **
Louisiana	Grant	1	-0.027	(0.078)	Pennsylvania	Philadelphia	24	0.074	(0.027) ***
Louisiana	Jefferson	1001	0.148	(0.063) ***					
Louisiana	Orleans	12	-0.039	(0.060)					
Louisiana	Pointe Coupee	1	-0.024	(0.043)					
Louisiana	St. Bernard	2	-0.049	(0.055)					
Louisiana	St. James	2	-0.063	(0.117)					
Louisiana	St. Mary	3	0.025	(0.079)					
Louisiana	West Baton Rouge	1	-0.054	(0.081)					
Nevada	Washoe	20	0.025	(0.092)					
Nevada	Washoe	1005	0.060	(0.037) *					
Tennessee	Davidson	11	0.051	(0.073)					
Tennessee	Davidson	26	-0.043	(0.045)					
Texas	Bexar	32	-0.035	(0.068)					
Texas	El Paso	37	0.045	(0.085)					
Texas	Gregg	1	0.024	(0.091)					
Texas	Jefferson	9	-0.081	(0.085)					
Texas	Jefferson	11	0.079	(0.054)					
Texas	Nueces	25	-0.001	(0.050)					
Texas	Nueces	26	-0.023						
Texas	Travis	14	0.050	(0.036)					

Effects shown are the monitor-specific estimated coefficients on the treatment dummies of the regression discontinuity specification (3)
 Standard errors are clustered on year-season
 Estimated effects of RVP phase II (less than or equal to 7.8 psi) and federal RFG are relative to the baseline of a 9.0 psi RVP standard
 Sample uses data from all seasons of 1989-2003
 * significant at 10%; ** significant at 5%; *** significant at 1%

Appendix: Monitor-specific regression discontinuity estimation results for CARB

State	County	Monitor ID	Effect on log(ozone max)	Standard error	State	County	Monitor ID	Effect on log(ozone max)	Standard error
CARB Gasoline					CARB Gasoline				
California	Alameda	3	0.140	(0.055) **	California	San Bernardino	5	-0.079	(0.066)
California	Alameda	5	0.025	(0.075)	California	San Bernardino	12	-0.051	(0.049)
California	Alameda	1001	0.067	(0.064)	California	San Bernardino	1004	-0.314	(0.134) **
California	Butte	2	0.079	(0.098)	California	San Bernardino	2002	-0.207	(0.063) ***
California	Contra Costa	2	0.092	(0.048) *	California	San Bernardino	4003	-0.075	(0.060)
California	Contra Costa	1002	0.058	(0.059)	California	San Bernardino	9004	-0.023	(0.030)
California	Contra Costa	3001	0.236	(0.044) ***	California	San Diego	1	-0.225	(0.078) ***
California	Fresno	7	0.192	(0.065) ***	California	San Diego	3	-0.135	(0.056) **
California	Fresno	4001	0.192	(0.092) **	California	San Diego	5	-0.231	(0.081) ***
California	Kern	7	-0.119	(0.057) **	California	San Diego	6	-0.068	(0.075)
California	Kern	8	0.009	(0.060)	California	San Diego	1001	-0.209	(0.064) ***
California	Kern	232	0.064	(0.061)	California	San Diego	1002	-0.129	(0.048) ***
California	Kern	5001	0.089	(0.060)	California	San Diego	1006	-0.119	(0.063) *
California	Kern	6001	0.061	(0.065)	California	San Diego	1007	-0.100	(0.067)
California	Lake	3001	0.001	(0.092)	California	San Francisco	5	-0.010	(0.079)
California	Los Angeles	2	-0.145	(0.083) *	California	San Joaquin	1002	0.061	(0.081)
California	Los Angeles	16	-0.130	(0.089)	California	San Luis Obispo	2001	-0.049	(0.049)
California	Los Angeles	113	-0.335	(0.115) ***	California	San Luis Obispo	2002	-0.148	(0.075) **
California	Los Angeles	1002	-0.325	(0.133) **	California	San Luis Obispo	3001	0.040	(0.039)
California	Los Angeles	1103	-0.446	(0.116) ***	California	San Luis Obispo	8001	-0.023	(0.041)
California	Los Angeles	1201	-0.108	(0.109)	California	San Mateo	1001	-0.148	(0.107)
California	Los Angeles	1301	-0.008	(0.153)	California	Santa Barbara	8	-0.047	(0.046)
California	Los Angeles	1601	-0.380	(0.086) ***	California	Santa Barbara	10	-0.204	(0.080) **
California	Los Angeles	1701	-0.434	(0.127) ***	California	Santa Barbara	1013	-0.023	(0.047)
California	Los Angeles	2005	-0.276	(0.071) ***	California	Santa Barbara	1014	-0.027	(0.065)
California	Los Angeles	4002	-0.085	(0.127)	California	Santa Barbara	1018	0.057	(0.053)
California	Los Angeles	5001	-0.115	(0.078)	California	Santa Barbara	1021	-0.032	(0.045)
California	Los Angeles	6002	-0.285	(0.063) ***	California	Santa Barbara	1025	-0.080	(0.058)
California	Marin	1	0.171	(0.060) ***	California	Santa Barbara	2004	-0.140	(0.047) ***
California	Monterey	2	-0.011	(0.043)	California	Santa Barbara	3001	-0.060	(0.046)
California	Napa	3	0.001	(0.055)	California	Santa Barbara	4003	0.066	(0.083)
California	Orange	1	-0.073	(0.117)	California	Santa Clara	4	0.039	(0.082)
California	Orange	2001	0.129	(0.079)	California	Santa Clara	1001	0.017	(0.080)
California	Orange	5001	-0.211	(0.081) ***	California	Santa Cruz	3	0.010	(0.048)
California	Riverside	2002	-0.360	(0.092) ***	California	Shasta	3003	-0.058	(0.048)
California	Riverside	5001	0.040	(0.037)	California	Solano	4	0.141	(0.051) ***
California	Riverside	6001	0.010	(0.073)	California	Sonoma	3	0.095	(0.058) *
California	Riverside	8001	-0.212	(0.045) ***	California	Stanislaus	5	0.101	(0.058) *
California	Riverside	9001	-0.029	(0.068)	California	Tulare	6	0.211	(0.064) ***
California	Sacramento	2	0.021	(0.085)	California	Tulare	2002	0.007	(0.060)
California	Sacramento	6	-0.185	(0.091) **	California	Ventura	4	-0.050	(0.062)
California	Sacramento	10	-0.060	(0.085)	California	Ventura	5	-0.144	(0.046) ***
California	San Benito	2	0.068	(0.086) *	California	Ventura	2002	-0.355	(0.086) ***
California	San Benito	3	-0.012	(0.073)	California	Ventura	2003	-0.006	(0.073)
California	San Bernardino	1	-0.012	(0.100)	California	Ventura	3001	-0.101	(0.100)

Effects shown are the monitor-specific estimated coefficients on the treatment dummies of the regression discontinuity specification (3)

Standard errors are clustered on year-season

Estimated effects of CARB are relative to the baseline of a 9.0 psi RVP standard

Sample uses data from all seasons of 1989-2003

* significant at 10%; ** significant at 5%; *** significant at 1%