Clearing the Air? The Effects of Gasoline Content Regulation on Air Quality[†]

By Maximilian Auffhammer and Ryan Kellogg*

This paper examines whether US gasoline content regulations, which impose substantial costs on consumers, have successfully reduced ozone pollution. We take advantage of spatial and temporal variation in the regulations' implementation to show that federal gasoline standards, which allow refiners flexibility in choosing a compliance mechanism, did not improve air quality. This outcome occurred because minimizing the cost of compliance does not reduce emissions of those compounds most prone to forming ozone. In California, however, we find that precisely targeted, inflexible regulations requiring the removal of particularly harmful compounds significantly improved air quality. (*JEL* L51, L71, L78, Q53, Q58)

Since the passage of the original Clean Air Act in 1963, US 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 asthma, increased susceptibility to pneumonia and bronchitis, and damage to crops and natural vegetation. Michelle L. Bell et al. (2004) have estimated that even marginal short-term changes in ozone concentrations can have substantial human mortality impacts.[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. Despite more than 40 years of emissions regulation, however, many areas of the US continue to experience ambient air concentrations of ozone that exceed standards set by the Environmental Protection Agency (EPA).

[1] Bell et al. (2004) estimate that a 10 parts per billion (ppb) increase in ozone concentrations (relative to average concentrations of about 60 ppb) would result in 3,767 additional premature deaths annually across 95 urbanized areas in the US. For evidence regarding ozone's morbidity and environmental impacts, see EPA (2006), Enrico Moretti and Matthew Neidell (2011), and Matthew Neidell (2004, 2009).

This paper examines the effectiveness of one particular set of regulations: 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 because they impact gasoline prices through two mechanisms: (i) an increase in production costs; and (ii) segmentation of the US gasoline market that leads to increased price volatility and increased opportunities for refiners to exert local market power. 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 prevents gasoline transporters from arbitraging price differences across areas with different gasoline standards. Several recent papers—Jennifer Brown et al. (2008), Ujjayant Chakravorty, Céline Nauges, and Alban Thomas (2008), and Erich Muehlegger (2006)—have found that this market segmentation significantly increases both gasoline price levels (beyond the increase in production cost) and price volatility. The US 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 price effects 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 several different forms of regulation have been implemented—all primarily targeting VOC emissions—it is not known whether some types of regulation are more effective than others, nor whether some locations are more likely to benefit from regulation. Our objective in this study is therefore to address these issues using a panel dataset of ambient ozone concentrations across the United States.

Our primary finding is 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. We attribute this result to the flexibility permitted by the regulations: refiners, free to choose which VOCs to remove from their gasoline, reduce 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.

In contrast, California's gasoline regulations place strict 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 percent 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.

These divergent outcomes speak to a trade-off inherent in setting the degree of flexibility of environmental regulations. Flexible regulatory approaches, such as the federal VOC requirements for gasoline, are designed to reduce abatement costs relative to more restrictive command-and-control regulations by allowing firms to choose the least-cost compliance mechanism. However, flexibility may also result in reduced environmental benefits if different compliance mechanisms result in different patterns of emissions across space, time, or specific pollutants. This trade-off seems unlikely to be unique to gasoline regulation. Tradable emission permit markets, for instance, have become popular because they allow compliance costs to be minimized across heterogeneous firms. Curtis Carlson et al. (2000), for example, find evidence of substantial abatement cost reductions stemming from trading of sulfur dioxide permits. However, standard permit trading systems may not achieve the first-best welfare outcome when the marginal benefits of abatement are spatially heterogeneous. Meredith Fowlie (2010), for instance, finds that the benefits of a major US NO_x cap-and-trade program were undercut because heterogeneity in compliance incentives caused NO_x abatement to be concentrated in low marginal damage areas rather than dense urban centers in the Northeast. A more restrictive regulation that weighted emissions by local marginal damages—attenuating the ability of firms to flexibly adjust abatement across different regions—would have yielded a superior outcome.

In our setting, the impact of regulatory flexibility is particularly severe. While the flexible federal VOC standards result in lower compliance costs than does California's restrictive standard (1–1.5 cents per gallon versus 8–11 cents per gallon),[2] they have no measurable effect on ozone pollution, whereas California's regulation yields substantial declines in ozone concentrations. These results highlight the importance of anticipating firms' likely response when considering the implementation of flexible regulations, even in a command-and-control setting such as the design of gasoline content standards. To the extent that firms' behavioral responses may mitigate the desired environmental benefits of regulation, these welfare losses should be weighed against the compliance cost reductions conferred by a flexible regulatory design.

We identify the impacts of gasoline regulations on ozone by taking advantage of (i) daily measurements of ambient ozone concentrations from hundreds of air quality monitors across the United States during 1989–2003; (ii) the rich spatial and temporal variation with which gasoline regulations were applied; and (iii) the discrete nature with which these regulations were phased in. Unlike, for example, standards for vehicle emissions control equipment that produce effects only 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: (i) a difference-in-differences (DD) estimator that also controls for time-varying observables in treated versus control areas; and (ii) a

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[2] The 1–1.5 cents per gallon cost range for federal Reid vapor pressure (RVP) is taken from Brown et al. (2008). The estimated 8–11 cents per gallon cost range for California Air Resources Board (CARB) comes from summing the 3 cents per gallon price effect of reformulated gasoline (RFG) from Brown et al. (2008) with a 5 to 8 cents per gallon estimated incremental cost of CARB (CARB 2008).

regression discontinuity (RD) design that examines changes in ozone concentrations immediately before and after gasoline regulations came into effect. Our RD design is similar to that of Lucas Davis' (2008) study of Mexico City's driving restrictions in that we flexibly control for location-specific unobservables that may have affected changes in air quality over time.[3]

The remainder of the paper is organized as follows: Section I provides a description of the gasoline reformulation policies examined in this paper. Section II describes the data we collected, and our identification strategy is given in Section III. Section IV presents the estimation results. Section V discusses the role of refiners' behavior in explaining our findings, and Section VI concludes.

I. Regulatory Background

A. *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 also 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 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 (Sanford Sillman 1999, Charles L. Blanchard 2001).[4] Finally, while NO_x emissions in one region can impact ozone levels up to 1,000 km downwind, VOC emissions only have a local effect (Jana B. Milford, Armistead G. Russell, and Gregory J. McRae 1989, Sillman 1999).

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[3] For other papers that measure the air quality and health benefits of US air quality regulations, see J. Vernon Henderson (1996), Kenneth Y. Chay and Michael Greenstone (2003, 2005), and Greenstone (2004).

[4] 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.

B. *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 emitted from gasoline. These emissions may occur either on the road, via vehicles' exhaust, or through evaporation. For example, the fumes one smells when fueling a vehicle are evaporative VOC emissions. RVP regulation limits the RVP of gasoline sold during the summer months when hot, sunny weather is conducive to ozone formation. Refiners meet the RVP limits by reducing the concentration of "light" components—particularly butane—in the gasoline they sell (Tancred C. M. 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 A1 in the online Appendix provides state-level detail of the RVP Phase I program.[5]

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 southern states that were designated as being in nonattainment of the EPA's National Ambient Air Quality Standard for ozone. This tight limit reduces VOC emissions from gasoline by at least 15 percent 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. 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 superseded by RFG or CARB standards, which are discussed below. RVP Phase II details are provided in Table A2 in the online Appendix. Figure 1 summarizes the timing with which RVP and subsequent regulations came into effect, and Figure 2 provides a map of affected areas.

C. *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 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

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[5] 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).
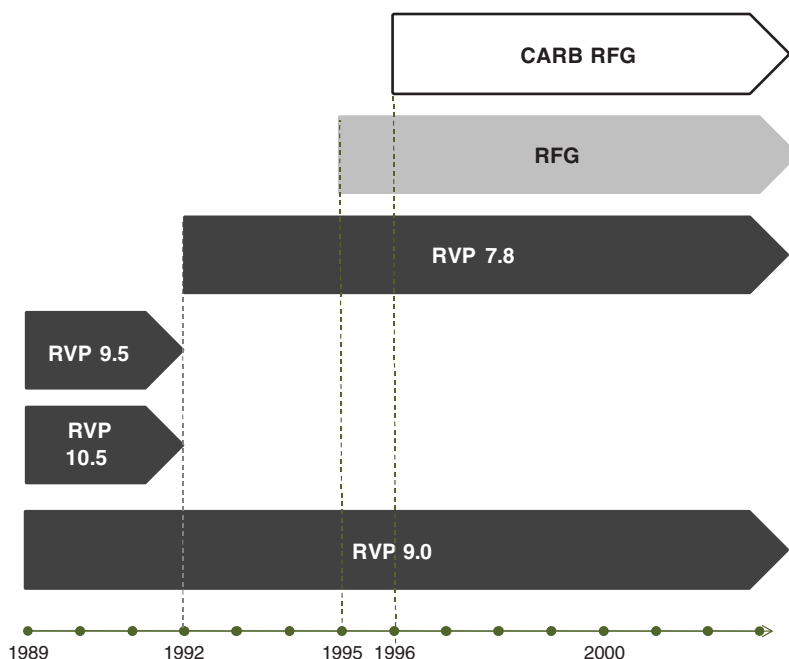
FIGURE 1. REGULATORY TIMELINE

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.

listing of where and when RFG has been implemented is provided in Table A3 in the online Appendix.

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 percent benzene, a toxic carcinogen that is also a VOC, and must contain at least 2 percent oxygen via use of an oxygenate such as MTBE or ethanol.[6] Phase I RFG must also reduce both VOC and toxic air pollutant (TAP) emissions by 15 percent relative to conventional gasoline. TAPs consist of five chemical compounds, including benzene, that are known carcinogens and are also VOCs.[7] 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 percent while also tightening the TAP standard to

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[6] 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.

[7] 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 nonexhaust (evaporative) emissions are estimated by the EPA to compose 70–75 percent of all toxics emissions from gasoline. All five toxics are VOCs, though benzene is not strongly reactive in forming ozone.
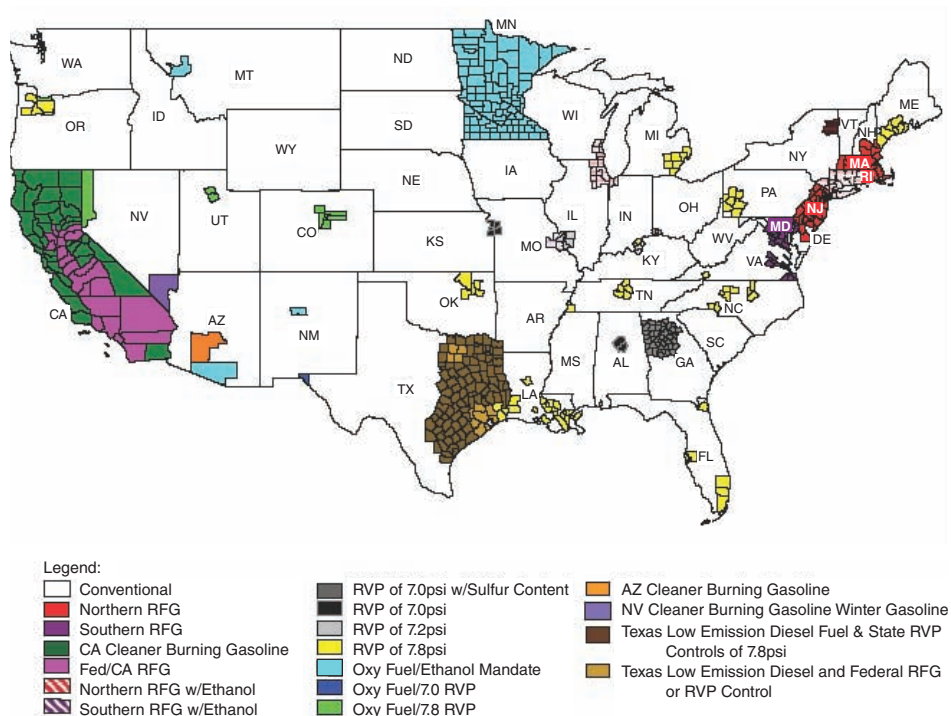
FIGURE 2. MAP OF RVP PHASE II AND RFG REGULATIONS AS OF 2006

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. This study does not evaluate the effect of oxygenates on carbon monoxide pollution.

Source: EPA (Dec. 2006)

20 percent. In addition, Phase II introduced a NO_x reduction requirement of 5.5 percent 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. This requirement included rural parts of the state, most of which were in attainment of the EPA's ozone standard. Like federal RFG, CARB gasoline caps the benzene content of gasoline at 1 percent by volume. CARB gasoline targets VOC emissions more stringently than RFG, applying both a seasonal 7.0 psi RVP limit and year-round content criteria that limit concentrations of olefins (6 percent by volume) and aromatic hydrocarbons (25 percent 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 choose to remove from gasoline to meet federal RVP standards. In addition, CARB gasoline mandates an 80 percent reduction in sulfur content to reduce emissions of both sulfur dioxide and NO_x.[8] These standards are collectively more stringent than those

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[8] 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.

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.

II. Data

A. *Air Quality Monitor Data*

We obtained data on ambient air concentrations of ozone from the EPA's Air Quality Standards database for 1989–2003.[9] 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 eight hour maximum. This latter measure is constructed by calculating the average ozone concentration within all eight 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 eight hour standard of 0.08 ppm. These standards reflect what the EPA believes are the maximum allowable ozone concentrations that protect public health.

We follow EPA data standards by disqualifying all monitor-days for which observations are not recorded for at least nine hours between 9 A.M. and 9 P.M. We also disqualify monitor-years for which more than 25 percent of the days during the summer ozone season (June 1–August 31) 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 percent and does not substantially affect the estimated results.

Table 1 describes the sample of monitors used in this study. We possess measured ozone concentrations for a total of 1,144,025 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 percent per year. Roughly 80 percent of the monitors are located in rural and suburban settings, with the remaining 20 percent located in urban areas.[10] The "total counties" column of Table 1 indicates that the set of monitored counties grew by 1.3 percent 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.

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[9] 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.

[10] 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.

TABLE 1—SUMMARY STATISTICS ON MONITORS AND REGULATION FOR THE SUMMER OZONE SEASON (*June–August*)

Year	Observations/ (counties)	Counts of active monitors			RVPI[a]	RVPII[b]	RFG95	CARB
		Total monitors	Urban	Rural				
1989	63,076/(418)	720	153	244	371	0	0	0
1990	66,108/(436)	751	157	268	381	0	0	0
1991	69,164/(451)	782	151	297	395	0	0	0
1992	69,848/(452)	789	155	300	0	132	0	0
1993	72,606/(469)	815	167	301	0	140	0	0
1994	74,440/(473)	835	163	316	0	140	0	0
1995	77,007/(477)	865	170	330	0	111	111	0
1996	76,462/(471)	854	165	330	0	76	106	48
1997	78,283/(478)	873	166	336	0	76	108	48
1998	79,544/(487)	889	165	344	0	82	108	49
1999	80,750/(485)	899	168	344	0	87	108	49
2000	82,466/(489)	915	178	346	0	97	107	49
2001	83,781/(490)	929	178	355	0	97	108	47
2002	85,230/(495)	943	177	361	0	100	109	49
2003	85,260/(498)	945	180	362	0	101	108	50
Total	1,144,025/(NA)							
Average	76,268/(471)	854	166	322				

Notes: Data used in the construction of this table are monitor-days for which at least nine hours were recorded between 9 A.M. and 9 P.M., and monitor-years for which valid monitor-days were recorded for at least 75 percent of the days between June 1 and August 31. This table uses data for only 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.

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

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

The right-most four columns of Table 1 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 superseded by the RFG standards. 1995 also saw about 80 monitored counties that had been observing an RVP standard of 9.0 psi adopt RFG.

Table 1 also demonstrates the introduction of CARB reformulated gasoline throughout the entire state of California in 1996. Six counties in the Los Angeles-San Diego area that had been observing the federal RFG standard 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.

B. *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.[11] 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 percent 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 percent 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 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 eight closest stations, then the seven closest, etc. At the end of this procedure, less than 0.1 percent 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 percent 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.

C. *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 dark line plots concentrations for "control" counties that have a standard 9.0 psi summer RVP limit under RVP Phase II. The dashed light 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 light line corresponds to counties treated with RFG but not CARB, and the dashed dark line represents CARB counties.

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[11] Modeled weather data at an even finer spatial scale are available from the PRISM group, but only at a monthly frequency.
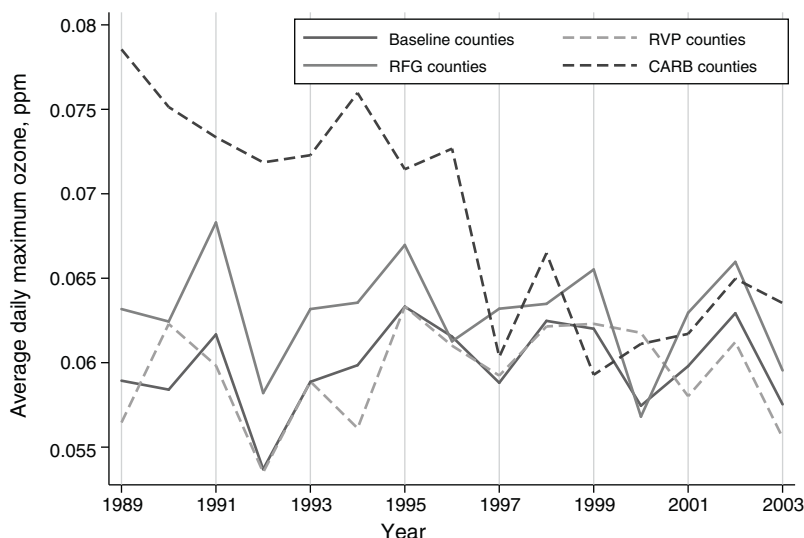
FIGURE 3. MEAN SUMMER OZONE CONCENTRATIONS
(*Broken out by regulation type*)

Note: For both Figures 3 and 4, data include only those monitors recording data in every summer.

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 value of using weather data to improve the efficiency of the estimators used in our formal empirical analysis.

III. 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:

(i) Summer RVP of 9.0 psi (some counties, 1989–1991; most ozone attainment counties, 1992 onward)
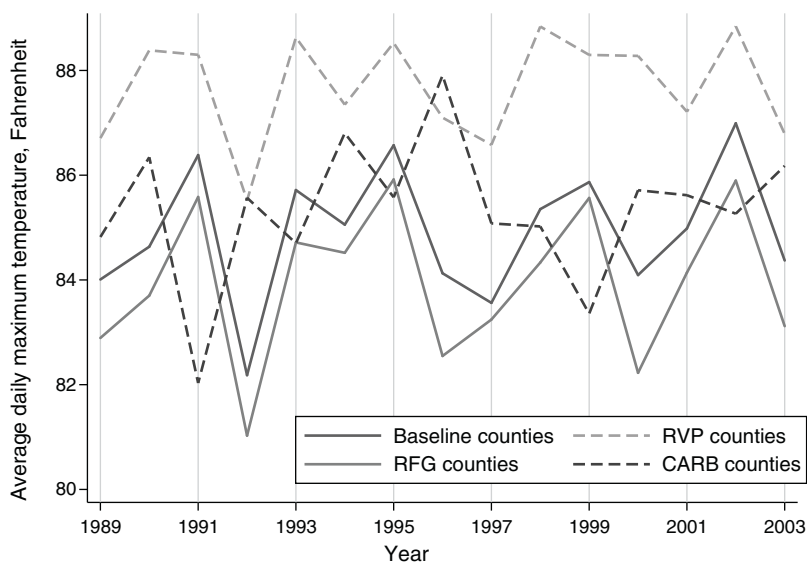
FIGURE 4. MEAN SUMMER DAILY TEMPERATURE MAXIMA
(*Broken out by regulation type*)

Note: For both Figures 3 and 4, data include only those monitors recording data in every summer.

(ii) Summer RVP of 9.5 psi or 10.5 psi (many counties, 1989–1991)

(iii) Summer RVP of 7.8 psi or below (southern ozone nonattainment counties and northern opt-in counties, 1992 onward)

(iv) Federal RFG (severe ozone nonattainment and opt-in counties, 1995 onward)[12]

(v) 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-differences (DD) method and a time series regression discontinuity (RD) design.

A. *Difference-in-Differences* (*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.

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[12] 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.

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 eight 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. **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). $\boldsymbol{\alpha}$ is a four-element vector of parameters whose estimation is of primary interest.

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

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, $\boldsymbol{\alpha}$, 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 US 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 $\boldsymbol{\alpha}$ requires that $\mathrm{E}[\mathbf{Treat}_{ct} \cdot \varepsilon_{it} | \mu_i, \eta_{ry}] = 0$. 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 nonattainment 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 versus control counties will bias the estimate of $\boldsymbol{\alpha}$: the first case will create upward bias, while the second will create downward bias.

To both improve the precision of our estimates and control for factors that affect treated and control counties differentially over time, we augment (1) with additional variables to form specification (2) below:

$$(2) \qquad \ln(y_{it}) = \boldsymbol{\alpha} \cdot \mathbf{Treat}_{ct} + \boldsymbol{\beta} \cdot \mathbf{W}_{it} + \gamma_r \cdot \mathbf{D}_t + \delta \cdot I_{ct}$$

$$+ \boldsymbol{\theta} \cdot \mathbf{Trend}_{rct} + \mu_i + \eta_{ry} + \varepsilon_{it}.$$

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.[13] $\mathbf{D}_t$ denotes a vector consisting

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[13] 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 vari-

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 (Bureau of Economic Analysis 2008). Finally, the set of variables denoted by $\mathbf{Trend}_{rct}$ 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.[14] These trends are included in the specification to attempt to distinguish the impacts of gasoline regulations from long-run trends driven by unobservables.[15] In some of our specifications, these trends include quadratic terms.

The identification assumption of the augmented DD model (2) is that unobserved factors are not correlated with treatment, conditional on the covariates; that is, $E[\mathbf{Treat}_{ct} \cdot \varepsilon_{it} \,|\, \mathbf{W}_{it}, \mathbf{D}_t, I_{ct}, \mathbf{Trend}_{rct}, \mu_i, \eta_{ry}] = 0$. 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 nonlinear 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, addressing both serial correlation, per Marianne Bertrand, Esther Duflo, and Sendhil Mullainathan (2004), and within-state cross-sectional correlation. The standard errors we report therefore use a robust variance estimator that is clustered on each state-year combination (Manuel Arellano 1987, Jeffrey M. Wooldridge 2003).[16]

B. *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: (i) 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 (ii) 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

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ables 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.

[14] 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.

[15] 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.

[16] 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 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.

ozone concentrations do so only through a linear time trend, the RD model permits unobserved factors to act nonlinearly over time, so long as they are not discontinuous when gasoline regulations phase in (Jinyong Hahn, Petra Todd, and Wilbert Van der Klaauw 2001).[17]

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.[18] In addition, the linear time trend in (2) is replaced in (3) with $f_i(Date_t)$, an eighth-order Chebychev polynomial in time that is also monitor specific.[19] We therefore estimate (3) one monitor at a time as a time series regression. This monitor-specific approach permits considerable flexibility in the manner in which both observed and unobserved factors can influence ozone concentrations while simultaneously allowing us to evaluate spatial heterogeneity in the treatment effects.

$$(3) \qquad \ln(y_{it}) = \alpha_i \cdot \mathbf{Treat}_{ct} + \beta_i \cdot \mathbf{W}_{it} + f_i(Date_t) + \mu_i + \varepsilon_{it}.$$

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 percent of each calendar quarter for 75 percent 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.[20]

To identify the effects of RVP Phase II, we focus on counties that were not also treated with RFG or CARB in a year subsequent to their RVP treatment. With only three years of pretreatment observations in most RVP counties, we ensure that there are a sufficient number of pretreatment observations by enforcing that all monitors be active for 75 percent of the days in 75 percent of the quarters prior to treatment. We model RVP II regulations with a treatment dummy that is active only during the summer VOC control periods, reflecting the seasonality with which these regulations are applied. Specifically, the element of $\mathbf{Treat}_{ct}$ in (3) 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.

In evaluating the impact of federal RFG, we control for the fact that some RFG counties, primarily those in the South, were also treated with RVP II in 1992 prior to initiating RFG in 1995. We therefore include in our RFG RD regressions all

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[17] 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 nonattainment 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 nonattainment 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 pretreatment ozone level.

[18] In the RD model (3) we expand the number of weather variables by interacting them with seasonal dummies, and we also include standalone month dummies.

[19] Use of a seventh-, ninth-, or tenth-order polynomial yields results very similar to those reported in this paper. Shortening the sample window from 1989–2003 to 1989–1999 also does not substantially alter the results.

[20] 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 3.

elements of **Treat**$_{ct}$ that are applicable to each county.[21] As with RVP, we model the RFG treatment dummy as active during only the summer VOC control periods.[22]

The regulatory discontinuity at the start and end of each summer's VOC control period—for both RVP and RFG—is not sharp. Gasoline at retail stations and in the gas tanks of vehicles does completely turn over in a single day. We therefore allow for a 30-day linear phase-in of the treatment effect between the date that refiners are required to produce the regulated gasoline and the date that gas stations are required to stock and sell it. 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 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: March 1, 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.[23] We allow for a linear ramp in the element of **Treat**$_{ct}$ corresponding to CARB over the 30 days prior to March 1, 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 southern California—Los Angeles, Orange, Riverside, San Bernardino, San Diego, and Ventura—were also treated with federal RFG in 1995. In estimating (3), we therefore include in our CARB 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.[24]

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).

IV. Results

A. *Difference-in-Differences (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

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[21] Omitting the RVP treatment dummy for those counties that were also treated with RVP has only a minor impact on the reported results.

[22] We have also examined RD regressions in which the RFG treatment effect is specified as a year-round impact, reflecting the potential for some of the year-round toxic emission reductions associated with RFG to reduce ozone formation. Consistent with our seasonal RFG results described below, we do not find evidence of a significant impact of RFG with this specification. Specifically, the average treatment effect across monitors is -0.014, and we find a statistically significant decrease in ozone (at the 5 percent level) at only three of 41 monitors. The significance of the results at these three monitors is not robust across alternative polynomial specifications.

[23] 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). We have examined RD specifications in which we allow for both a year-round and summer-specific impact of CARB. Estimates from these specifications indicate that, while there is a strong year-round impact of CARB per the results discussed below, there is no evidence of an additional seasonal effect.

[24] Omitting the RVP and RFG treatment dummies yields slightly stronger CARB treatment effects than those reported here.

Panel A. RVP II versus baseline counties

Panel B. RFG versus baseline counties
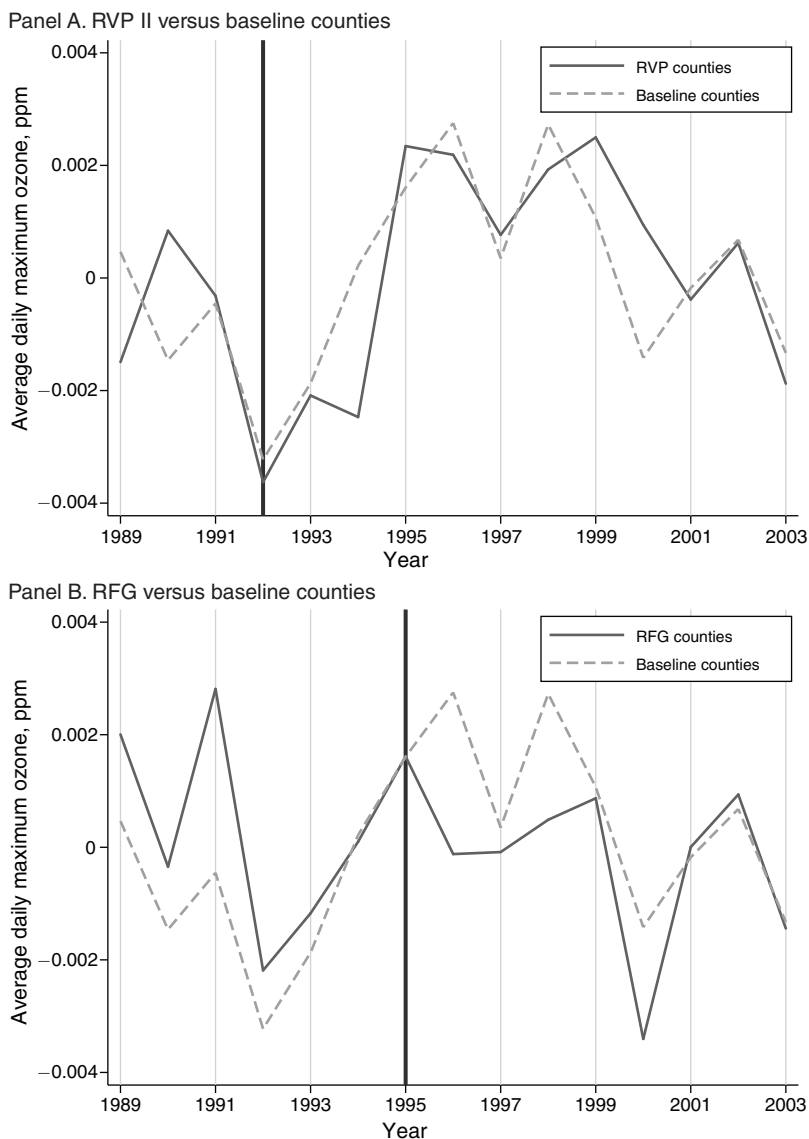
FIGURE 5. MEAN SUMMER OZONE CONCENTRATIONS   (*Continued*)

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 $\mathbf{W}_{it}$ and $\mathbf{D}_t$, 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
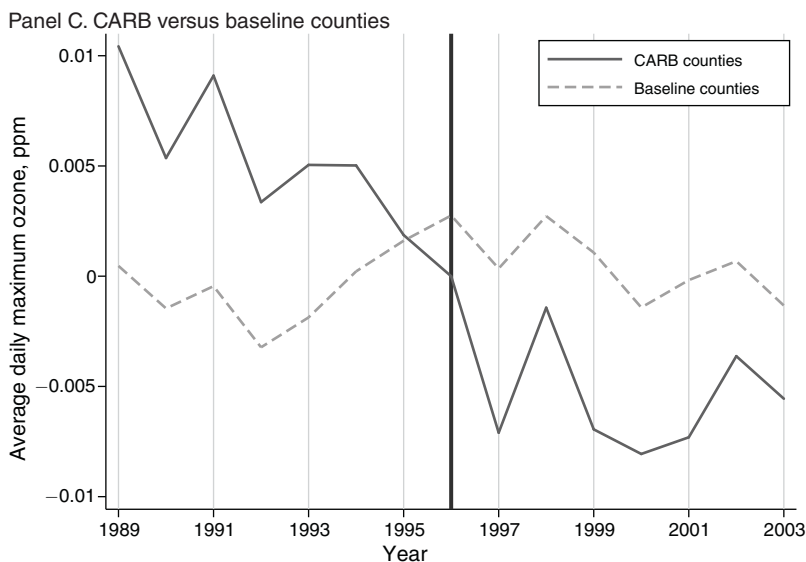
FIGURE 5. MEAN SUMMER OZONE CONCENTRATIONS (*Concluded*)

Notes: Values plotted are averaged residuals of a regression of daily maximum ozone on weather variables W_{it} and D_{it} described in Section IIIA 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.

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 multiyear 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 2. 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

TABLE 2—DIFFERENCE-IN-DIFFERENCES ESTIMATION RESULTS

Regressand	Dependent var: ln(daily maximum ozone concentration)					ln(daily max 8 hour concentration)		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
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)	0.004 (0.018)	0.018 (0.017)	0.015 (0.017)	0.004 (0.020)
RVP Phase II: 7.8 psi or lower	−0.007 (0.008)	−0.011 (0.007)	−0.007 (0.007)	−0.012 (0.009)	−0.012 (0.011)	−0.005 (0.008)	−0.009 (0.007)	−0.011 (0.012)
Federal RFG	−0.029 (0.009)***	−0.030 (0.007)***	−0.016 (0.008)**	−0.036 (0.011)***	−0.019 (0.012)	−0.028 (0.009)***	−0.028 (0.008)***	−0.022 (0.013)*
CARB gasoline	−0.095 (0.013)***	−0.090 (0.011)***	−0.077 (0.011)***	−0.065 (0.019)***	−0.064 (0.020)***	−0.090 (0.013)***	−0.086 (0.012)***	−0.063 (0.021)***
County income ($ billion)	— —	— —	−1.379 (0.285)***	−0.225 (0.245)	−0.302 (0.236)	— —	— —	−0.102 (0.246)
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	Yes	No	Yes	Yes
Region FE— DOY interaction	No	Yes	Yes	Yes	Yes	No	Yes	Yes
Weather controls	No	Yes	Yes	Yes	Yes	No	Yes	Yes
Income	No	No	Yes	Yes	Yes	No	No	Yes
Regulation— region trends	No	No	No	Yes	Yes	No	No	Yes
Regulation— region quad trends	No	No	No	No	Yes	No	No	Yes
Observations	1,144,025	1,144,025	1,144,025	1,144,025	1,144,025	1,144,025	1,144,025	1,144,025
R^2 (within-monitor)	0.024	0.261	0.261	0.264	0.264	0.026	0.255	0.259

Notes: Values shown 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 the 1 percent level.
    **Significant at the 5 percent level.
     *Significant at the 10 percent level.

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(ozone) of −0.029, statistically significant at the 1 percent level and statistically distinct from the effect of RVP II (the *p*-value of the *F*-test for equality of these coefficients is 0.078). 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(ozone) of −0.095 (equivalent to a 9.1 percent decrease in absolute ozone concentration) that is statistically significant at the 1 percent level. The data reject equality of the CARB coefficient with that of either RVP II or RFG (the *p*-values are less than 0.001 in both cases).

Columns 2 through 5 of Table 2 progressively add control variables to the specification, moving from an estimate of equation (1) in column 1 to equation (2) in columns 4 and 5. Column 2 includes variables for weather ($\mathbf{W}_i$) as well as day-of-week and day-of-year ($\mathbf{D}_t$). 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 3 controls for county-level annual personal income. The estimated coefficient on income is negative and statistically significant, consistent with increases in pollution abatement in high-growth counties. Relative to column 2, controlling for income causes modest declines in the estimated effects of RVP II, RFG, and CARB regulations. In this specification, we no longer reject equality of the coefficients on RVP II and RFG (*p*-value: 0.328).

Columns 4 and 5 add linear and quadratic regulation-specific time trends to the specification. These additions result in minor changes to the estimated impact of RVP and slightly attenuate CARB's impact. The estimated effect of RFG, however, varies substantially across these specifications: with a linear time trend we estimate that RFG reduces log(ozone) by a statistically significant 0.036, but with a quadratic trend this effect is only -0.019 and not statistically significant. The equality of the RVP and RFG coefficients is rejected in column 4 (*p*-value: 0.046) but not column 5 (*p*-value: 0.623).[25] The sensitivity of these results to changes in the specification of the time trends underscores the importance of carefully controlling for time-varying unobservables, motivating our more flexible RD design.

Columns 6 through 8 of Table 2 repeat the specifications in columns 1 through 5 but use the logarithm of the daily eight hour ozone concentration as the dependent variable rather than the daily maximum. These estimated effects vary little from those presented in columns 1 through 5.

Table 3 presents results that are broken out by whether each monitor is in an urban, suburban, or rural area. The specification used in columns 2, 4, and 6 is exactly that given by (2), while columns 1, 3, and 5 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 marginally significant estimate in suburban areas when linear time trends are included. The effect of RFG is estimated to be strongest in suburban areas; in urban and rural areas RFG is estimated to have only a marginally statistically significant effect, reducing ozone concentrations by 0.4 to 3.1 percent depending on the specification. CARB gasoline has significant effects in both urban and suburban areas of about 7 percent and 10 percent, respectively. CARB's effectiveness in rural areas is weaker: it is estimated to significantly decrease ozone concentrations by 4 percent in specification 5, but the inclusion of time trends in specification 6 yields a small, insignificant effect of 1.7 percent.

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 4 presents results obtained by estimating the same pooled specifications presented in Table 2, 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 2, 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

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[25] The equality of the effects of RVP II and CARB is rejected across all specifications at the 1 percent level. The equality of RFG and CARB is rejected at at least the 5 percent level in all specifications save column 4, in which the *p*-value is 0.144.

Table 3—Difference-in-Difference Estimation Results: Urban versus Suburban versus Rural

| | Dependent var: ln(daily maximum ozone concentration) | | | | | |
| | Urban | | Suburban | | Rural | |
Regressand	(1)	(2)	(3)	(4)	(5)	(6)
RVP Phase I: 9.5 or 10.5 psi	0.020	0.007	0.024	−0.001	0.011	5.0E-04
	(0.021)	(0.021)	(0.018)	(0.016)	(0.018)	(0.022)
RVP Phase II: 7.8 psi or lower	0.002	0.002	−0.011	−0.020	−0.006	−0.011
	(0.014)	(0.014)	(0.009)	(0.011)*	(0.009)	(0.011)
Federal RFG	−0.004	−0.032	−0.025	−0.049	−0.018	−0.027
	(0.013)	(0.015)**	(0.009)***	(0.014)***	(0.011)	(0.013)**
CARB gasoline	−0.071	−0.072	−0.113	−0.102	−0.040	−0.017
	(0.016)***	(0.025)***	(0.014)***	(0.022)***	(0.013)***	(0.024)
County income ($ billion)	−1.236	0.470	−1.614	−0.727	−1.145	0.051
	(0.397)***	(0.428)	(0.268)***	(0.219)***	(0.629)*	(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	222,982	222,982	490,539	490,539	430,504	430,504
R^2 (within-monitor)	0.281	0.285	0.275	0.278	0.243	0.244

Notes: Values shown 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 through August each year.

   ***Significant at the 1 percent level.

   **Significant at the 5 percent level.

   *Significant at the 10 percent level.

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(ozone) in Table 4 range from −0.118 to −0.148, and estimates for RFG range from −0.018 to −0.055. *F*-tests reject equality of the RFG and CARB coefficients at the 1 percent level across all specifications. The effect of RVP Phase II is now statistically significant in columns 4 and 5, in which time trends are included, with estimated magnitudes of −0.025 and −0.022, respectively. However, the effects of RVP Phase I standards weaker than the 9.0 psi baseline are also estimated to be negative in these specifications, with magnitudes of −0.019 and −0.015 that are 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 RVP gasoline does not. The evidence for federal RFG is mixed, with some specifications indicating a modest effect and others not. The magnitudes of the estimated effects are somewhat sensitive to the inclusion of time trends and the choice of monitors included in the sample. The RD design addresses these issues by allowing for time-varying unobservables and substantial monitor-level heterogeneity.

TABLE 4—DIFFERENCE-IN-DIFFERENCES ESTIMATION RESULTS: MONITORS RECORDING DATA IN EVERY YEAR

Regressand	Dependent var: ln(daily maximum ozone concentration)					ln(daily max 8 hour concentration)		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
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)	−0.014 (0.018)	−0.007 (0.016)	−0.003 (0.017)	−0.015 (0.020)
RVP Phase II: 7.8 psi or lower	−0.009 (0.009)	−0.014 (0.008)*	−0.009 (0.008)	−0.025 (0.010)**	−0.022 (0.012)*	−0.009 (0.009)	−0.013 (0.009)	−0.023 (0.013)*
Federal RFG	−0.031 (0.010)***	−0.034 (0.008)***	−0.018 (0.009)**	−0.055 (0.013)***	−0.031 (0.015)**	−0.031 (0.010)***	−0.034 (0.009)***	−0.036 (0.016)**
CARB gasoline	−0.148 (0.014)***	−0.144 (0.013)***	−0.118 (0.013)***	−0.134 (0.023)***	−0.123 (0.024)***	−0.139 (0.014)***	−0.137 (0.014)***	−0.121 (0.025)***
County income ($ billion)	— —	— —	−1.851 (0.326)***	−0.289 (0.265)	−0.414 (0.247)*	— —	— —	−0.201 (0.270)
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	Yes	No	Yes	Yes
Region FE—DOY interaction	No	Yes	Yes	Yes	Yes	No	Yes	Yes
Weather controls	No	Yes	Yes	Yes	Yes	No	Yes	Yes
Income	No	No	Yes	Yes	Yes	No	No	Yes
Regulation— region trends	No	No	No	Yes	Yes	No	No	Yes
Regulation— region quad trends	No	No	No	No	Yes	No	No	Yes
Observations	455,084	455,084	455,084	455,084	455,084	455,084	455,084	455,084
R^2 (within-monitor)	0.031	0.278	0.280	0.285	0.285	0.030	0.270	0.280

Notes: Values shown 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 the 1 percent level.

**Significant at the 5 percent level.

*Significant at the 10 percent level.

B. *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 fitted line for each monitor is the time series of predicted values of the treatment effect and polynomial time trend $(\alpha_i \cdot \mathbf{Treat}_{ct} + f_i(Date_t))$ obtained from estimating equation (3), centered so that its mean value is zero. The points plotted are the sum of this fitted line with the residuals from estimating (3). 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 3007 in Madison County, Illinois (just east of St. Louis, Missouri), which was treated with an RVP Phase II standard of 7.2 psi in 1995. A shift in neither the residuals nor the fitted line is apparent in 1995. Accordingly, the RD estimate of the effect of RVP on log(ozone) for this monitor is +0.004 and statistically insignificant.

The dotted line in Figure 7, panel A displays a kernel-smoothed cross-monitor distribution of the RD estimates of RVP Phase II's effect on the logarithm of ozone

Panel A. Madison County, Illinois (site 3007) RVP II (7.8 psi) begins in summer 1995
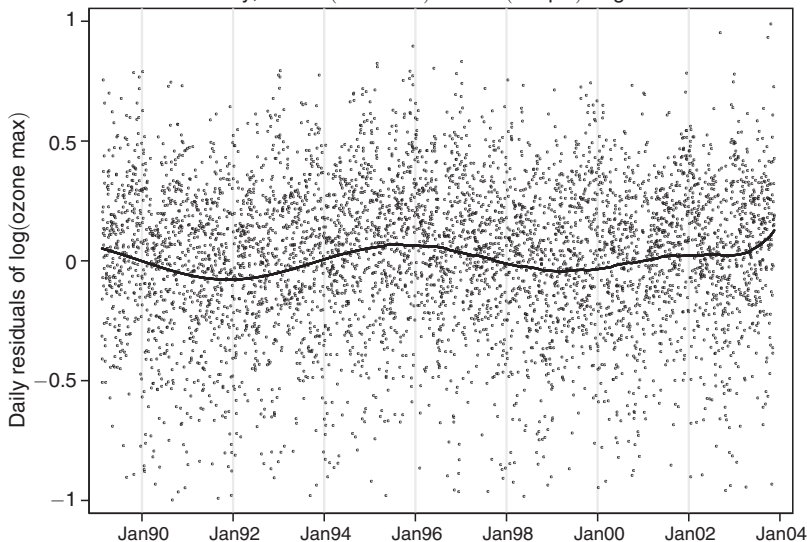
Panel B. Camden County, New Jersey (site 1001) RFG begins in summer 1995
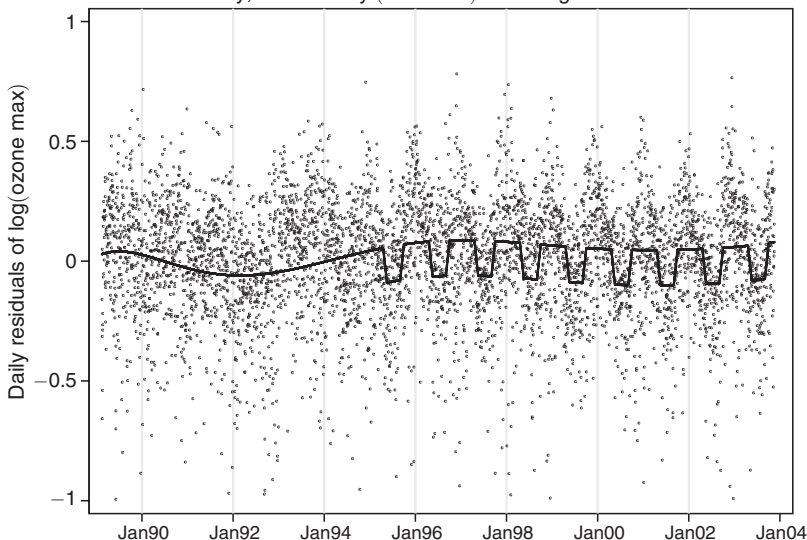
FIGURE 6. DAILY MAXIMUM OZONE CONCENTRATIONS   (*Continued*)

concentration. This plot also displays our estimated effects for RFG (dashed) and CARB (solid). The mean of the RVP distribution, across 46 monitors, is −0.0001, and monitor 3007 in Madison County, Illinois, depicted in Figure 6, lies nearest this mean. Table A4 in the online 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.[26]

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[26] The only monitors for which we find negative and statistically significant impacts of RVP are located in southern Florida, where Hurricane Andrew struck in August 1992. That summer was the first in which RVP was in effect.

Panel C. Harris County, Texas (site 47) RVP begins in summer 1992;
RFG in summer 1995
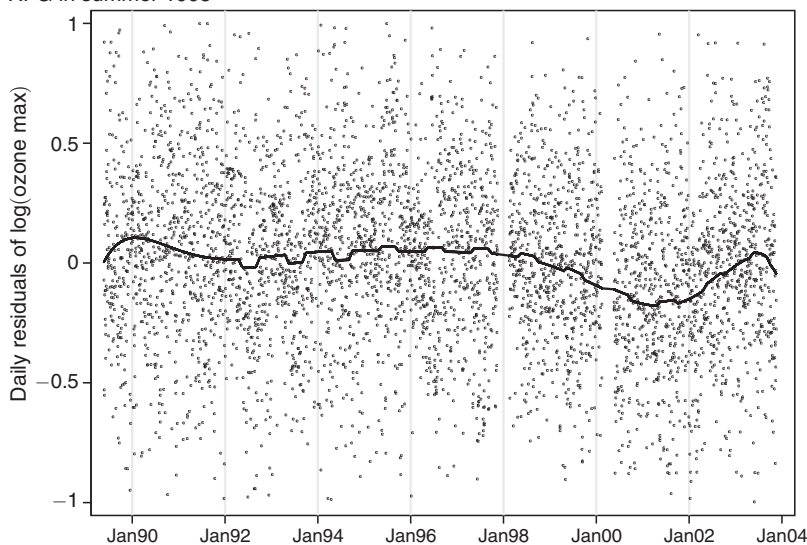
FIGURE 6. DAILY MAXIMUM OZONE CONCENTRATIONS   (*Concluded*)

Notes: Fitted lines are the predicted values of the treatment dummies and eighth-order polynomial time trend from estimating equation (3), centered at zero. Points plotted are the residuals from (3) plus the fitted line.

The distribution of the RFG estimates depicted in panel A of Figure 7 is shifted slightly to the left relative to that of RVP. Its mean is -0.021, which is smaller in magnitude than most of the DD estimates of RFG's impact. This distribution includes results from 41 monitors, 13 of which are found to have reductions in ozone that are statistically significant at the 5 percent 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 Table A4 in the online Appendix). Figure 6 panel B plots residual ozone concentrations and a fitted line for monitor 1001 in Camden County, New Jersey: ozone at this location clearly exhibits substantial seasonality following the 1995 introduction of RFG.

Why might ozone concentrations have decreased in summer 1995 (and the following summers) along the eastern seaboard, but not in other RFG locations? This pattern of effects seems consistent with the introduction of substantial NO_x emission controls in Delaware, New Jersey, New York, and Pennsylvania (the state immediately upwind) in 1994 and 1995. Table 5 lists the frequency of installation of NO_x control equipment at electric generating units by year for several groups of states. Delaware, Pennsylvania, New Jersey, and New York together account for about one-third of all electric generation NO_x control installations in the United States during

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The severe economic disruption caused by the hurricane seems likely to explain these observed decreases in ozone.

Panel A. All locations

Panel B. Southern California
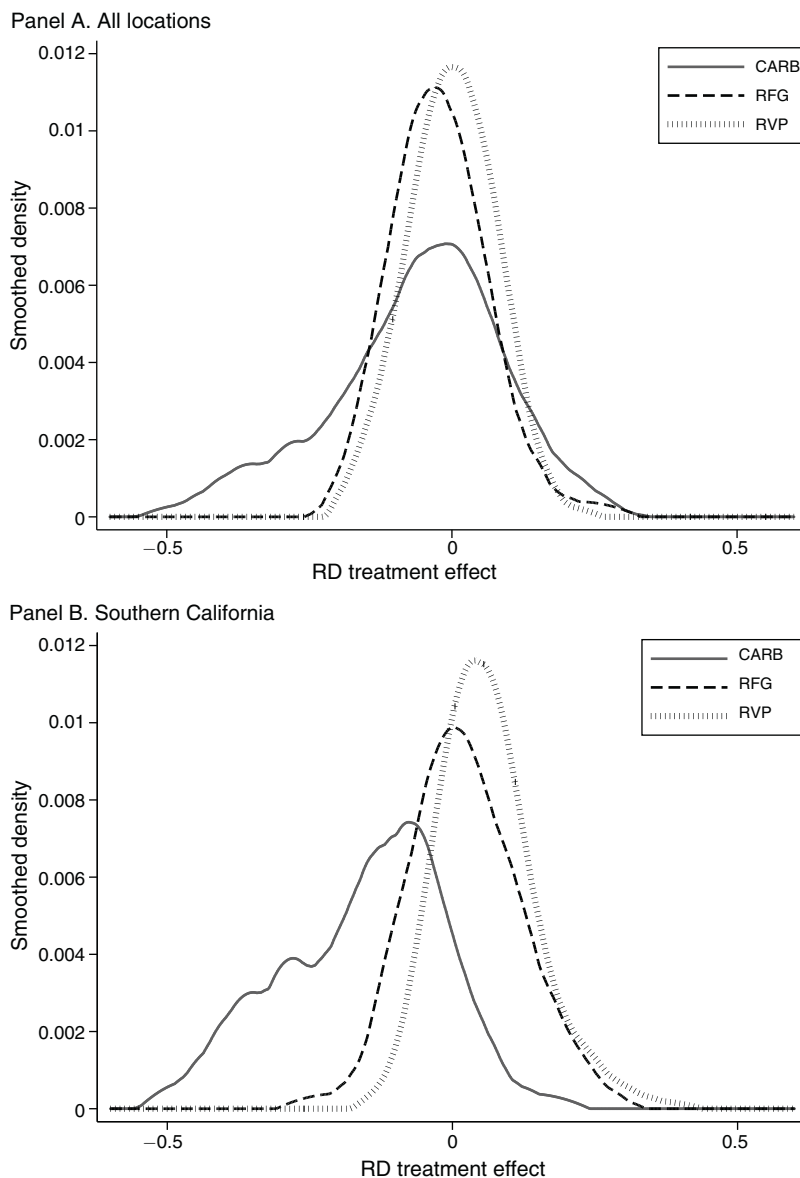
FIGURE 7. DISTRIBUTION OF ESTIMATED RD TREATMENT EFFECTS BY POLICY TYPE

Notes: The figures display the smoothed cross-monitor distribution of estimated treatment effects from equation (3). The smoother uses an Epanechnikov kernel with a bandwidth of 0.05. The RVP and RFG results shown in panel A do not include California. Panel B includes only Los Angeles, Orange, Riverside, San Bernardino, San Diego, and Ventura counties. These are the only counties in California in which RFG was ever implemented.

1994 and 1995 and were the only RFG control areas to experience such a surge in activity at this time.[27]

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[27] There were also a substantial number of installations in North Carolina; however, this state is not an RFG area, nor is it usually upwind of any such areas.

TABLE 5—NO$_x$ CONTROL INSTALLATIONS AT ELECTRIC GENERATION PLANTS
BY STATE AND YEAR

Year	Delaware, New Jersey, New York, Pennsylvania	California	All other states
1989	1	0	4
1990	5	0	7
1991	1	1	11
1992	7	0	15
1993	9	4	32
1994	33	6	60
1995	49	6	89
1996	19	0	47
1997	2	2	36
1998	8	0	60
1999	10	2	105
2000	5	4	68
2001	23	11	53
2002	54	4	68
2003	16	1	90

Source: Platts' BaseCase Continuous Emissions Monitoring System Unit Summary Data

We test this proposition by incorporating Table 5's data on NO$_x$ control instal-
lations into the RD regressions for monitors in Delaware, New Jersey, New York,
and Pennsylvania. We create a *TreatNOx$_t$* variable that is a cumulative count of
the NO$_x$ installations that have occurred in Delaware, New Jersey, New York,
and Pennsylvania by date t. We set *TreatNOx$_t$* to zero for all months outside of
the ozone season to reflect the seasonal use of NO$_x$ control equipment.[28] When
TreatNOx$_t$ is included in the regressions, the average coefficient on the RFG treat-
ment dummy falls from -0.072 to -0.011 over the 17 monitors in the region, and
the average t-statistic falls from -2.29 to -0.307 (monitor-by-monitor results
are given in Table A5 in the online Appendix). In contrast, we find a significant
impact from NO$_x$ control: the average impact of 100 additional NO$_x$ installations
on log(ozone) is estimated to be -0.050 with an average t-statistic of -1.88.[29]
These results are evidence that the summer ozone reductions along the eastern
seaboard were driven by local and upwind reductions in NO$_x$ emissions rather
than an effect of the RFG program.

At locations outside of Delaware, New Jersey, and New York, the average esti-
mated impact of RFG is $+0.016$. The estimated impact at monitor 47 in Harris
County, Texas (Houston) nearly matches this mean, and Figure 6 panel C plots
ozone residuals and a fitted trend at this location. A shift in neither the residuals nor
the fitted line is apparent in 1995, when RFG was imposed.

Finally, we note that the lack of evidence tying RFG to reductions in ozone is not
caused by an absence of VOC-limited areas in our sample of monitors. A number

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[28] Electric generators deactivate NO$_x$ control equipment outside of the ozone season because it imposes high
operating costs. The EPA-designated ozone season for NO$_x$ control is May 1 through September 30.

[29] Separate identification of the NO$_x$ control effect from the RFG effect comes from the fact that the RFG treat-
ment is constant across all summers after 1995, whereas the NO$_x$ treatment increases in magnitude each summer as
generators make more investments in pollution control equipment. In particular, a second wave of NO$_x$ abatement
installations in 2001 and 2002 appears to have contributed to additional reductions in summer ozone that cannot be
explained by RFG.

Panel A. Los Angeles County, California (site 1201)
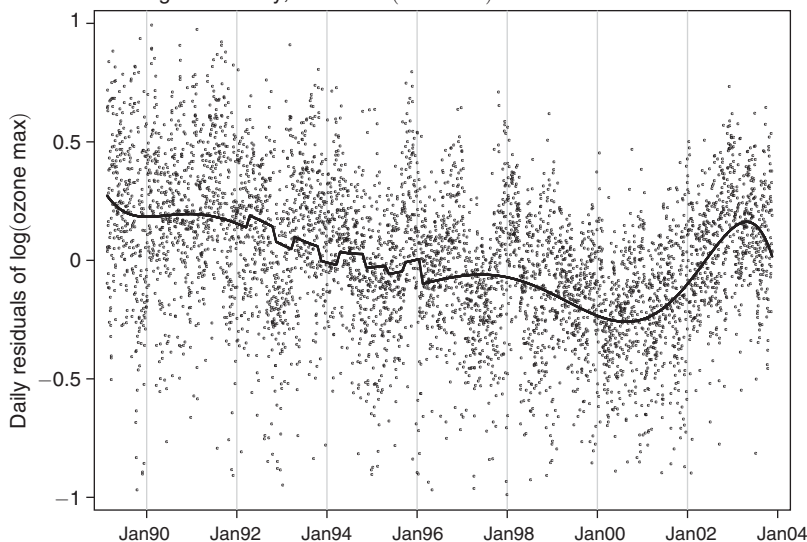
Panel B. Los Angeles County, California (site 1701)
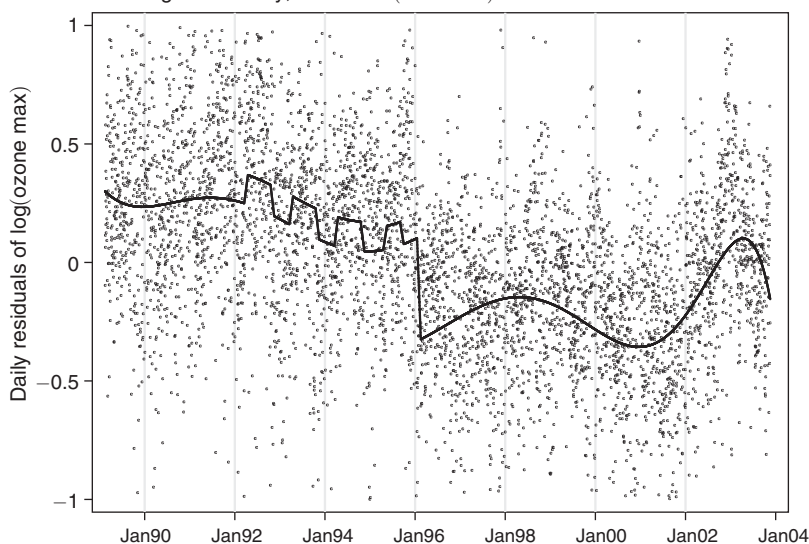
FIGURE 8. DAILY MAXIMUM OZONE CONCENTRATIONS

Notes: Fitted lines are the predicted values of the treatment dummies and eighth-order polynomial time trend from estimating equation (3), centered at zero. Points plotted are the residuals from (3) plus the fitted line. Regulations include RVP (summer 1992–1994), RFG (summer 1995), and CARB (March 1996–).

of monitors are located in urban areas such as Chicago, Houston, Philadelphia, and New York that are thought to be VOC-limited (Sillman 1999; Blanchard 2000, 2001; and Steven D. Reynolds, Blanchard, and Stephen D. Ziman 2004). At none of these monitors do we find evidence of a substantial decrease in ozone associated with RFG. In fact, the eastern seaboard monitors at which we find ozone reductions are suburban locations that are likely to be NO_x-limited (Blanchard 2001),

Panel A

Panel B
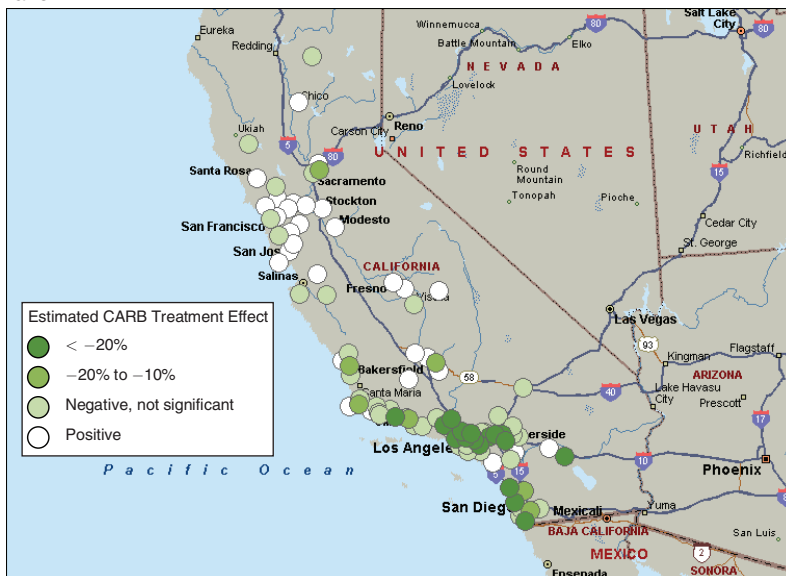
Figure 9. Maps of Estimated CARB RD Treatment Effects

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

further supporting the claim that these reductions were driven by NO_x emission abatement rather than RFG. Overall, we conclude that RFG, like RVP, does not substantially reduce ozone pollution.

C. *Regression Discontinuity Results: CARB*

Figure 8 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 with 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 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 in Figure 9, panel A.

While the coastal monitor in panel A of Figure 8 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 percent; 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 percent, statistically significant at the 1 percent level.

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 Table A4 in the online Appendix.[30] 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.[31]

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[30] We have also used a local linear regression estimation strategy, which first strips out seasonal and weather effects and then evaluates the CARB treatment effect using regressions on data limited to a specified bandwidth around the March 1996 treatment date. Using bandwidths of 365 and 180 days on both sides of this date, we find results that are very similar to those presented in Table A4 in the online Appendix. At a 90-day bandwidth, point estimates are similar to those in Table A4, though standard errors increase so that most estimates are not statistically significant at conventional levels.

[31] To the best of our knowledge, and after extensive checking with CARB, no new VOC or NO_x regulations were coincident with CARB in 1996. There were zero NO_x emission control installations at California power plants in 1996 (Table 5). Of the six installations in California in 1995, four were in Los Angeles County, and two were in Ventura County. Five of these six were installed by June, nine months before the onset of CARB and the discontinuity in the ozone data. Even putting aside this mis-timing, these installations cannot explain the March 1996 decrease in ozone in San Diego county, well to the South (and not downwind) of Los Angeles. Finally, Meredith Fowlie,

The kernel density plot of Figure 7, panel A 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(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 left tail is drawn almost entirely from monitors in the Los Angeles and San Diego area.

One difficulty in interpreting Figure 7, panel A is that the southern California monitors driving the left tail of CARB results are not represented in the RVP and RFG results. Even though urban areas that are thought to be VOC limited are represented in the RVP and RFG regressions, it may be that unique features of southern California drive the differences in estimated regulatory effectiveness rather than the regulations themselves. Panel B of Figure 7 addresses this issue by plotting distributions of the estimated impacts of RVP, RFG, and CARB in southern California.[32] The distribution of RFG's estimated impacts has a mean near zero at $+0.021$, and the RVP distribution is centered slightly to the right at $+0.055$. These last results demonstrate that RVP and RFG regulations were ineffective at the same locations for which CARB regulation significantly reduced ozone concentrations.[33]

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 no evidence that federal RVP or RFG standards are effective in reducing ozone pollution. While we find decreases in summer ozone in Delaware, New Jersey, and New York that are coincident with the onset of RFG regulation in these locations, these impacts are better explained by local and upwind NO_x emissions controls. In California, however, the adoption of CARB standards in 1996 caused a large, significant decrease in ozone concentrations in the densely populated and VOC-sensitive southern part of the state. RVP and RFG controls that were introduced in this region prior to adoption of CARB did not result in reductions in ozone.

V. The Importance of Refiners' Behavioral Response

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

Refiners meet RVP and RFG requirements primarily by removing the VOC butane from their gasoline, as noted by EPA rulemaking.[34] Butane is a light, highly vola-

Stephen P. Holland, and Erin T. Mansur's (2009) study of the NO_x cap-and-trade market in California indicates that NO_x emissions in the Los Angeles basin did not substantially decrease in 1996 (Figures 2 and 3 in their paper).

[32] The seasonal RVP and RFG treatment effects shown in panel B of Figure 8 were estimated jointly with the CARB treatment effect per the discussion in Section IIIB. We have also estimated these effects using data that exclude 1996 onward, when CARB was in effect. While doing so results in noisier estimates due to the diminished sample size, we still find no evidence that either RVP or RFG was effective in southern California.

[33] Moreover, the spatial distribution of the estimated RVP and RFG effects are not systematic, as is the case with CARB. That is, the negative part of the RVP and RFG distributions are not concentrated at the inland southern California monitors, as would be expected if RVP and RFG were effective in reducing ozone concentrations. We also find no evidence that RFG has a year-round impact in southern California.

[34] 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).
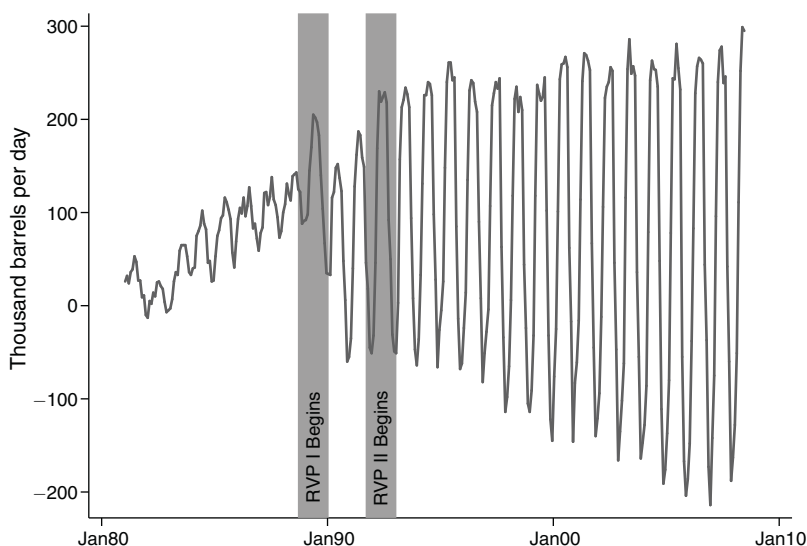
FIGURE 10. REFINERY NET PRODUCTION OF BUTANE

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.

tile compound that refiners typically blend into conventional gasoline to increase its octane rating. Reducing the amount of butane that is blended is the most cost-effective avenue available to refiners to meet VOC emission reduction standards. However, butane is not highly reactive in forming ozone (CARB 2007). Thus, even though gasoline that meets RVP or RFG standards emits a lower volume of VOCs than does conventional gasoline, this emissions reduction does not translate into reductions in ground-level ozone.[35]

Evidence from both the butane market and air quality measurements indicates that the VOC emission reduction mandates of RVP and RFG substantially reduced the use of butane in summer gasoline. Lidderdale (1999) evaluates the impact of RVP and RFG on refining operations and finds that refiners' summer blending of butane substantially decreased following the imposition of these 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

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[35] 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. With regard to RVP, conversations with EPA personnel have indicated that removing butane from gasoline can, in principle, lead to reduced emissions of other, more reactive compounds (when butane evaporates from gasoline, it carries other VOCs with it), and that this belief likely played a role in EPA forecasts of ozone benefits from RVP. However, the only study we have identified that directly examines this effect (Robert M. Reuter et al. 1992) found highly inconclusive results regarding the difference between the ozone forming potential of emissions from RVP and non-RVP gasoline, leading us to conclude that the science regarding the magnitude of this effect is unsettled. As for RFG, according to its final Regulatory Impact Analysis (EPA 1993), the EPA claims that the Clean Air Act Amendments (CAAAs) of 1990 forbid it from using reactivity weighting when setting VOC emission reduction standards because 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.
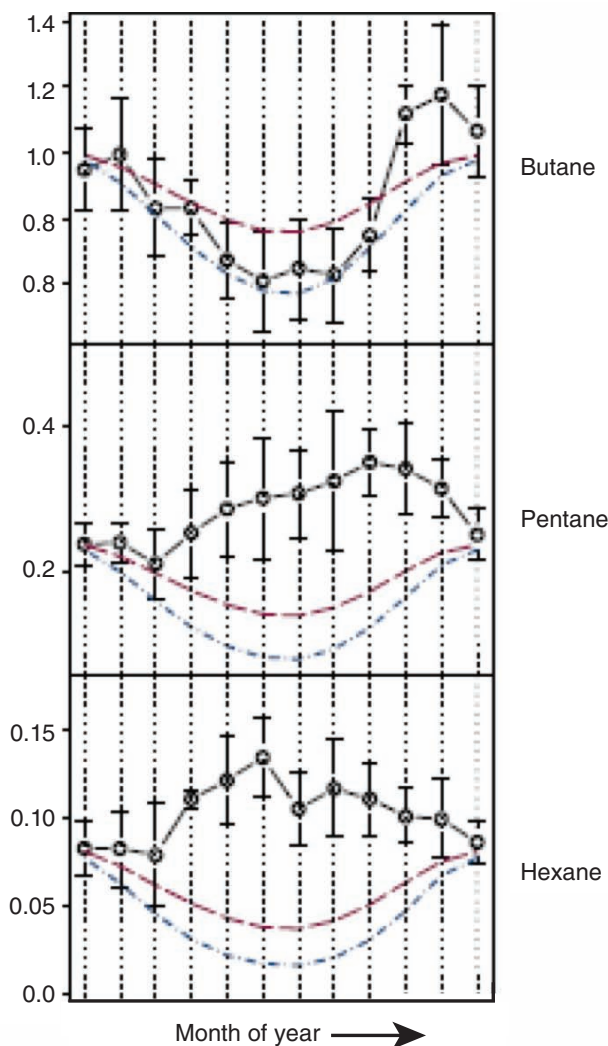
FIGURE 11. AMBIENT VOC CONCENTRATIONS IN MASSACHUSETTS, 1992–1996

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.

Source: Reproduced by permission of American Geophysical Union.

production becomes highly seasonal beginning in 1989, when RVP standards are first implemented. This seasonality is accentuated following the imposition of RVP Phase II in 1992 and more modestly following RFG in 1995, which affected fewer areas. Under RVP and RFG, 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 the VOC standards are not in effect.

The decrease in summer gasoline's butane content is also observable in ambient air quality measurements. Ben H. Lee et al. (2006) measure air concentrations of a variety of anthropogenic VOCs in Massachusetts over 1992–1996. They find that, unlike other VOCs, 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 concentrations during the winter. The authors attribute this result to the RVP and RFG standards in place in Massachusetts during the years these measurements were taken.

In contrast to RVP and RFG, CARB regulations 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.

VI. 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. There is no evidence, however, that the RVP or RFG regulations result in significant ozone reductions, even at the same locations for which CARB was effective.[36] RVP and RFG nonetheless impart substantial costs on consumers, since the entire country is subject to one of them during the summer months. Given US non-California 2008 summer gasoline consumption of 47 billion gallons and a $0.01–$0.015 per gallon price effect estimated in Brown et al. (2008), the VOC standards imposed by these regulations increase US annual gasoline expenditures by $524–$784 million.[37]

The ineffectiveness of RVP and RFG in reducing ozone can be explained by the cost-minimizing response of refiners to the regulations. Because these standards grant refiners broad flexibility in deciding which specific VOCs to remove from their gasoline, they are able to reduce the content of a particular VOC, butane, which is relatively cheap to remove but is not prone to forming ozone. In contrast, CARB gasoline mandates reductions in concentrations of highly reactive VOCs and yields substantial reductions in ground-level ozone pollution. These outcomes highlight

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[36] RFG also has elements directed at reducing carbon monoxide and carcinogenic toxics emissions. This paper does not evaluate these potential benefits. RVP is directed solely at reducing VOC emissions.

[37] 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_mbbl_a.htm), using data for May through August and half of September.

a potential pitfall of flexible environmental regulations: while allowing flexible responses to standards can mitigate abatement costs, flexibility can also reduce the desired environmental benefits.

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 percent at some monitoring locations. Our regression discontinuity estimates indicate that the average ozone reduction across monitors in the Los Angeles–San Diego severe ozone nonattainment area is 15.6 percent. Other California counties that are cooler or less densely populated, however, generally do not experience large reductions in ozone pollution following the imposition of CARB. Fortunately, these counties are those for which ozone levels are typically below unhealthy levels.[38]

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 et al.'s (2004) estimates of ozone's mortality impacts, our RD estimates translate into 660 saved lives in California each year.[39] 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, 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 of 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.

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[38] These heterogeneous effects were 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.

[39] We calculate this impact by first averaging our monitor-level results to the county level and assuming no effect in nonmonitored counties. We then use Bell et al.'s (2004) formula, in combination with data on population and pre-CARB ozone levels, to compute county-level estimates of lives saved.

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Web Appendix

Clearing the Air? The Effects of Gasoline Content Regulation on Air Quality

Maximilian Auffhammer and Ryan Kellogg

Table A1: 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

[1]The 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.

[2]These 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 A2: Reid vapor pressure (RVP) phase II regulatory details

Area	Number of Counties	RVP First Year	RVP Last Year	VOC Control Period[1] Seasonal Start Date	Seasonal End Date	RVP level (psi)
Federally mandated						
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
State Implementation Plans						
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

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

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

[3] Phoenix adopted RFG on 4 August, 1997.

[4] Baltimore, 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.

[5] Adopted RFG in the following summer.

[6] Designated attainment following summer 1993

[7] Adopted CARB in the following summer.

[8] Seasonal start and end dates are county-specific.

[9] GA gasoline also restricts sulfur content

[10] RVP did not begin until 1 July in 1996.

Table A3: 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
Federally mandated					
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
Opt-in					
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
State-specific reformulations					
Phoenix, AZ (AZCBG)	1	1998		01 Jun	30 Sep
Entire state, CA (CARB)	58	1996		varies[7]	varies[7]

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

[2]LA-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.

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

[4]Baltimore, 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.

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

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

[7]Seasonal start and end dates are county-specific.

Table A4: 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	0.055	(0.028) **		Arizona	Maricopa	19	-0.090	(0.044) **
Colorado	Arapahoe	2	0.100	(0.031) ***		Arizona	Maricopa	1004	-0.078	(0.032) **
Colorado	Denver	14	0.080	(0.040) **		Delaware	New Castle	1003	-0.116	(0.059) *
Colorado	Jefferson	2	0.035	(0.032)		District of Columbia		25	0.059	(0.060)
Florida	Broward	2003	-0.030	(0.031)		Illinois	Cook	50	-0.003	(0.050)
Florida	Broward	8002	-0.109	(0.032) ***		Illinois	Cook	64	-0.055	(0.047)
Florida	Duval	77	0.021	(0.025)		Illinois	Cook	7002	0.061	(0.030) **
Florida	Hillsborough	81	0.044	(0.034)		Illinois	DuPage	6001	0.027	(0.027)
Florida	Hillsborough	1035	0.009	(0.024)		Illinois	Kane	5	0.084	(0.029) ***
Florida	Miami-Dade	21	-0.115	(0.030) ***		Illinois	Lake	1002	3.4E-04	(0.037)
Florida	Miami-Dade	27	-0.078	(0.027) ***		Illinois	Lake	3001	-0.012	(0.037)
Florida	Miami-Dade	29	0.022	(0.034)		Illinois	Will	1008	0.073	(0.030) **
Florida	Miami-Dade	30	-0.105	(0.043) **		Maryland	Baltimore	3001	-0.052	(0.043)
Florida	Palm Beach	2004	-0.109	(0.112)		Maryland	Harford	1001	-0.036	(0.025)
Florida	Pinellas	4	-0.014	(0.027)		Massachusets	Hampden	8	-0.019	(0.042)
Florida	Pinellas	18	-0.046	(0.038)		Massachusets	Hampshire	4002	-0.029	(0.027)
Florida	Pinellas	5002	-0.070	(0.035) **		New Jersey	Atlantic	5	-0.134	(0.026) ***
Illinois	Madison	8	0.024	(0.032)		New Jersey	Camden	3	-0.039	(0.034)
Illinois	Madison	1009	0.014	(0.036)		New Jersey	Camden	1001	-0.147	(0.031) ***
Illinois	Madison	2007	0.026	(0.027)		New Jersey	Cumberland	7	-0.116	(0.025) ***
Illinois	Madison	3007	0.004	(0.026)		New Jersey	Gloucester	2	-0.100	(0.029) ***
Illinois	Saint Clair	10	0.068	(0.031) **		New Jersey	Hudson	6	-0.029	(0.029)
Louisiana	Beauregard	2	0.009	(0.054)		New Jersey	Hunterdon	1	-0.030	(0.033)
Louisiana	Calcasieu	2	-0.011	(0.057)		New Jersey	Mercer	5	-0.117	(0.041) ***
Louisiana	East Baton Rouge	3	0.025	(0.039)		New Jersey	Monmouth	5	-0.056	(0.028) **
Louisiana	East Baton Rouge	1001	-0.013	(0.037)		New Jersey	Morris	3001	-0.065	(0.034) *
Louisiana	Grant	1	0.009	(0.035)		New York	Dutchess	7	-0.029	(0.031)
Louisiana	Jefferson	1001	0.154	(0.042) ***		New York	Essex	2	-0.082	(0.023) ***
Louisiana	Orleans	12	-0.058	(0.047)		New York	Essex	3	-0.065	(0.023) ***
Louisiana	Pointe Coupee	1	-0.024	(0.033)		New York	New York	63	-0.078	(0.050)
Louisiana	St. Bernard	2	-0.077	(0.048)		New York	Suffolk	2	-0.073	(0.032) **
Louisiana	St. James	2	-0.044	(0.069)		Pennsylvania	Philadelphia	24	0.061	(0.029) **
Louisiana	St. Mary	3	0.049	(0.054)		Texas	Galveston	1002	0.001	(0.066)
Louisiana	West Baton Rouge	1	-0.056	(0.039)		Texas	Harris	46	0.001	(0.045)
Nevada	Washoe	20	0.040	(0.029)		Texas	Harris	47	0.018	(0.043)
Nevada	Washoe	1005	0.035	(0.032)		Texas	Harris	62	0.016	(0.053)
Tennessee	Davidson	11	0.068	(0.045)		Texas	Harris	1035	0.022	(0.048)
Tennessee	Davidson	26	-0.022	(0.051)		Texas	Tarrant	1002	0.219	(0.032) ***
Texas	Bexar	32	-0.013	(0.057)		Texas	Tarrant	2003	0.111	(0.034) ***
Texas	El Paso	37	0.088	(0.033) ***		Virginia	Fairfax	1004	8.4E-05	(0.056)
Texas	Gregg	1	0.019	(0.031)		Virginia	Fairfax	5001	0.028	(0.051)
Texas	Jefferson	9	-0.101	(0.066)						
Texas	Jefferson	11	0.087	(0.065)						
Texas	Nueces	25	-0.016	(0.047)						
Texas	Nueces	26	-0.030	(0.054)						
Texas	Travis	14	0.049	(0.038)						

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%

Table A4 continued: 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	-0.049	(0.048)
California	Alameda	1001	0.066	(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	0.093	(0.048) *	California	San Bernardino	4003	-0.074	(0.061)
California	Contra Costa	1002	0.057	(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	0.193	(0.065) ***	California	San Diego	3	-0.135	(0.056) **
California	Fresno	4001	0.191	(0.091) **	California	San Diego	5	-0.231	(0.081) ***
California	Kern	7	-0.118	(0.057) **	California	San Diego	6	-0.064	(0.076)
California	Kern	8	0.007	(0.059)	California	San Diego	1001	-0.209	(0.064) ***
California	Kern	232	0.064	(0.061)	California	San Diego	1002	-0.127	(0.048) ***
California	Kern	5001	0.088	(0.060)	California	San Diego	1006	-0.119	(0.063) *
California	Kern	6001	0.061	(0.065)	California	San Diego	1007	-0.099	(0.067)
California	Lake	3001	0.002	(0.092)	California	San Francisco	5	-0.010	(0.079)
California	Los Angeles	2	-0.145	(0.083) *	California	San Joaquin	1002	0.062	(0.080)
California	Los Angeles	16	-0.130	(0.089)	California	San Luis Obispo	2001	-0.051	(0.049)
California	Los Angeles	113	-0.325	(0.111) ***	California	San Luis Obispo	2002	-0.149	(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	-0.007	(0.153)	California	Santa Barbara	8	-0.047	(0.046)
California	Los Angeles	1601	-0.375	(0.086) ***	California	Santa Barbara	10	-0.203	(0.080) **
California	Los Angeles	1701	-0.434	(0.127) ***	California	Santa Barbara	1013	-0.022	(0.047)
California	Los Angeles	2005	-0.276	(0.071) ***	California	Santa Barbara	1014	-0.027	(0.065)
California	Los Angeles	4002	-0.084	(0.126)	California	Santa Barbara	1018	0.058	(0.053)
California	Los Angeles	5001	-0.115	(0.078)	California	Santa Barbara	1021	-0.030	(0.044)
California	Los Angeles	6002	-0.285	(0.063) ***	California	Santa Barbara	1025	-0.079	(0.057)
California	Marin	1	0.172	(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	0.002	(0.055)	California	Santa Barbara	4003	0.065	(0.083)
California	Orange	1	-0.073	(0.117)	California	Santa Clara	4	0.040	(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	0.011	(0.047)
California	Riverside	2002	-0.360	(0.092) ***	California	Shasta	3003	-0.045	(0.044)
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	0.102	(0.057) *
California	Riverside	9001	-0.028	(0.068)	California	Tulare	6	0.210	(0.064) ***
California	Sacramento	2	0.020	(0.085)	California	Tulare	2002	0.008	(0.059)
California	Sacramento	6	-0.190	(0.092) **	California	Ventura	4	-0.050	(0.062)
California	Sacramento	10	-0.060	(0.085)	California	Ventura	5	-0.142	(0.046) ***
California	San Benito	2	0.068	(0.037) *	California	Ventura	2002	-0.353	(0.086) ***
California	San Benito	3	-0.014	(0.040)	California	Ventura	2003	-0.006	(0.073)
California	San Bernardino	1	-0.012	(0.083)	California	Ventura	3001	-0.103	(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%

Table A5: Monitor-specific regression discontinuity estimation results for summer RFG and NO$_x$ controls. Treatment effects shown are the impact on log(ozone max)

State	County	Monitor ID	Original regression RFG treatment Beta	Std error	Control for NO$_x$ installations RFG treatment Beta	Std error	NO$_x$ installations /100 Beta	Std error
Delaware	New Castle	1003	-0.116	(0.059) *	-0.001	(0.051)	-0.099	(0.041) **
New Jersey	Atlantic	5	-0.134	(0.026) ***	-0.079	(0.034) **	-0.044	(0.020) **
New Jersey	Camden	1001	-0.039	(0.034)	0.070	(0.054)	-0.091	(0.036) **
New Jersey	Camden	3	-0.147	(0.031) ***	-0.043	(0.040)	-0.084	(0.022) ***
New Jersey	Cumberland	7	-0.116	(0.025) ***	-0.063	(0.037) *	-0.042	(0.022) *
New Jersey	Gloucester	2	-0.100	(0.029) ***	-0.036	(0.041)	-0.051	(0.022) **
New Jersey	Hudson	6	-0.029	(0.029)	0.045	(0.042)	-0.059	(0.030) *
New Jersey	Hunterdon	1	-0.030	(0.033)	0.040	(0.047)	-0.057	(0.028) **
New Jersey	Mercer	5	-0.117	(0.041) ***	-0.008	(0.057)	-0.087	(0.029) ***
New Jersey	Monmouth	5	-0.056	(0.028) **	-0.011	(0.047)	-0.042	(0.030)
New Jersey	Morris	3001	-0.065	(0.034) *	0.021	(0.044)	-0.072	(0.022) ***
New York	Dutchess	7	-0.029	(0.031)	0.027	(0.037)	-0.051	(0.021) **
New York	Essex	2	-0.082	(0.023) ***	-0.047	(0.036)	-0.032	(0.023)
New York	Essex	3	-0.065	(0.023) ***	-0.086	(0.029) **	0.018	(0.018)
New York	New York	63	-0.078	(0.050)	-0.086	(0.088)	0.008	(0.063)
New York	Suffolk	2	-0.073	(0.032) **	-0.038	(0.047)	-0.029	(0.032)
Pennsylvania	Philadelphia	24	0.061	(0.029) **	0.112	(0.040) **	-0.042	(0.025) *

Effects shown are the monitor-specific estimated coefficients on the treatment variables discussed in section IV(B)

NOx installations include those in Delaware, New Jersey, New York, and Pennsylvania, per table 5

Standard errors are clustered on year-season

Estimated effects of 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%