Localizing Environmental Regulation: The Case of Boutique Fuels

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Sharing Our Work

LOCALIZING ENVIRONMENTAL REGULATION: THE CASE OF BOUTIQUE FUELS.*

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Abstract

The Clean Air Act has authorized an array of fuel regulations to reduce the precursors to ambient ozone pollution, among other pollutants. With the emergence of stringent fuel regulations for the most pollution-intensive cities, and the opportunity for states to adopt fuel content regulations, the U.S. gasoline market has evolved over the past three decades to address local pollution. We have evaluated the pollutant concentration, emissions, and price impacts of Federal RFG, RVP, California RFG, and other boutique fuel rules. We find that California RFG continues to deliver large improvements in air quality, while the benefits from RFG, RVP and boutique fuels are either small or statistically insignificant. We note, that ex post impacts of reformulated fuels are smaller than those predicted by ex ante analyses.

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1. Introduction

To improve air quality and enhance public health, the Clean Air Act has relied on a mix of national standards as well as state and local regulatory implementation (Carlson and Burtraw (2019), Aldy et al. (2022)). Locally-tailored regulations reflect both requirements under the Clean Air Act for the most heavily-polluted areas as well as state discretion in crafting implementation strategies to improve local air quality. As a result, the benefits and costs of the Clean Air Act likely have varied substantially across space and time.

In this paper, we undertake a retrospective evaluation of an array of fuel content regulations applied at the local and state levels under the Clean Air Act. Specifically, we estimate the impacts of reformulated gasoline (RFG), Reid vapor pressure (RVP) volatility standards, and various other boutique fuel regulations adopted by states as a part of their state implementation plans on ambient ozone concentrations, emissions of ozone precursors, and gasoline prices. In conducting these analyses, we distinguish the impacts of the fuels regulations before and after 2004, when EPA began implementing the Tier 2 standards on both new vehicles and the sulfur content of gasoline (which affected the pollution reduction efficacy of tailpipe exhaust equipment in both new and existing vehicles).

Through 2003, we find that reformulated gasoline regulations reduced ambient ozone concentrations in the areas using RFG by about 3 to 5 percent, with slightly smaller reductions in concentrations as a result of RVP fuels. California RFG (CARB fuel) reduced ozone concentrations 10 to 15 percent. Boutique fuels had small and statistically insignificant impacts on ozone concentrations. After 2003, we find a 3 percent improvement in the ozone concentrations under RVP, but no impact of RFG or boutique fuels on ozone concentrations. CARB fuel continued to show reductions in ozone concentrations, with more than 20 percent reductions in the post-2003 period, some of which may be driven by other California specific efforts targeted at mobile sources.

Light-duty vehicle emissions of volatile organic compounds (VOCs) and nitrogen oxides (NO_X) were lower under RFG, RVP, and boutique fuels. The estimated emission reductions were more modest than what EPA had projected for RVP and only about half the magnitude of emission reductions for VOCs and NO_X under RFG than what EPA estimated in its prospective assessment. Boutique fuels realized significant emission reductions, of 23 percent for VOCs and 17 percent of NO_X, but these results represent a curious contrast with the ex post estimated null impact of boutique fuels on ozone concentrations.

In terms of gasoline prices, California CARB regulations contributes to the significantly higher price of gasoline during 2000-2012. The estimated difference in California gas prices to that of control locations is on the order of about 25 cents per gallon. Federal RFG standards increased gasoline prices by about 6 to 9 cents per gallon, while RVP rules had very small and statistically insignificant impacts. Boutique fuel regulations also had statistically insignificant price impacts.

Our analyses replicate and extend several papers in the literature. Our pre-2004 ozone concentration analyses deliver very similar results for RFG, CARB, and RVP standards as in Auffhammer and Kellogg (2011). It's important to note that we created new datasets for our regulatory variables, ozone concentration and weather measures, and other controls in this project. By looking beyond the 2003 end date in Auffhammer and Kellogg (2011), we also illustrate potential impacts of layering new regulations on top of RFG. The Tier 2 regulation appears to have reduced the environmental efficacy of RFG. Suppose that RFG delivered a 22 percent reduction in NO_X emissions, as specified in the rule-making and associated regulatory impact analysis, for all cars. Such a 22 percent reduction of a typical model year 2000 vehicle would result in 132 milligrams per mile lower emissions. In contrast, the same percentage reduction for a typical model year 2010 vehicle – with more stringent tailpipe emission standards – would result in 15 milligrams per mile fewer emissions. We also caution that the overlap of California CARB fuel standards and increasingly stringent California tailpipe standards over the 2000s and 2010s may be influencing our estimated impacts for California in our later period models. I.e., our estimated ozone concentration impacts could reflect both tailpipe standards and fuel regulations.

Our fuel price impacts extend the work of Brown et al. (2008) by focusing on the second phase of RFG. We find larger price impacts on average than they found for phase I, although that would be expected given the more stringent standards in the second phase. Our price impacts are comparable to those in Sweeney (2014), although based on a completely different empirical strategy.

The next section provides an overview of the regulatory landscape, including the prospective (ex ante) estimated impacts of various EPA Clean Air Act fuel regulations and relevant research literature evaluating these impacts. The third section summarizes the key data employed in our empirical models, which we describe in section four. The fifth section presents the results of our regulatory evaluation for ambient ozone concentrations, emissions of volatile organic compounds and nitrogen oxides, and gasoline prices. The final section concludes with a discussion of policy impacts, including a comparison of ex post estimates from this study and ex ante estimated impacts from regulatory impact analyses for these fuel rules, and next steps for scholarship.

2. Regulatory Landscape

2.1 National Ambient Air Quality Standards and State Implementation Plans

A core element of the Clean Air Act has been the authority granted the Environmental Protection Agency to establish National Ambient Air Quality Standards (NAAQS) for pollutants from diverse mobile and stationary sources that endanger public health and welfare. Such standards set the maximum permissible concentrations of common air pollutants, including carbon monoxide, lead, nitrogen dioxide, ozone, particulate matter, and sulfur dioxide. Under the law, EPA periodically reviews and updates the standards for a given pollutant. For example, EPA set new NAAQS for ozone in 1971, 1979, 1997, 2008, and 2015 (see Figure A1 in Aldy (2019)).

Upon setting a new NAAQS, EPA then designates non-attainment areas – counties (or portions thereof) with measured concentrations that violate the standard. Under the 1990 Clean Air Act Amendments, the non-attainment designations for ozone are characterized by a classification, ranging from marginal to extreme, based on the extent of non-compliance with the standard. EPA typically takes several years to designate non-attainment areas under a revised NAAQS (refer to Figure 1).

Once a state learns of its designated non-attainment areas, it has three years to produce a state implementation plan (often referred to as a SIP) for review by EPA. The SIP should demonstrate how a state's actions to reduce pollution would enable eventual attainment of a given pollutant's standard (or, in the case of a state that is fully attaining the standard, to demonstrate that it would not backslide into non-attainment). The agency may approve, reject, or approve in part and require modification of submitted SIPs. The agency may also substitute a federal implementation plan if it cannot reach agreement with a state on a suitable SIP for a given NAAQS pollutant (Garrett and Winner 1992).

Under the Clean Air Act, states have discretion over the sources of emissions that they may control and the regulatory tools they may use to control those sources. The law stipulates several requirements for the information submitted with a SIP, including: a state emissions inventory, attainment demonstrations based on air quality models, descriptions of emission control strategies and enforcement measures to enable required emission reductions, and provisions regarding downwind states' impacts.[1]

2.2 Boutique Fuels Regulations of the 1990s

Through most of the first two decades of the Clean Air Act, the Environmental Protection Agency had implemented its authority to reduce pollution from mobile sources by regulating transportation fuels to address only one problem: lead emissions (Aldy 2019). Through a series of regulations in the 1970s and 1980s, EPA phased down the lead content of gasoline. In 1989, the agency regulated gasoline volatility – through so-called Reid Vapor Pressure limits – to reduce volatile organic compound emissions that contribute to the formation of ground-level ozone.

The Clean Air Act Amendments of 1990 established a number of key changes in the regulation of air pollution, and ozone precursors such as volatile organic compounds and nitrogen oxides in particular. First, the Act charged EPA to develop new regulations for reformulated gasoline (RFG) to reduce volatile organic compound and nitrogen oxide emissions through two phases: 1995-1999

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[1] Refer to Boyd (2019) for more details on NAAQS and SIPs.

and 2000 and beyond (Auffhammer and Kellogg (2011), Aldy (2019)). The RFG rule required fuels to result in 15 percent less VOCs in the first phase and at least 26 percent in the second phase, with 22 percent reductions for NO_X emissions in the second phase. Those ozone non-attainment areas classified as severe or worse were required to use RFG during the mid-May to mid-September summer ozone season. In practice, about 30 percent of the summertime U.S. gasoline market has been comprised of reformulated gasoline.

Second, the Clean Air Act granted states some discretion in how they crafted and implemented fuel content regulations. A state could opt-in to the RFG program and, under certain conditions, opt out of the program (Garrett and Winner (1992), Brown et al. (2008)). California has a long-standing waiver policy under the Clean Air Act that enables it to craft a state analogue to federal policy so long as it is at least as stringent as the federal rule. In the context of RFG, California opted for its own, so-called CARB gasoline or California RFG, which specified the VOCs to be reduced in fuels (Auffhammer and Kellogg 2011). The act also provided for an array of boutique fuels programs, including RVP volatility, low-emission diesel, oxyfuels, and limits on sulfur, that states could adopt as a part of the policy program represented in their SIPs.

Figure 4 shows how gasoline content regulations, and ozone non-attainment designations (in red), evolved over 1995-2015. The map reveals the prevalence of more ambitious fuel content regulations in the most densely populated regions of the country, as well as the considerable spatial and temporal heterogeneity in fuels regulations. As a preview of our empirical strategy, this variation over time and space will serve as the primary basis for identifying the causal impacts of fuel content regulations.

2.3 Subsequent Fuels and Light-Duty Vehicle Regulations

After promulgating RFG and RVP regulations of the 1990s, the EPA turned its attention to regulating fuels and light-duty vehicles as a system to reduce air pollution. In 2000, the agency implemented the Tier 2 regulation that prescribed more stringent emission exhaust controls on light-duty vehicles and reduced the sulfur content of gasoline. The latter would make exhaust controls both in existing and new vehicles, starting with the 2004 model year, more efficient in removing VOCs and NO_X emissions, as well as reduce ambient concentrations of fine particulate matter. This pollution strategy built on a long regulatory history of limiting tailpipe emissions dating to the 1970s, and accelerated reductions in emissions in the mobile sources sector as the light-duty vehicle fleet turned over. The agency focused on air toxic and benzene emissions in a rule that applied to vehicles and fuels starting in 2011, and then again with more stringent emission exhaust and fuel sulfur standards in the Tier 3 regulation that took effect in 2017 (see Figure 1).

Under the Clean Air Act waiver process, California could secure EPA approval for more stringent vehicle emission standards (Rabe 2019). California has consistently established more ambitious NO_X standards for new vehicles than the federal government, although, with federal standards two orders of magnitude lower today than three decades ago, these standards have effectively converged (see Figure 2). The Clean Air Act permits other states to adopt California emission standards, and, over 1993-2014, a dozen states did so (see Table 1).

The evolution of light-duty vehicle emission standards – especially with respect to the California waiver and its adoption by other states – overlapped with RFG and some boutique fuel standards over time. Moreover, the national regulations on fuels (Tier 2, Air Toxics and Benzene, and Tier 3) coupled with the national regulations on vehicles (which are effectively implemented in the vehicle fleet over time as new models replace retiring and scrapped vehicles), lowered the emissions expected from conventional gasoline-powered vehicles outside of areas with boutique fuel regulations. Recent engineering analyses indicate that the national fuel regulations have resulted in considerable convergence among conventional and reformulated gasoline in terms of emissions and air quality impacts (Hoekman et al. 2019).

The dramatic improvement in vehicle standards also illustrates the diminishing returns to fuel content regulations. For example, a model year 2000 vehicle with NO_X emissions equal to the federal standard of 600 milligrams per mile operated on phase II RFG would be expected to result in a 132 milligram per mile (22 percent) reduction in emissions. This reduction is nearly double the allowed emissions for a model year 2010 vehicle, on average (70 milligrams per mile). A 22 percent reduction in NO_X emissions of this model year 2010 vehicle running on RFG would be about 15 milligrams per mile, 89 percent fewer reductions per mile than the model year 2000 vehicle. As a result of the national fuels and vehicle standards becoming markedly more stringent starting in 2004, our empirical analyses below will distinguish the impacts of RFG, RVP, and other boutique fuel regulations before and after this date.

2.4 Ex Ante Estimates and Related Research Literature

When promulgating these regulations, EPA issued regulatory impact analyses that characterized the estimated impacts of the rules expected upon full implementation. Table 2 presents the prospective estimates of the costs, measured in cents per gallon of gasoline, change in VOC emissions and NO_X emissions, and the change in ambient ozone concentrations. The phase I and phase II of RFG were expected to result in fairly significant price impacts, 5 cents per gallon, during a period of time when gasoline prices ranged from about \$1.00-\$1.50 per gallon. The RFG regulatory impact analysis did not estimate expected changes in ozone concentrations or quantify or monetize benefits of the rule. Indeed, many of the analyses of these rules did not report changes in NO_X emissions or ozone concentrations. In our concluding section, we revisit these ex ante estimates and compare them with our ex post evaluation estimates.

To put the EPA prospective estimates and our subsequent ex post evaluations in context, also consider several alternative ex ante and ex post assessments of boutique fuel regulations. As EPA finalized the RFG rulemaking, Council (1993) published estimated per gallon costs of reformulated gasoline ranging from 8 to 14 cents per gallon over 1995-2010 (in 1990 dollars). A variety of ex post evaluations find that the gasoline price impacts of RFG reflect both regulatory compliance costs and segmentation of markets under the regulation that results in imperfect competition (Brown et al. (2008), Chakravorty et al. (2008), Sweeney (2014). In their assessment of phase I of RFG, Brown et al. (2008) find that the rule increased prices on average about 3 cents per gallon, but with significant heterogeneity as the price increase ranged by as much as 8 cents per gallon across markets using RFG. Sweeney (2014) estimates higher costs per gallon in phase II of RFG, averaging about 7 cents per gallon, but with similarly large heterogeneity. Anderson and Elzinga (2014) show that state bans of MTBE over 2000-2006 increased the price impacts of RFG by 3 to 6 cents per gallon.

Ex post evaluations of the emissions and health impacts of RFG appear to be modest outside of California. Auffhammer and Kellogg (2011) estimate that the CARB gasoline (California RFG) mandated by California as its alternative to the Federal RFG standard reduced ozone concentrations in California 16 percent. In contrast, they find 2 to 3 percent reductions in ozone concentrations under RFG, and statistically insignificant and small changes in ozone under RVP regulations. Area-specific empirical evaluations showed that many areas experienced no statistically meaningful change in ozone concentrations under RFG. These analyses reflect the average of RFG phases I and II over 1995-2003. Marcus (2017) shows that the California CARB gasoline reduced children's asthma admissions to hospitals by 8 percent, and may have closed disparities in respiratory health outcomes in the state.

3. Data

3.1 Pollution Data

We obtained the universe of hourly ambient monitored concentrations for Ozone (O_3) and NO$_X$ from the Environmental Protection Agency's Air Quality System Environmental Protection Agency (2022) from 1992 - 2021. We downloaded the hourly annual files and processed them using the filters applied by Auffhammer and Kellogg (2011). For each monitoring site, we drop hourly observations with quality control issues flagged by EPA, and then calculate two pollution measures at the monitoring site - day level, which are the daily maximum concentration and the daily 8 hour maximum value. The 8 hour maximum value measures the average concentration over all eight hour periods in a given day and chooses the highest one thereof. These two measures of pollution are consistent with the statistics the EPA has used to regulate air pollution since the 1970s. Consistent with EPA documentation, we discard all monitor-days, for which there are not at least 9 hourly measurements available during the daylight hours of 9am - 9pm. We also discard monitor years, for which more than 25% of the ozone season data are missing. Further, we discard any monitor located in a county that is adjacent to a county that is subject to either RVP, RFG or boutique fuel regulation due to "gasoline toursim" concerns. We follow this filtering strategy for both the ambient concentrations of Ozone and NO_X. Figure 3 displays the historical record of all measured Ozone concentrations in the lower 48 United States. For each day, we display the full unweighted distribution of measurements by incrementally shading the deciles of the distribution. Two things emerge from this record. First, it appears that the median unweighted Ozone concentration seems to not have decreased much since the 1980s. But what is clear from the figure is that the extremes of the distribution have dropped massively over time. If we look at the upper tail of the distribution, which straddled a concentration of 0.1 parts per million (ppm), well above the current 8-hour standard of 0.070 ppm); the last decade brought these extreme values down to 0.06 ppm, which is significant.

Ambient concentrations are obviously the measure most relevant to human health, yet since we are concerned with different types of reformulated gasoline, it is instructive to examine emissions of pollutants from the transport sector. We compiled on-road gasoline emissions of NO_X and VOCs from the EPA National Emissions Inventory (NEI) by county and year for 1990, 1996, 1999, 2002, 2005, 2008, 2011, 2014, and 2017. These are made available by the EPA in their Tier 2 summary files for the NEI. While EPA reports monitored emissions for some NEI source categories (e.g., fuel combustion at utility power plants), the NEI data for on-road gasoline emissions are estimates produced by EPA transportation models. Due to periodic updating of the transportation models, there may be model-specific, and hence year-specific, influences on the estimated emissions from on-road gasoline combustion. In our statistical models described below, we account for the year of the NEI to control for these influences (to the extent that they do not vary across space within a year).[2]

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[2] We downloaded all datasets from the EPA NEI webpage, `https://www.epa.gov/air-emissions-inventories/national-emissions-inventory-nei`. Contact the authors for more details on the extracted files for each year of the NEI.

3.2 Regulatory Data

There are three types of regulatory interventions we examine in this paper: Reid Vapor Pressure Regulations, Reformulated Gasoline Regulations and Boutique Fuels. Further, we separate out a fourth category, which is California's Reformulated Gasoline. We have amended the regulatory data used by Auffhammer and Kellogg (2011) by going beyond the year 2003 and collecting beginning and end dates for boutique fuels.[3] For each type of regulation we know first date the regulation was in place in a given county and, if it was retired, the last date it was active. Further, we know the seasonal begin and end date of the regulation, as many of the reformulated fuel regulations are only active during the ozone season, which is summer (defined slightly differently across the country). Figure 4 displays which regulation was active in each county for years 1995 and year 2015.[4] There is significant time series and spatial variation in these regulations over time. It is worth noting that California's reformulated gasoline went online March 1, 1996 and has been active year-round since then. This creates identification issues, which we discuss below, as there is no within year variation and hence any regulation affecting air quality post March 1996 in California will confound the effect of this policy.

3.3 Weather Data

Weather is a major driver of Ozone concentrations. Weather data are provided by the PRISM project at Oregon State University (PRISM Climate Group 2014). This dataset contains daily gridded maximum and minimum temperature for the continental United States at a grid cell resolution of roughly 2.5 miles. In order to match weather observations to the monitors, we select the grid cell of the PRISM data that overlaps the latitude/longitude of the pollution monitor. Our data used in the empirical analyses start in 1992, hence we construct daily time series for each monitor and weather indicator and match them to the pollution data.

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[3] We thank colleagues at the US EPA for helping us uncover the location of these data.

[4] In the empirical model, we use these data at the annual level.

3.4 Gasoline Price Data

We acquired from the Oil Price Information Service city-average, daily gasoline prices for 50 cities over 1998-2012. We deflated these to 2019 dollars using the GDP implicit price deflator. The set of cities includes 28 of the 30 largest cities by population in the United States (Fort Worth and El Paso, Texas are the two exceptions), and spans most other cities that have been covered by RFG standards as well as comparable, nearby cities that have consistently used conventional gasoline during our study period (see Table 3).

3.5 Other Data

We have also compiled county-year population data from the U.S. Census and county-year personal income data from the U.S. Bureau of Economic Analysis.

4. Econometric Estimation Strategy

4.1 Ambient Pollution Concentrations

Building on the work of Auffhammer and Kellogg (2011), we employ a conventional difference-in-differences estimator of air quality. Through this strategy, the estimated causal impact of regulations on ambient ozone concentrations is identified based on the year-to-year changes in concentrations for those monitors that have experienced a change in fuel content regulatory status in comparison to the changes in ozone concentrations for the control monitors in those areas without a change in regulatory status. Our core empirical model is specified as:

$$\ln[O_3] = \alpha \cdot Treat_{ct} + \beta \cdot W_{it} + \gamma_r \cdot D_t + \delta \cdot I_{ct} + \theta \cdot Trend_{rct} + \mu_i + \eta_{ry} + \epsilon_{it} \tag{1}$$

where $\ln[O_3]$ represents the natural logarithm of the highest 8-hour average ozone concentration at monitor i on date t; Treat_{ct} represents the vector of indicator variables for regulatory treatment (RVP, RFG, CARB, and boutique fuel rules for all other boutique fuel standards) for county c and date t; the vector W_{it} controls for monitor-specific weather shocks through polynomial functions of temperature and precipitation, their interactions, and their interactions with day-of-year and day-of-week; the vector D_t represents indicator variables for day-of-week and day-of year interacted with indicators for Census region, r; the variable I_{ct} represents county-level total annual personal income; the vector Trend_{rct} represents region-specific and regulation-specific time trends (in some specifications, these are linear time trends, and others quadratic); μ_i represents monitor fixed effects; and η_{ry} represents region-by-year fixed effects. As in Auffhammer and Kellogg (2011), we cluster the standard errors by state-year, to account for both serial correlation and within-state cross-sectional correlation.

As Auffhammer and Kellogg (2011) note, the identification assumption is that unobserved factors are not correlated with treatment by a regulatory standard, conditional on the covariates. To the extent that there are factors that are not accounted for in our controls or are non-linear over time, then this assumption may not hold. For example, approximately midway through our sample, new regulations (Tier 2) come online. The Tier 2 rules are likely to have an increasingly larger impact on ozone concentrations over time as new vehicles, subject to Tier 2 standards, enter the U.S. private vehicle fleet and older, more polluting vehicles are scrapped. As one way to explore this potential effect, we estimate models with a cut-off at 2003, the last year before implementation of the Tier 2 standard. Thus, we estimate a set of 1992-2003 models and 2004-2020 models.

4.2 Emissions

We employ a similar strategy to estimate the impact of regulatory status on emissions, although the triennial nature of the NEI data limit the extent to which we can include some of the controls (e.g., weather polynomials and trends) from the ambient concentration models. Our core empirical model for emissions is specified as:

$$\ln\left[Emissions_{cy}\right] = \alpha \cdot Treat_{cy} + \eta \ln\left[pop_{cy}\right] + \phi \ln\left[wageincome_{cy}\right] + \mu_c + \eta_y + \epsilon_{cy} \tag{2}$$

where $\ln\left[Emissions_{cy}\right]$ represents the natural logarithm of emissions of VOCs or NO_X for county c and year y; Treat_{cy} is the county-year analogue to that in the ambient ozone concentration estimating equation; $\ln pop_{cy}$ is the natural logarithm of county population for that year; $\ln\left[wageincome_{cy}\right]$ is the natural logarithm of county labor income (deflated to 2021 dollars) for that year; and μ and η represent county and year fixed effects, respectively. Standard errors are clustered by county. As for ozone concentrations, we estimate separate models with pre-2004 and post-2003 samples.

We include the county-year population measure, given the significant within-county change, and cross-county heterogeneity in that change, in population over the nearly three decades in our data. The high degree of correlation of county vehicle count and use with population is evident in statistical models that omit a control for population. We also include labor income as a measure of economic activity that may be correlated with vehicle use, and hence emissions.

4.3 Prices

We also employ a similar strategy to estimate the impact of fuel regulations on gasoline prices. Our core empirical model is specified as:

$$Gasprice_{nt} = \alpha \cdot Treat_{nt} + \beta \cdot W_{nt} + \eta_y + \xi_m + \rho_d + \phi_p + \epsilon_{mt} \tag{3}$$

where $Gasprice_{nt}$ represents the gasoline price per gallon in 2019 dollars for city n on date t; $\mathbf{Treat}_{nt}$ is the city-date analogue to that in the ambient ozone concentration estimating equation; $\mathbf{W}_{it}$ represents temperature and precipitation controls; and η_y, ξ_m, ρ_d, and ϕ_p represent year, month, day-of-week, and PADD fixed effects, respectively. We estimate these models for the period 2000 to 2012, due to the transition to phase 2 of RFG in the spring of 2000. In some specifications, we estimate the models with all months of the year, and others we focus on the summer ozone season of June, July, and August. All models are estimated with standard errors clustered by city.

In contrast to the models for ozone concentrations and emissions, we do not estimate our gasoline price regressions with pre-2004 and post-2003 samples. While fuels were subject to more stringent sulfur content regulations starting in 2004, these were a part of a nationwide fuels regulation implemented through a market-based cap on sulfur content per gallon of gasoline. As a result, we expect that the price impacts of the sulfur component of the Tier 2 regulation to be common across the U.S. gasoline market, and would be picked up in our year fixed effects in our models. We also note that California CARB gas has been in place for the duration of our sample, hence differences in gas prices include other mobile source regulations and any exercised market power specific to California.

5. Results

5.1 Ambient Pollution Concentrations

The empirical estimates of the impact of various boutique fuel regulations on ambient ozone concentrations are presented in Table 4, for the 1992-2003 panel, and Table 5, for the 2004-2020 panel. We summarize the results of each table, and then compare them for key fuel regulations to illustrate the impacts of overlapping fuel and vehicle standards, such as the Tier 2 standards that came online in 2004.

Column (1) of Table 4 presents the results for the model with the fuel regulation indicators and monitor site fixed effects. Each successive column includes additional controls to account for unobservable confounders, such as Census region by year fixed effects (column 2), Census region by day of week and day of year fixed effects (column 3), precipitation and temperature controls (column 4), income (column 5), and linear and quadratic time trends by region and regulation in columns 6 and 7, respectively. All models show statistically significant and environmentally meaningful reductions in ambient ozone concentrations, measured by the daily maximum 8-hour average, under Federal RFG and California RFG. The Federal standard reduced ozone concentrations 3 to 5 percent, while the California standard reduced ozone concentrations 8 to 15 percent. Our preferred specification, with the greatest set of controls and quadratic regulation- and region-specific time trends, indicates a 5 percent reduction in ozone concentrations under Federal RFG and a 10 percent reduction under California RFG.

These results are generally consistent with, but modestly higher than the results in Auffhammer and Kellogg (2011). For example, column (4) in our analysis replicates the model in column (7) of Table 2 in Auffhammer and Kellogg (2011), and our column (7) replicates column (9) in their paper. In the first comparison, we find a 2.7 percent reduction in ozone under Federal RFG, while they find a 2.8 percent reduction. In the latter comparison, we find a 4.6 percent reduction in ozone, while they find a 2.2 percent reduction (and weakly statistically significant) under Federal RFG. For California RFG, we find a 14.5 percent reduction in ozone as they find a 8.6 percent reduction in ozone in the former comparison, and 9.7 percent versus 6.3 percent in the latter comparison. Over 1992-2003, we estimate small (generally less than one-half of one percent) and statistically insignificant impacts of boutique fuels on ambient ozone concentrations. We find some mixed evidence that RVP regulations reduce ozone concentrations, perhaps on the 2 to 4 percent range, which is larger than the statistically insignificant impacts estimated in Auffhammer and Kellogg (2011).

Table 5 presents the same empirical specifications across the seven columns for the 2004 to 2020 panel. This distinct window of time is intended extend the original Auffhammer and Kellogg (2011) analysis (which ran through 2003) and to illustrate potential changes in the impacts of boutique fuel regulations, especially in the presence of emerging, overlapping fuels and vehicle regulations as illustrated in Figures 1 and 2. We find that Federal RFG has mixed impacts, with some models indicating that ambient ozone concentrations are higher in the presence of RFG, although our preferred model with quadratic time trends yields a small (less than one-half of one percent) and statistically insignificant reduction in ozone under RFG. The models in columns (1) through (6) show large, statistically significant reductions in ozone under California RFG, ranging from 13 to 31 percent, although our preferred model, in column (7), results in a small, statistically insignificant impact. In contrast, we find RVP rules reduce ozone concentrations 3 to 4 percent across most models. There is weak evidence that boutique fuels may reduce concentrations as much as 3 percent, although most models result in smaller, statistically insignificant impacts.

In comparing the impacts of the fuel regulations across the two time periods, three results stand out: (1) the diminishing returns to Federal RFG; (2) the continuing air quality benefits of California RFG; and (3) the improvement in air quality from Federal RVP. The first result on Federal RFG may reflect the dramatic improvement in tailpipe emission controls in new vehicles, starting in 2004, as well as the improved pollution control in existing vehicles expected with low-sulfur gasoline. The second result could reflect the efforts of the California Air Resources Board to tailor the fuel requirements under California RFG to target the most environmentally-important volatile organic compounds (Auffhammer and Kellogg 2011). Given the nature of ozone formation in California, the California RFG blend may thus continue to deliver ozone pollution benefits. We should acknowledge, however, that these results could be confounded by California-specific tailpipe standards that evolved over this time period. While most models for California RFG yield negative and statistically significant negative impacts on ozone concentrations over 2004 to 2020, our preferred specification with quadratic trends resulted in a statistically insignificant (and positive) impact. The final result on RVP could reflect the fact that RVP targets VOC reductions, while the tailpipe standards primarily focused on NO_X emission reductions. So these could complement the Tier 2 and subsequent rules. Having said that, it's important to recognize that Federal RFG also includes volatility requirements, so it is a bit puzzling how RVP rules could result in lower ozone concentrations but RFG would not.

5.2 Emissions

The empirical estimates of the impact of various boutique fuel regulations on VOC and NO_X county-level emissions from on-road gasoline combustion are presented in Tables 6 and 7, respectively, for the 1990-2002 panel. The first column in each table presents a model with fuel regulation indicators, year, and state fixed effects. As evident in the implausibly large, positive coefficient estimates for column (1) in each table, doing so fails to account for the differences in the population size and economic activity of counties. Column (2) in each table includes annual population and total labor income measures by county. When accounting for population and income, we estimate that boutique fuel regulations reduce on-road gasoline VOC emissions by nearly 20 percent, while Federal RVP and Rederal RFG each reduce VOCs by 6 and 18 percent, respectively (column 2). Employing county fixed effects in lieu of population and income (each of which vary annually by county), results in an 18 percent reduction from boutique fuels and a 12 percent reduction from Federal RFG, but a small, insignificant impact from RVP rules (column 3). Including county fixed effects and population and income results in a 23 percent reduction from boutique fuels, 15 percent reduction from Federal RFG, and a 6 percent reduction from RVP in terms of on-road gasoline VOC emissions.

In Table 7, similar results hold for boutique fuels and Federal RFG. Across the specifications in columns 2 through 4, boutique fuels reduce NO_X emissions from on-road gasoline by 11 to 17 percent and Federal RFG reduces NO_X emissions 6 to 11 percent. RVP rules do not appear to reduce NO_X emissions, and, in one specification (column 3), emissions NO_X from on-road gasoline combustion would appear to increase under RVP rules. RVP rules are not designed to target NO_X, since volatility is associated with VOCs, and thus a null effect would be expected.

Estimated models for that include the post-2003 period yield implausibly large estimated reductions of NO_X emissions from on-road gasoline, on the order of 40 percent for Federal RFG and 10 percent for RVP. We believe this may reflect the impact of numerous states with RFG markets adopting California tailpipe emission standards. It could also reflect potential biases in the transportation model that generates estimated emissions of VOCs and NO_X from gasoline-powered light-duty vehicles.

5.3 Prices

Table 8 presents the results for our gasoline price models. The first three columns use daily data from all months of the year, and columns 4 through 6 use daily data from the summer months of June, July, and August - the so-called ozone season, when many boutique fuel rules are in effect.

Since our price data do not pre-date the start of the California RFG program, we cannot estimate impacts with models that include state fixed effects. In order to focus on the price impacts of the second phase of RFG, we estimate our models with data starting in 2000, the first year of more stringent RFG requirements. Our models vary by their inclusion of polynomial time trends, some of which are interacted by PADD (Petroleum Area Defense District).

We find statistically insignificant impacts of boutique fuels and RVP on gasoline prices. Federal RFG appears to increase gasoline prices by 6 to 9 cents per gallon, although the estimates are weakly statistically significant. California RFG commands a much higher price, ranging from 24 to 26 cents per gallon across our specifications, each of which is statistically significant. The absence of a price impact under RVP differs from what Brown et al. (2008) find in their analysis of the late 1990s. They estimate that RVP increased 1.5 to 2.5 cents per gallon.[5] They also show that the first phase of RFG increased gasoline prices by about 4.5 cents per gallon, about half of what we estimate in the summer months under the second phase of RFG. The large estimated impacts of California RFG on gasoline prices from our regression cannot fully be attributed to reformulated gas, as the regulation is on during the entirety of our price sample. Hence, effects from other gasoline regulations and market power different from control states could contribute to the estimated difference.

6. Policy Implications and Conclusions

The Clean Air Act has authorized an array of fuel regulations to reduce the precursors to ambient ozone pollution, among other pollutants. With the emergence of stringent fuel regulations for the most pollution-intensive cities, and the opportunity for states to adopt fuel content regulations either to demonstrate continued compliance with or progress toward attaining national ambient air quality standards, the U.S. gasoline market has evolved over the past three decades to address local pollution. We have evaluated the pollutant concentration, emissions, and price impacts of Federal

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[5] Brown et al. (2008) do not report the base year dollars for their analyses. For comparison purposes, we have assumed that their data are in 1996 dollars, representing the mid-year of their panel, and deflated their results to 2019 dollars using the GDP implicit price deflator.

RFG, RVP, California RFG, and other boutique fuel rules. To summarize our results, we will place them in the context of the ex ante estimated impacts from the regulatory impact analyses associated with several of these rules. Then we close with comments about future research.

For Federal RFG, we estimate a 3 to 5 percent reduction in ambient ozone concentrations before 2004, but null effects after 2003. For California RFG, we estimate larger impacts ranging from 8 to 15 percent reductions in ozone concentrations. The EPA regulatory impact analysis for the RFG rule does not estimate this impact. In contrast, the ex ante analysis and final rule included estimated changes in emissions of VOCs and NO_X under the second phase of RFG of 27 and 22 percent, respectively. We find smaller impacts on emissions before 2003: 15 percent reduction in VOCs and 9 percent reduction in NO_X. When promulgating this rule, EPA estimated that fuel prices would increase 8 cents per gallon (in 2019 dollars) under the second phase of the program. In contrast, the Council (1993) estimated fuel price increases under RFG would range between 21 and 25 cents per gallon over 2000-2010 (again, we have adjusted the 1993 estimates to 2019 dollars and the price difference cannot be fully attributed causally to CARB alone). We find Federal RFG to yield price impacts of about 9 cents per gallon, similar to the EPA ex ante estimates. However, the California RFG price impacts of about 25 cents per gallon are consistent with the Council (1993) estimates. For RVP rules, we find modest improvements of ozone concentrations of 2 to 4 percent. The EPA regulatory impact analyses for RVP rules do not provide a prospective estimate of ozone concentrations. EPA estimated a 7 percent reduction in VOCs, and we find over 1990-2002 a 6 percent reduction in VOCs. EPA did not estimate changes to NO_X emissions, and we do not find statistically significant changes in NO_X emissions. EPA estimated about a 2 cent per gallon increase in gasoline prices, but we find small and statistically insignificant impacts. Other boutique fuel rules adopted by individual states, including California RFG, do not have EPA regulatory impact analyses associated with them. In general, we do not find statistically significant impacts of boutique fuels on ozone concentrations or prices, although there is some evidence of lower emissions of ozone precursors under these rules.

A key challenge we explore in our evaluation focuses on distinguishing and identifying the impacts of a local boutique fuel regulation in the presence of other, overlapping regulations. The post-2003 period is characterized by more stringent vehicle standards, under both Federal and California authorities, and nationwide sulfur fuel regulations that can improve the performance of tailpipe controls on new and existing vehicles. Given the correlation among more stringent boutique fuel standards, in California and major cities across the country, and states adopting California vehicle standards, the estimated impacts we find post-2003 could be confounded by these other regulations.

Future research could explore new sources of identifying variation for quasi-experimental estimation of the impacts of these fuel rules. Alternatively, structural models, along the lines of Sweeney (2014), could be expanded to estimate the emissions and concentration impacts of fuel regulations. In addition, emerging big data sets on vehicle usage and vehicle-specific pollution could enable more credible estimation of the incremental impacts of fuel content regulations. More generally, the development of methods to estimate empirical impacts of individual regulations in overlapping regulatory and policy environments could better inform policymakers and the public on the incremental impacts, including social benefits and costs, of a given regulation or policy (Aldy et al. 2022).

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Table 1: States Adopting California Tailpipe Emission Exhaust Standards

State	Model Year
New York	1993
Massachusetts	1995
Vermont	2000
Maine	2001
Pennsylvania	2001
Connecticut	2008
Rhode Island	2009
Washington	2009
Oregon	2009
New Jersey	2009
Maryland	2011
Delaware	2014

Notes: This table displays the first model year for which various states required new vehicles sold in their states to meet the California tailpipe emission exhaust standards.

Table 2: Ex Ante Estimated Impacts of Fuels and Fuel-Vehicle Rules

Rule	Cost (cents/gal)	Δ VOCs	Δ NO_X	Δ [O3]
RVP-1	0.5	-3%	*	*
RVP-2	1.1	-7%	*	*
RFG-1	3.9	-17%	-2%	*
RFG-2	5.1	-27%	-22%	*
Tier 2	1.7	-10%	-26%	-2 ppb
MSAT	0.3	-34%	*	*
Tier 3	0.6	-3%	-10%	-0.5 ppb

Notes: Estimates from final regulatory text published in Federal Register notices or EPA regulatory impact analyses for each rule. Costs reported in nominal terms. * denotes rule/RIA does not estimate this impact.

Sources: RVP-1 (54 FR 11880): "EPA projects the refinery cost of the Phase I program to be \$247 million dollars per year, which can be expressed as 0.54 cents per gallon of controlled gasoline during the summer control periods. Offsetting this cost will be savings for consumers of about \$104 million per year, or'0.23 cents per gallon resulting from increased fuel economy as gasoline's energy density increases and as less fuel is lost through evaporation."; "Based on the DRIA analysis, we project that this Phase I RVP control program will reduce VOC emissions nationally by 0.674 million tons per year (on an annual basis), or 3 percent of total VOC emissions from all sources." RVP-2 (55 FR 23663 for costs, 55 FR 23661-2 for emissions): "The resulting nationwide non-Northeast cost to refiners of the Phase II RVP regulations in 1995 will be about \$464 million per year, or approximately 1.1 cents per gallon of gasoline. However, as discussed earlier, these Phase II costs will be offset by savings to the consumer of around \$127 million per year for increased fuel economy and \$107 million per year for evaporative emissions recovered through reduced volatility fuel, with a resulting net cost to society of \$230 million per year."; "Phase II volatility controls will result in a total non-Northeast VOC reduction of about 1,315,000 tons per year or 710,000 tons per year in ozone nonattainment areas (these values are presented on an annual equivalent basis for comparison with year round control programs). These reductions represent about 14.4 percent of 1987 non-Northeast nonattainment area mobile source VOC emissions and about 0.7 percent of 1987 non-Northeast nonattainment area VOC emissions from all sources." Note per mile impacts: "On a per-vehicle basis, total light-duty vehicle hydrocarbon emissions in 1995 should decrease by approximately 0.77 grams per mile to about 1.98 grams per mile." RFG-1: Costs are the U.S. average Phase I RFG costs from Table V-4, p. 295 of the RIA; VOC reductions reflect the Basic I/M scenario in Table V-8, p. 298 of RIA; RFG-2: cost estimate is p. 7810 of the rule; emission reductions are from EPA RFG Brochure. Tier 2: NO_X emission reductions for 2007, Updated Tier 2 Model in Table III.A-3, p. III-11 of Tier 2 RIA; VOC emission reductions for 2007, Updated Tier 2 Model in Table III.A.-7, p. III-22 of Tier 2 RIA; for ozone concentration "The reduction in daily maximum ozone is nearly 2 ppb, on average in 2007 and over 5 ppb, on average in 2030" (p. III-46, RIA). Costs are for the US average per gallon cost for desulfurizing gasoline to 30 ppm in 2007 (Table V-36, p. V-61, RIA). MSAT: VOC emission reductions for 2030 from Table 3, ES-4, RIA; the costs are for the benzene standard from p. ES-5, RIA. Tier 3: NO_X and VOC emission reductions for 2018 from Table ES-7, p. ES-7, RIA). The cost reflects the cost per gallon at refiners, based on the median refinery cost (Figure 5-1, p. 5-63, RIA); for ozone concentrations, see 2018 value for all population in Table 7-42, p. 7-83, RIA.

Table 3: Sample of Cities with Gasoline Price Data, 1998-2012

Atlanta
Austin
Baltimore
Birmingham
Boston
Buffalo
Charlotte
Chicago
Cincinnati
Cleveland
Columbus
Dallas
Denver
Detroit
Hartford
Houston
Indianapolis
Jacksonville
Kansas City
Las Vegas
Los Angeles
Louisville
Memphis
miami
Milwaukee
Minneapolis
Nashville
New Orleans
New York
Oklahoma City
Orlando
Philadelphia
Phoenix
Pittsburgh
Portland
Providence
Raleigh
Richmond
Riverside
Sacramento
Saint Louis
Salt Lake City
San Antonio
San Diego
San Francisco
San Jose
Seattle
Tampa
Virginia Beach
Washington DC

Notes: This table displays the cities for which we have daily, city-average gasoline prices from the Oil Price Information Service.

Table 4: Ambient Ozone Concentrations, 1992-2003

Regulation	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Boutique	-0.036*	-0.004	-0.004	0.001	0.001	-0.019	-0.005
	(0.019)	(0.012)	(0.012)	(0.011)	(0.012)	(0.014)	(0.016)
LE Diesel	-0.087***	0.047	0.047	0.063**	0.061**	0.069*	0.068**
	(0.029)	(0.030)	(0.030)	(0.027)	(0.028)	(0.036)	(0.034)
Federal RVP	-0.005	-0.024**	-0.024**	-0.029***	-0.029***	-0.039***	-0.020
	(0.014)	(0.012)	(0.012)	(0.010)	(0.010)	(0.011)	(0.012)
Federal RFG	-0.034***	-0.028***	-0.028***	-0.027***	-0.027***	-0.052***	-0.046***
	(0.013)	(0.011)	(0.011)	(0.009)	(0.009)	(0.011)	(0.013)
California RFG	-0.083***	-0.148***	-0.148***	-0.145***	-0.146***	-0.099***	-0.097***
	(0.018)	(0.015)	(0.015)	(0.014)	(0.015)	(0.018)	(0.025)
Observations	784,599	784,599	784,599	784,599	784,599	784,599	784,599
R-squared	0.004	0.066	0.071	0.218	0.218	0.220	0.223
Site FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region/Year	No	Yes	Yes	Yes	Yes	Yes	Yes
Region/DOW	No	No	Yes	Yes	Yes	Yes	Yes
Region/DOY	No	No	Yes	Yes	Yes	Yes	Yes
Weather	No	No	No	Yes	Yes	Yes	Yes
Income	No	No	No	No	Yes	Yes	Yes
Linear Trends	No	No	No	No	No	Yes	Yes
Quad. Trends	No	No	No	No	No	No	Yes

Notes: Regressor in all models: $ln(8hour[O_3])$. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Linear and quadrantic trends are region and regulation-specific. Regression results clustered at the state-year level.

Table 5: Ambient Ozone Concentrations, 2004-2020

Regulation	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Boutique	-0.067**	-0.015	-0.014	-0.011	-0.009	-0.009	-0.029*
	(0.027)	(0.015)	(0.015)	(0.013)	(0.012)	(0.013)	(0.017)
LE Diesel	-0.110	0.058	0.057	0.069	0.036	-0.025	0.332***
	(0.068)	(0.067)	(0.067)	(0.047)	(0.046)	(0.078)	(0.101)
Federal RVP	-0.023	-0.036***	-0.036***	-0.036***	-0.032***	-0.033***	-0.038***
	(0.025)	(0.013)	(0.013)	(0.011)	(0.011)	(0.012)	(0.013)
Federal RFG	-0.132***	0.041***	0.042***	0.040***	0.030**	0.011	-0.004
	(0.024)	(0.015)	(0.015)	(0.014)	(0.012)	(0.014)	(0.016)
California RFG	-0.220***	-0.287***	-0.287***	-0.289***	-0.310***	-0.127***	0.070
	(0.055)	(0.032)	(0.032)	(0.030)	(0.030)	(0.042)	(0.089)
Observations	1,182,250	1,182,250	1,182,250	1,182,250	1,182,250	1,182,250	1,182,250
R-squared	0.005	0.088	0.098	0.231	0.231	0.233	0.234
Site FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region/Year	No	Yes	Yes	Yes	Yes	Yes	Yes
Region/DOW	No	No	Yes	Yes	Yes	Yes	Yes
Region/DOY	No	No	Yes	Yes	Yes	Yes	Yes
Weather	No	No	No	Yes	Yes	Yes	Yes
Income	No	No	No	No	Yes	Yes	Yes
Linear Trends	No	No	No	No	No	Yes	Yes
Quad. Trends	No	No	No	No	No	No	Yes

Notes: Regressor in all models: $ln(8hour[O_3])$. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Linear and quadrantic trends are region and regulation-specific. Regression results clustered at the state-year level.

Table 6: On-Road Gasoline VOC Emissions, 1990-2002

Regulation	(1)	(2)	(3)	(4)
Boutique	1.171***	-0.196***	-0.177***	-0.231***
	(0.134)	(0.037)	(0.021)	(0.022)
Federal RVP	1.493***	-0.063***	0.010	-0.062***
	(0.105)	(0.023)	(0.021)	(0.018)
Federal RFG	1.293***	-0.176***	-0.123***	-0.151***
	(0.117)	(0.027)	(0.019)	(0.017)
Observations	12,564	12,549	12,563	12,548
R-squared	0.358	0.931	0.978	0.979
Year FE	Yes	Yes	Yes	Yes
State FE	Yes	Yes	No	No
County FE	No	No	Yes	Yes
PopIncome	No	Yes	No	Yes

Notes: Regressand in all models: $ln(VOCEmissions)$. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Regression results clustered at the county level.

Table 7: On-Road Gasoline NO_X Emissions, 1990-2002

Regulation	(1)	(2)	(3)	(4)
Boutique	1.221***	-0.119***	-0.114***	-0.169***
	(0.132)	(0.036)	(0.021)	(0.022)
Federal RVP	1.509***	-0.011	0.047**	-0.027
	(0.104)	(0.024)	(0.022)	(0.018)
Federal RFG	1.332***	-0.107***	-0.057***	-0.085***
	(0.117)	(0.029)	(0.018)	(0.016)
Observations	12,564	12,549	12,563	12,548
R-squared	0.357	0.919	0.977	0.979
Year FE	Yes	Yes	Yes	Yes
State FE	Yes	Yes	No	No
County FE	No	No	Yes	Yes
PopIncome	No	Yes	No	Yes

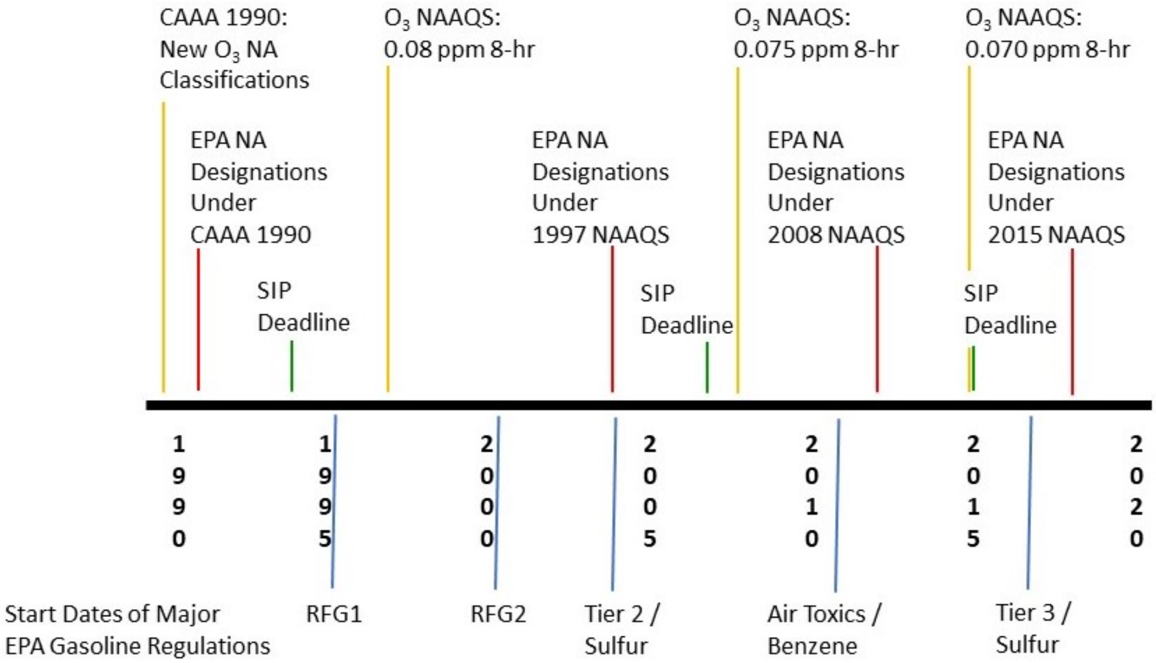
Notes: Regressand in all models: $ln(VOCEmissions)$. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Regression results clustered at the county level.

Table 8: Gasoline Price Impacts, 2000-2012

Regulation	(1)	(2)	(3)	(4)	(5)	(6)
Boutique	0.049	0.049	0.049	0.090	0.090	0.091
	(0.059)	(0.060)	(0.060)	(0.068)	(0.068)	(0.068)
Federal RVP	-0.015	-0.015	-0.014	-0.002	-0.001	-0.002
	(0.029)	(0.029)	(0.028)	(0.033)	(0.033)	(0.033)
Federal RFG	0.064*	0.064*	0.059*	0.091*	0.091*	0.083*
	(0.034)	(0.034)	(0.034)	(0.046)	(0.046)	(0.047)
California RFG	0.258***	0.258***	0.258***	0.247***	0.246***	0.245***
	(0.043)	(0.043)	(0.043)	(0.042)	(0.042)	(0.041)
Observations	232,457	232,457	232,457	58,345	58,345	58,345
R-squared	0.842	0.848	0.847	0.954	0.959	0.957
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Month FE	Yes	Yes	Yes	Yes	Yes	Yes
DOW FE	Yes	Yes	Yes	Yes	Yes	Yes
PADD FE	Yes	Yes	Yes	Yes	Yes	Yes
Time Polynomial	No	Yes	No	No	Yes	No
PADD-Time Polynomial	No	No	Yes	No	No	Yes
Season	Annual	Annual	Annual	Summer	Summer	Summer

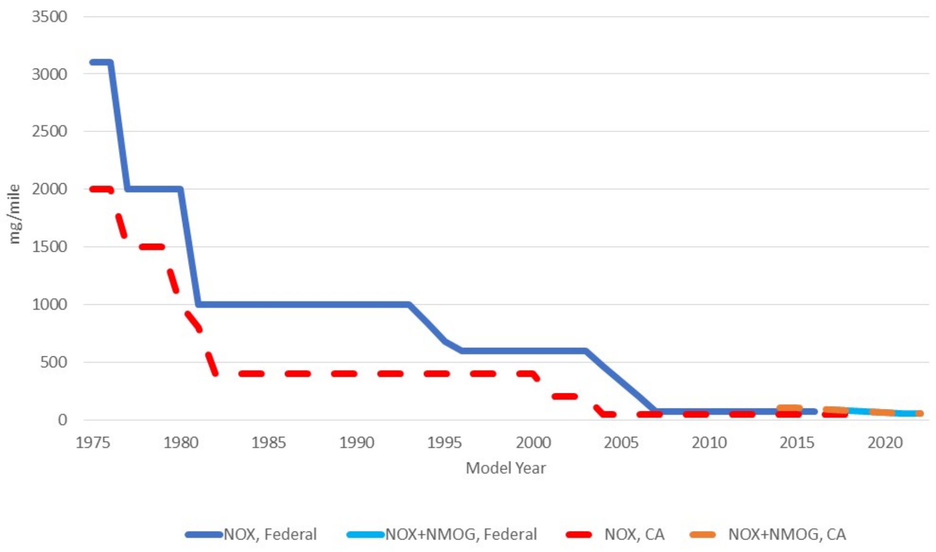
Notes: Regressand in all models: Gasoline price per gallon in 2019 dollars. Summer season refers to a panel of observations for June, July, and August. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Regression results clustered at the city level.

Figure 1: NAAQS, Nonattainment Designations, SIP Deadlines, and Major EPA Rules, 1990-2020



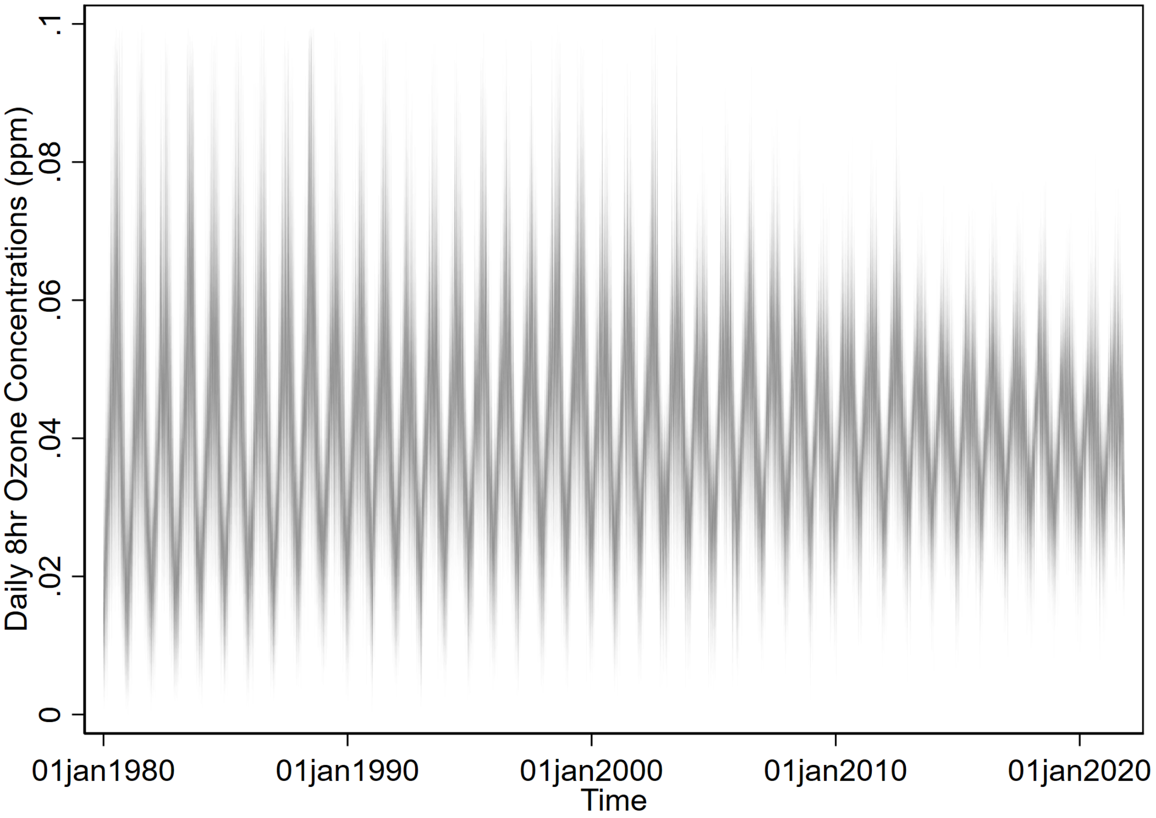
Notes: This figure displays the dates for the promulgation of the final rules revising the ozone NAAQS, the dates for EPA designation of nonattainment areas through a final rulemaking, the effective deadline for SIPs under the Clean Air Act given the dates of nonattainment status, and the dates various fuel and light-duty vehicle regulations enter into force.

Figure 2: LIGHT-DUTY VEHICLE EMISSION STANDARDS, 1975-2020



Notes: This figure displays the maximum permissible emissions, in milligrams per mile, for new light-duty vehicles for NO_X and non-methane organic gas (as a measure of volatile organic compounds) under Federal and California regulations.

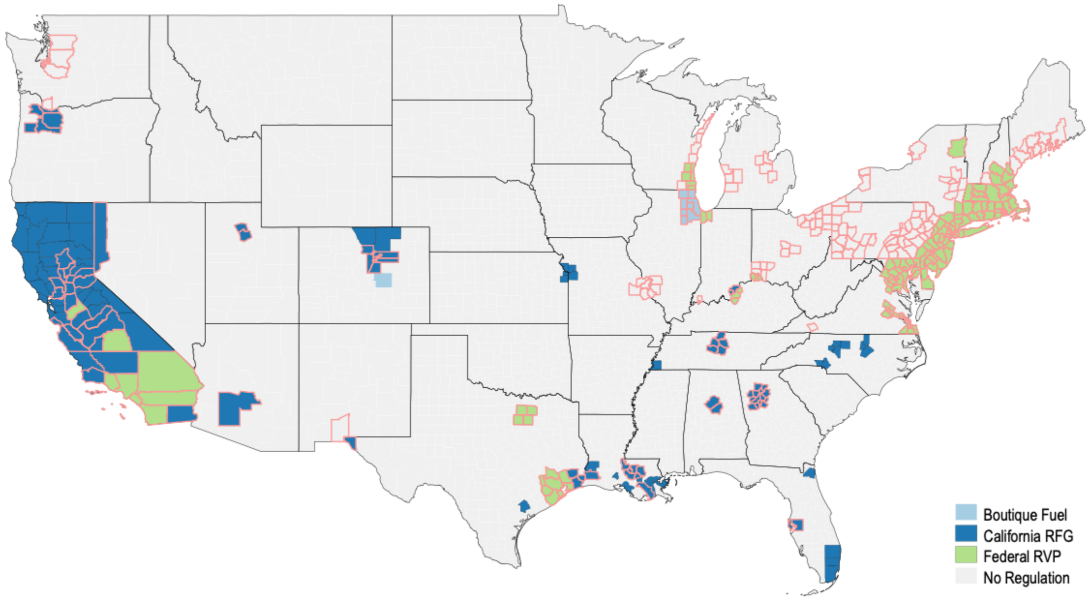
Figure 3: Distribution of Daily Ozone Concentrations 1980 - 2021



Notes: This figure displays the empirical distribution of the daily maximum 8-hour Ozone concentration monitored since January 1, 1980. The lightest grey shading indicates the range of the 5^{th} to 95^{th} percentile. Each darker shading represents a 5% increase in the percentile. It is important that these are not population weighted.

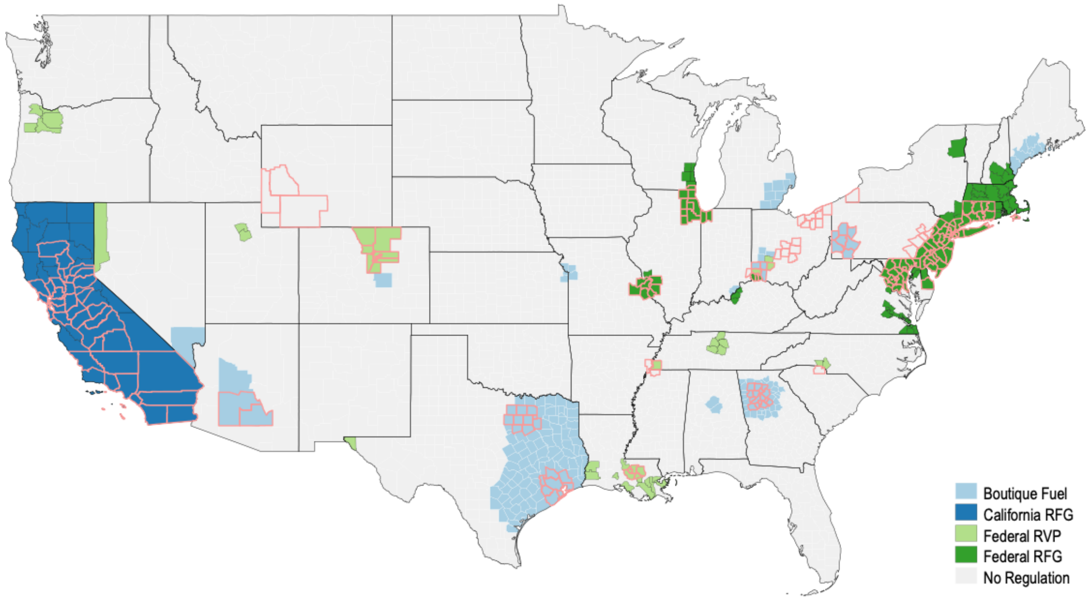
Figure 4: Gasoline Regulations and Non-Attainment Status

Gasoline Content Regulation(s), 1995



Data source: Environmental Protection Agency, Federal Register, California Air Resources Board

Gasoline Content Regulation(s), 2015



Data source: Environmental Protection Agency, Federal Register, California Air Resources Board

Notes: This figure displays county level fuel regulations for two randomly chosen years (1995 and 2015). The color shades indicate the type of fuel regulation active in a given year as indicated by the legend. The magenta borders indicate counties in non-attainment with NAAQS.