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DISCUSSION PAPER SERIES

IZA DP No. 13428

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ISSN: 2365-9793

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ABSTRACT

Timing Matters: Shifting Economic Activity and Intra-Day Variation in Ambient Ozone Concentrations*

Ground-level ozone has been shown to have significant health consequences from short-term exposure, and as such has been regulated in the U.S. since the 1970s by the Environmental Protection Agency (EPA). Ozone is not emitted directly; instead formation occurs due to a complex, Leontief-like combination of air pollutants and sunlight that results in high levels mid-day and low levels at night. Despite this known relationship, EPA regulations only consider the total emissions of ozone precursors and not when these emissions occur. Using hourly data on ambient ozone from 1980-2017 near the U.S. time zone borders, we provide evidence that the 1-hour time difference on either side of a border leads to a nontrivial change in ozone levels over the course of the day. We then examine a cap-and-trade program targeting ozone precursor emissions – the NOx Budget Program – finding that while it reduced ozone overall it did not have an economically significant effect on shifting when these emissions occurred. We conclude by outlining a possible policy solution to account for the time value of reductions in precursor emissions.

JEL Classification: Q53, Q58

Keywords: ambient ozone concentration, timing of ozone precursor emissions, time zone border, shifting economic activity, NOx Budget Program (NBP)

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* We would like to thank the invaluable comments and suggestions by Akshaya Jha, Karen Clay, Lowell Taylor, Brian Kovak, and Andrea La Nauze, seminar participants at Carnegie Mellon University, and conference participants at the 89th Annual Meeting of the Southern Economic Association, and the AERE 2020 Summer Conference.

1. Introduction

Recent research has explored the importance of considering the spatial dimension, or *where* emissions of local air pollutants occur, in evaluating policy. The literature has focused on critical topics including firm relocation decisions (e.g., Henderson, 1996; Becker and Henderson, 2000; Gibson, 2019), emissions leakage (e.g., Baylis, Fullerton and Karney, 2013, 2014), and marginal damages that vary by location (e.g., Holland et al., 2016, 2019; Callaway, Fowlie and McCormick, 2018; Fowlie and Muller, 2019). Relatively little attention has been paid to *when* during the day emissions occur. In the U.S., standards regulating emissions are usually based on temporally uniform thresholds.

Tropospheric or ground-level ozone is not emitted directly, but instead forms through a Leontief-like complex combination of nitrous oxides (NO_x), volatile organic compounds (VOCs), sunlight, and temperature. Due to the role of sunlight, ozone forms over the course of the day and peaks in the early afternoon before largely dissipating overnight. Short-term exposure to ambient ozone has been shown to decrease lung function (Lippman, 2009; U.S. EPA, 2015) and labor productivity (Graff Zivin and Neidell, 2012), and to increase hospital admissions (Neidell, 2009; Moretti and Neidell, 2011) and mortality (Deschenes, Greenstone and Shapiro, 2017). Thus, unlike other pollutants, ambient ozone may impose differential externalities over the course of the day.

Unlike the National Ambient Air Quality Standards (NAAQS) for ambient ozone, which at least in its first iteration focused on the highest hourly ozone monitor readings, other regulations targeting ozone reductions have predominately aimed at reducing emissions of its precursors. A prominent recent example was the NO_x Budget Program, a regional cap-and-trade program that covered parts of the East and Midwest United States from 2003-2008. The program targeted states facing problems with ambient ozone and created a permit market for NOx emissions during the ozone season, defined as May 1st – September 30th. Each permit was for a single ton of NO_x emissions at any point during the ozone season. The program has been evaluated positively in recent work, having been shown to be successful at reducing daily mean ozone levels and summer mortality (Deschenes, Greenstone, and Shapiro, 2017).

However, the program did not distinguish between when in the ozone season emissions occurred, nor did it consider the time of day. Since high levels of ozone are concentrated in a few peak hours during the late morning/early afternoon, it is possible that the social costs from these few hours exceed the benefits to firms from continuing their normal operations. If the externality generated from elevated ambient ozone concentrations in these peak hours were sufficiently large, it could justify regulation that was targeted at reducing precursor emissions in these peak hours. Hence, our main research question: is there a role for intra-day varying corrective policies to reduce peak ambient ozone concentrations?

In order to evaluate the effectiveness of an intra-day corrective policy, we first need to know whether it is feasible to reduce ozone levels by shifting economic activity within a day. To answer this, we will take advantage of an existing discontinuity – U.S. time zone borders. On either side of a time zone border ambient conditions are nearly identical, yet the times when people are going to work and businesses are operating are one hour apart. In other words, we argue that the lone difference is that the conventional start time for school or work is one hour later on the western side of the border compared to the east. For the same local hour, we analyze the hourly profile of ozone on either side of a time zone border from 1980-2017 to see how this one hour shift in activity affects measured hourly ozone concentrations through differences in solar intensity. Our findings indicate that ozone levels on the western side of the time zone border are higher for the morning hours (5:00–9:00am local time) relative to the eastern side. This is particularly the case for the counties in compliance with the NAAQS for ambient ozone, where the constraints on emissions of ozone precursors might not be binding.

Having shown that shifting economic activity is both feasible and able to affect hourly ambient ozone concentrations, we then examine whether recent U.S. policies have leveraged this effect to reduce peak ambient ozone. As discussed above, the NO_x Budget Program was a cap-and-trade program targeting ozone reductions that was in effect during the ozone season (May – September) from 2003–2008. However, it did not distinguish between intra- or inter-day emissions in that period. We indirectly examine how firms may have complied with the regulation – did they shift their production activity away from periods of high ozone formation? We estimate a triple-differences model controlling for contemporaneous temperature to analyze hourly ozone concentrations for states that did and did not participate in the Program. Because the pattern of ozone precursor emissions might change over the ozone season, we focus our analysis on a sample of hourly data from across the U.S. for 1980-2008, for the month before (April) and the month after (May) the Program took effect. Our results indicate that while the

Program reduced ozone during the ozone season overall, it did not cause firms to shift their production over the course of the day.[1] Therefore, the Program may have caused firms to cut precursor emissions in hours with low ambient ozone (e.g., evening hours) and thus minimal external cost, while leaving the potential for additional reductions to peak ozone hours with high external cost. The pattern is even more pronounced in counties complying with the NAAQS for ambient ozone, likely due to the lack of incentives to use the emissions trading market to help reduce ozone concentrations during peak hours.

Finally, we consider how to incentivize firms to shift production away from these hours with the highest social cost. Henderson (1996) first examined the possibilities of shifting production across counties to comply with ozone regulation, and suggested that areas out of attainment of the EPA standard could comply with air quality regulation by reducing their precursor emissions in late morning hours. We introduce a simple conceptual framework building on Fowlie and Muller (2019) to illustrate how allowing for intra-day variation could improve policy. We consider how policymakers could modify a standard cap-and-trade program to incentivize firms to reduce ozone precursor emissions around peak ozone hours.

This study makes two main contributions to the literature and policymaking. *First*, it provides clear evidence that the timing of economic activity matters for the concentration of local air pollutants. Previous studies have considered only the spatial dimension (Henderson, 1996; Baylis, Fullerton and Karney, 2013; Holland et al., 2016, 2019; Callaway, Fowlie and McCormick, 2018; Fowlie and Muller, 2019; Gibson, 2019). The estimated time-specific impacts on ambient ozone might have implications for key economic outcomes. Indeed, short-term exposure to ambient ozone has been shown to affect health and productivity outcomes (Neidell, 2009; Moretti and Neidell, 2011; Graff Zivin and Neidell, 2012; Deschenes, Greenstone and Shapiro, 2017).

Second, it highlights that prominent programs to reduce ozone concentrations by targeting emissions of ozone precursors, such as the NBP, might not be effective in reducing peak ozone levels. This is likely due to the lack of properly aligned incentives, analogous to the context of energy efficiency. Boomhower and Davis (2020) introduce the concept of a "timing premium" when examining the energy efficiency benefits of a residential air-conditioning rebate program

[1] In the Appendix we perform a robustness check where we restrict the sample to the last effective month of the Program (September) and the 1st month after (October); the results are qualitatively similar.

and show how much timing matters. In their setting, reductions in energy consumption during peak afternoon hours are more valuable than an identical reduction overnight because of the type of power plants needed to provide electricity at peak times (e.g., less efficient coal and natural gas plants). The policy recommendation arising from our conceptual framework discussed above follows the same logic: achieving reductions in peak ozone hours in the afternoon may be more beneficial than comparable reductions in other hours of the day.

The paper also adds to the literature on the economic impacts of daylight savings time (DST). Several recent studies have found significant negative health and productivity effects from DST (e.g., Smith, 2016; Gibson and Shrader, 2018; Giuntella and Mazzonna, 2019). Other studies have shown a null impact of DST or a surprising increase in electricity consumption (Kellogg and Wolff, 2008; Kotchen and Grant, 2011). Our analysis reveals changes in ambient ozone concentrations due to shifting economic activity through the natural effect of time zones.

The paper proceeds as follows. Section 2 provides general background on the formation of ozone and the NO_x Budget Program. Section 3 presents results from our analysis of ozone levels by hour across U.S. time zone borders, while Section 4 does the same for our analysis of the NO_x Budget Program. Section 5 outlines a conceptual framework for an alternative policy that could make use of the hourly profile of ozone. Finally, Section 6 concludes.

2. Background

2.1. Ozone Formation and Regulation

There are two forms of ozone: stratospheric ozone and tropospheric (ground-level) ozone. Stratospheric ozone occurs naturally in the atmosphere and is considered beneficial; it is not the focus of this paper.[2] In contrast, ground-level ozone does not occur naturally nor is it emitted into the atmosphere, and is considered harmful to both human health and the environment.[3] Ground-level ozone forms through a combination of two other pollutants: oxides of nitrogen (NO_x) and volatile organic compounds (VOCs). The ozone formation process is a complex, non-linear combination of NO_x, VOCs, sunlight, and temperature. Due to the role of sunlight and temperature in this relationship, ozone is generally highest in the hot summer months.

[2] When we refer to ozone in this paper we mean ground-level or ambient ozone, unless otherwise noted.
[3] We will focus on the impacts to human health, but the EPA provides a brief overview of the impacts on the environment (https://www.epa.gov/ozone-pollution/ecosystem-effects-ozone-pollution).

To illustrate the unique effect of sunlight and temperature on ozone, we plot the average hourly concentrations of ozone from EPA's AirData database for a representative summer against particulate matter (PM) and ozone's precursors – NO_2 and VOCs – in Figure 1. Hourly ambient ozone concentrations are presented in the solid line at the top, and show demonstrably more variation over the course of the day as compared to $PM_{2.5}$, NO_2, and VOCs. In the first few hours of the day during the middle of the night, ozone levels are at their lowest due to an absence of sunlight and minimal economic activity. As people wake up and leave for school or work (hours ending [HE] 7-10), there is a gradual increase in ozone levels from increased activity and sunlight. Levels continue increasing until they peak in the mid-afternoon at around 50ppb, compared to a trough of about 20ppb in the early morning. We see a steady, steep decline as the sun sets in the evening until the cycle starts again the next day. In contrast, particulate matter levels remain quite flat over the course of the day (Figure 1 Panel A), while concentrations of NO_2 and VOCs both follow a similar downward trend in the later morning/early afternoon hours as these local air pollutants are converted to ozone (Figure 1 Panel B).[4]

These observed peaks in ozone concentrations over the day matter, as short-term exposure of as little as 5 minutes to ambient ozone has been shown to have significant negative health impacts on lung function (Lippman, 2009; US EPA, 2015). Exposure to ozone has been shown to reduce productivity for outdoor laborers (Graff Zivin and Neidell, 2012), and increase hospital admissions (Neidell, 2009; Moretti and Neidell, 2011) and mortality rates (Deschenes, Greenstone and Shapiro, 2017). Given these negative health outcomes, people have also been shown to engage in avoidance behavior (Neidell, 2009; Graff Zivin and Neidell, 2009; Moretti and Neidell, 2011) and insure themselves against the health risks of ozone through other defensive investments such as remediation (Deschenes, Greenstone, and Shapiro, 2017).

Therefore, ozone is regulated by the U.S. Environmental Protection Agency (EPA) as one of six criteria air pollutants through the National Ambient Air Quality Standards (NAAQS). The EPA standard for ozone has evolved over time: in 1979, a county would be designated as in non-attainment if the 2nd highest hourly concentration exceeded 120 parts per billion (ppb). The standard was substantially revised in 1997, when it was redefined as 80 ppb based on the 4th

[4] Ozone formation involves the destruction of NO_2 and VOCs in the presence of sunlight through a series of chemical reactions. In the absence of sunlight, a similar set of reactions to those that had previously produced ozone instead work to destroy ozone.

highest daily maximum ozone level (based on an 8-hour average) over a 3-year period.[5] The standard has subsequently been reduced to the current standard of 70 ppb based on the same 4th highest daily 8-hour average methodology.[6] A number of counties have been (and still are) in non-attainment of the ozone standard; Deschenes, Greenstone, and Shapiro (2017) note that: "…as of 2015, 126 million Americans, or about 40 percent of the population, live in areas that violate this new air quality standard for ozone."

2.2. NO_x Budget Program

Efforts in addition to the NAAQS have thus been undertaken to try and reduce ozone pollution, such as the NO_x Budget Program that targeted ozone precursor emissions. The NO_x Budget Program was a cap and trade program covering parts of the East and Midwest United States, designed to help reduce pollution from ozone. The program period covered May 1st through September 30th, as these months are most harmful for the formation of ozone. After an initial program was put in place from 1999-2002, the program was fully initiated beginning in May 2003.[7]

Allowances under the NO_x Budget Program were for emissions of a single ton of NO_x during the ozone season (May 1 – September 30th). Unused allowances from a given year could be sold or banked for usage in a future year. The program was successful at significantly reducing NO_x emissions during the summer months, and recent research has shown that the program was also successful at reducing mean levels of summer ozone and the mortality rate (Deschenes, Greenstone, and Shapiro; 2017).

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[5] At the time of the change, the EPA claimed that the new standard was equivalent to the prior 1-hour standard: "The 1-expected-exceedance form essentially requires the fourth-highest air quality value in 3 years, based on adjustments for missing data, to be less than or equal to the level of the standard for the standard to be met at an air quality monitoring site" (U.S. EPA, 1997, p.38868). The new standard was not put into effect until 2004 due to lawsuits, with EPA noting that: "[i]n setting the 8-hour NAAQS in 1997, we concluded that replacing the current 1-hour NAAQS with an 8-hour NAAQS is appropriate to provide adequate and more uniform protection of public health from both short-term (1 to 3 hours) and prolonged (6 to 8 hours) exposures to ozone in the ambient air (62 FR 38863)" (U.S. EPA, 2004, p. 23970).

[6] The history of all revisions made to the ozone NAAQS can be found in Table A6 in the Appendix. Revisions to the standards for particulate matter and nitrogen dioxide can be found in Table A7 and Table A8, respectively.

[7] The program was set to begin in 2003 for all participating states, however litigation from a handful of states delayed their implementation until May 31, 2004.

3. Ozone by Hour – Across Time Zone Borders

Time zone borders in the U.S. can trace their history back to the 1880s. The advent of railroads at the time made traveling long distances possible at much faster speeds – trips could be measured in hours as opposed to days or weeks. However, in the early 1880s most towns in the U.S. had their own local time, resulting in over 300 different time zones across the country. Railroad operators and riders became frustrated with the confusing train schedules where departure and arrival times were based on all of these varying time zones. To relieve this coordination problem, the railroad companies themselves adopted four major time zones across the U.S. in November, 1883. The time zones were later solidified in the 1884 International Meridian Conference in Washington, D.C., where the prime meridian was adopted and Greenwich Mean Time was recognized as the official world time. Although they were recognized around the time of the conference, U.S. time zones were not made official until the Standard Time Act was passed in 1918 (Hamermesh, Myers and Pocock, 2008).

While many studies have examined the impacts of air pollution on health (see Section 2.1), to the best of our knowledge no study has ever examined how the *timing* of reductions in ozone over the course of a day might impact health. The closest analogue in another context is recent work by Boomhower and Davis (2020) that examines energy efficiency in electricity markets. The authors introduce the concept of a "timing premium" in the context of an ex-post analysis of the energy efficiency benefits of a residential air-conditioning energy efficiency rebate program in Southern California. In their setting, reductions in energy consumption during peak afternoon hours are more valuable than an identical reduction overnight because of the type of power plants needed to provide electricity at peak times (e.g., less efficient coal and natural gas plants). Our policy suggestion in Section 5 follows this logic, namely that achieving reductions in peak ozone hours in the afternoon may be more beneficial than comparable reductions in other hours of the day.

Our analysis of changes in ozone levels due to shifting economic activity through the natural effect of time zones can be linked to the existing literature on the impacts of daylight savings time (DST). Several recent studies have found significant negative health and productivity effects from DST (Giuntella and Mazzonna, 2019) due to shifting sleep patterns in terms of increased incidents of workplace injuries (Barnes and Wagner, 2009), fatal vehicle accidents (Smith, 2016), heart attacks (Sandhu et al., 2014), and reduced earnings (Gibson and Shrader, 2018). Other studies have examined the impact of DST on energy consumption. Kellogg and Wolff (2008) utilize a quasi-experiment in Australia surrounding preparations for the 2000 Olympics in Sydney, finding a shift in electricity consumption from the evening to the morning with no net change. Kotchen and Grant (2011) examine a 2006 policy change in Indiana, finding a statistically significant increase in residential electricity consumption attributed to DST.

This section describes how we analyze the hourly shape of ozone across U.S. time zone borders from 1980-2017. We outline our empirical strategy in Section 3.1. Section 3.2 presents summary statistics on the average levels of ozone and number of monitors by time zone border across our period of analysis. Our empirical results are presented and discussed in Section 3.3.

3.1. Empirical Strategy

In our analysis, we are interested in examining how concentrations of ambient air pollutants vary over the day and across time zone borders. Because ozone formation varies with sunlight and temperature, we would expect ground-level ozone to vary both over the course of the day (peaking in the early afternoon when temperatures are highest) and across time zone borders (for the same local time, a higher level would be expected on the western side in the morning and the eastern side of the border in the evening). In contrast, we would not expect similar trends in other common pollutants such as nitrogen dioxide (NO_2) and particulate matter (PM_{10} and $PM_{2.5}$).

The main estimating equation we use to estimate the hourly changes in ambient concentrations of a pollutant on either side of the time zone border is:

$$P_{it} = \beta_0 + \beta_1^E East_{i1} + \beta_1^W West_{i1} + \cdots + \beta_{23}^E East_{i23} + \beta_{23}^W West_{i23} + \eta_i + \delta_{dmy} + \epsilon_{it} \quad (1)$$

where the dependent variable P_{it} is the hourly level of a pollutant at pollution monitor *i* in time *t*. Variable *East* (*West*) indicates a monitor being on the eastern (western) side of a U.S. time zone border for a given hour.[8] Standard errors are clustered at the monitor level. The omitted hour in

[8] As outlined in Kotchen and Grant (2011) and Smith (2016), there have been a number of changes to Daylight Savings Time (DST) from its most recent implementation in the Uniform Time Act of 1966. These changes altered the duration of the start and end dates of DST, but for our analysis of ozone the summer period (June-August) in all years has remained covered by DST in the contiguous U.S. minus Arizona and parts of Indiana (see Kellogg and Wolff, 2008 for details on the latter).

the specification is hour ending 24 (HE24). For the results that follow, we limit to observations within 50 miles of the time zone border. Observations in our dataset are further limited to valid ozone days, as defined by the EPA and outlined in Auffhammer and Kellogg (2011). The restrictions on a monitor-year observation are: 1) at least 9 hours reported between 9AM and 9PM and 2) at least 75% of hours June 1 - August 31 report an observation.[9]

The coefficients of interest from Equation (1) are the series of β's for *East* and *West* by hour. With the included monitor and date fixed effects, the coefficients on *East* and *West* in hour ending 24 are normalized to zero; thus β_t^E and β_t^W are relative to HE24 x *East* and HE24 x *West*, respectively. Based on the known relationship between sunlight, temperature, and ozone, we expect to see an hourly shape to the β's that is lowest in the morning and peaks in the afternoon.

Given the narrow geographic window of analysis, we would expect the same or significantly similar meteorological conditions to affect locations on either side of a time zone border. We further argue that the levels of economic activity between places on either side at the same local time are similar. The primary difference would then be the amount of sunlight on the eastern or western side of the border for the same local time: all else equal, one would expect more sunlight at 8am CST vs. 8am EST. Therefore, in our setting the one hour shift in activity due to the time zone border will cause changes in concentrations of ambient ozone through the mechanism of differing levels of solar intensity on either side of the border. We test the validity of these assumptions through an extensive series of robustness checks with controls for meteorological and county status variables in the Appendix, summarized in Section 3.3.

3.2. Data and Summary Statistics

Data comes from EPA's AirData monitoring network, with information on hourly concentrations of various pollutants of interest from 1980-2017. Figure 2 presents the locations of the ozone monitors and counties in our full sample; the majority of monitors in our sample are located around the Central time zone border between the Eastern and Central time zones. Summary statistics for ozone as well as NO_2, VOC, and particulate matter by decade for a 50- or

[9] In a series of sensitivity analyses, we run identical regressions for other pollutants that we would not expect to have significant variation over the course of the day. We apply the same data restrictions outlined here for valid ozone-days to these other pollutants, and the results are presented and discussed in Section 3.3.

75-mile radius around the Central time zone border are presented in Table 1.[10] The table presents the average hourly concentration of each pollutant on the east and west side of the Central time zone border in each decade. Figure 3 presents a more detailed look at our pollutant of interest, with both the hourly concentration and number of ozone monitors per year on either side of the Central time zone border in our sample. Average concentrations of ambient ozone are generally higher on the western side of the border over our sample period, but the trend over time on each side is quite similar. In Figure 4 and Figure 5, we plot the hourly average level for ozone, $PM_{2.5}$, and NO_2 on the eastern and western sides of the border, averaging across all years in the sample.[11]

Figure 4 illustrates the magnitude of the variation in ozone levels over the course of the day, as well as the differences in unadjusted levels of ozone on the eastern and western sides of the time zone border. For the first half of the day (HE1-HE12), levels on the eastern side are lower than their western counterparts by about 2 to 5 ppb every hour. This gap shrinks considerably in the peak afternoon hours (HE13-HE17), before reversing sign with the eastern side reporting levels around 2ppb higher than the western side of the border. Putting these differences in the context of the recent 5ppb revisions to the ozone NAAQS, they make up 40% - 100% of the change in standards for non-attainment. The results in the figure suggest significant differences persist between places on either side of the time zone border that could be attributed to many potential factors – topography, local industry, etc. In our analysis, we seek to specifically isolate the effect of shifting economic activity (such as the start of the workday/school) by one hour on concentrations of ambient ozone.

In addition to NO2, we examine particulate matter to look for differences between counties on either side of a time zone border. There is insufficient coverage (i.e. not enough monitors on either side of a border) when we restrict to our main 50 mile radius, so we extended the radius to 75 miles for $PM_{2.5}$ and plot the results in Panel A of Figure 5.[12] It should be noted that we have

[10] As discussed below, we use a 75-mile radius for particulate matter due to insufficient coverage at the 50-mile level.

[11] An analogous figure presenting the summary for ozone across all time zone borders can be seen in Figure A5 in the Appendix.

[12] For comparison's sake, we created versions of Figure 4 and Panel B of Figure 5 with a 75 mile radius instead of 50; these results can be seen in Figure A6 and Figure A7 in the Appendix. There are no substantive differences between the 50 and 75mile radii versions of each Figure.

more observations for our main dataset of ambient ozone as compared to both the particulate matter and the NO_2 datasets. Given this caveat, we see some differences between the east and west sides of the time zone borders for these other pollutants as compared to ambient ozone. For example, the west side of the time zone border has average NO_2 levels that are up to 4ppb higher than the eastern side across all hours.[13] However, in all cases where the levels on the eastern and western side of the time zone border are different, the *trends* on either side of the border are the same.

To check for evidence of differences in the timing of economic activity between counties on the eastern and western side of a time zone border we utilize data from the U.S. Census' American Community Survey (ACS) for 2012-2016. The 5-year ACS data contains data for survey respondents on items including the average time when a person leaves home and arrives to work (in their local time) and their mean travel time. We present the share of responses from the 5-year ACS to these questions for counties within 50 miles of the Central time zone border in Figure 6.[14] The figure shows a nearly identical distribution of when people leave for and arrive at work on either side of the border. Not shown are the large standard errors on each point estimate; we have insufficient evidence to reject a null hypothesis that the times are the same on either side. Factoring in the 1-hour time difference, this suggests the time zone border is generating a shift in economic activity of up to 1-hour in the morning. As a robustness check, the same summary is presented for counties within 200 miles of the Central time zone border in Appendix Table A3; the results are unchanged.

As an additional check, we look at data from the American Time Use Survey (ATUS) for 2003–2017 on worker demographics, occupations, and when people travel to work. We first show summary statistics on the share of workers on either side of a U.S. time zone border in Table 2. We find no significant differences in the demographic composition on either side of the border in terms of sex, race, age, marital status, homeownership, income, or education. Next, we present the results from a series of regressions of the share of workers in each major occupation category from the ATUS on an indicator for being on the eastern side of a U.S. time zone border

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[13] On either side of the time zone border, we see a pattern of lower NO_2 levels in both the middle of the day and the middle of the night. These may be due to NO_2 being used up in ozone formation during hours of peak sunlight and a relative lack of production activity, respectively (NRC, 1991).

[14] The ACS data used was presented at the county-level and accessed through the U.S. Census Bureau's American FactFinder.

in Table A4. With or without a series of demographic controls, we find no evidence of significant differences in the composition of occupations within 50 miles on either side of the border. Finally, we calculate the average departure time for work in the morning within 50 miles of a time zone border and present the summary in Table A5; again there are no differences between departure times on either side of the border.

3.3. Ozone by Hour – Time zone Results

We plot the estimated β's from estimating Equation (1) with hourly ambient ozone as the dependent variable in Figure 7. For the same local time, we see that ozone concentrations are higher for counties on the western side of a time zone border in the morning and lower in the evening as compared to counties on the eastern side. There is a statistically significant difference in hourly ozone levels from HE6 - HE10 (i.e. 5:00am–9:00am) between the western and eastern sides of a time zone border, totaling just over 2 ppb or 40% of the latest changes to the ozone standard.[15] As compared to the data plotted in Figure 4, the gap between hourly ozone levels on the east and west is considerably narrower. However, the fact that a gap remains at all is noteworthy – after controlling for a robust set of both time and locational factors, a difference in levels of this local air pollutant persists between counties separated only by a time zone border.

One potential concern is that the trends we find for ozone may be common to other pollutants, due to potentially unobserved or confounding factors not captured in our model. We therefore estimate Equation (1) for several other pollutants and report these results in Figure 8. Results with hourly measures of particulate matter (PM_{10} and $PM_{2.5}$) and NO_2 as our dependent variables do not demonstrate the same hourly pattern seen in our main results for ozone; i.e. there are no significant differences in the levels of these pollutants on either side of the time zone border.[16]

The results for particulate matter in Figure 8 are noteworthy as more than just a placebo test of our preferred specification in Equation (1).[17] Emissions of particulate matter can be both

[15] The hourly differences between east and west from estimating Equation (1) can be seen in Table A1.
[16] While there are no differences across the time zone border, there are some trends in these pollutants over the course of the day. For example, when examining NO_2 we see a pattern of lower NO_2 levels in the middle of the night and the middle of the day. These patterns may be attributable to a relative lack of production activity in the evening and NO_2 being converted to ozone in the afternoon, respectively (NRC, 1991).
[17] There may be reason to expect a relationship between temperature and PM ex-ante; the U.S. EPA currently states that the relationship between climate change and particulate matter is unclear (https://www.epa.gov/air-research/air-quality-and-climate-change-research). See also Jacob and Winner (2009).

primary and secondary: sources of PM_{10} and $PM_{2.5}$ include fuel combustion processes from power plants and industrial activities, similar to the sources of ozone precursors. If there were persistent differences in emissions from the industrial composition on either side of the border affecting our results in Figure 7, we would expect to see significant differences between east and west in Figure 8. Similarly, differences in transit across the border – both in terms of people commuting and wind or other meteorological factors moving pollution from one side to the other – would lead to persistent variation between levels on the east and west. The results in Figure 8 provide evidence that our model seems to be appropriately specified; we see no such differences between counties on the eastern or western side of the time zone border and their levels are centered at zero across the day.

We also perform a series of robustness checks to Equation (1) in Section A of the Appendix. Broadly, these checks look for potential underlying differences between counties on the eastern and western sides of the time zone border that might be confounding our estimating of the effect of shifting economic activity. For example, if one side of the border was persistently warmer/cooler than the other, then the effect on ozone concentrations we attribute to shifting activity could simply be due to differences in temperature. Similarly, wind patterns could consistently blow ozone across the time zone border from one side to the other. Therefore, we perform a series of sensitivity analyses where we explicitly include controls for meteorological variables – hourly temperature, wind direction, and wind speed; and whether a county is NO_x - or VOC-Limited. The results remain qualitatively similar across all of these alternative specifications. Further discussion of these results can be found in Section A of the Appendix.

3.3.1. Non-Attainment Status

It is possible that the hourly profile of ozone, and the subsequent effect we find from shifting economic activity, may vary as a function of the counties' baseline ozone concentrations due to differing levels of regulation. In particular, EPA's standards for ozone under the NAAQS program identify counties as being in attainment or non-attainment based on their 4th highest daily 8-hour maximum over a 3-year period.[18] We examine potential differences for counties in- and out- of attainment in Equation (2):

[18] See Table A6 in the Appendix for a history of the changes to the NAAQS standard over time.

$$P_{it} = \beta_0 + \beta_1^E East_{i1} x\ Attain_{cy} + \beta_2^E East_{i1} x\ NonAttain_{cy} + \beta_1^W West_{i1} x\ Attain_{cy} \quad (2)$$
$$+ \beta_2^W West_{i1} x\ NonAttain_{cy} + \cdots + \beta_{45}^E East_{i23} x\ Attain_{cy} + \beta_{46}^E East_{i23} x\ NonAttain_{cy}$$
$$+ \beta_{45}^W West_{i23} x\ Attain_{cy} + \beta_{46}^W West_{i23} x\ NonAttain_{cy} + \eta_i + \delta_{dmy} + \epsilon_{ict}$$

Equation (2) is similar to Equation (1), except here the hourly coefficients on *East* and *West* are interacted with a county's annual attainment status. Data on a county's annual attainment status comes from EPA's GreenBook and is available from 1992-2017.

We plot the coefficients for *East* and *West* separately for counties in and out of attainment in Panels A and B of Figure 9, respectively. Focusing first on counties in attainment, we find a larger difference between ambient ozone concentrations on the eastern and western sides of a time zone border as compared to our main results in Figure 7. When focusing on counties out of attainment (Figure 9, Panel B), the results look nearly identical to our findings in Figure 7. Keeping in mind that the sample size is considerably smaller for these subsamples as compared to our main results, the results in Figure 9 collectively suggest a few interesting points. First is that our main results may be driven by non-attainment counties, which is not surprising when considering the high proportion of counties that have been in non-attainment of the ozone standards. Second is that Figure 9 suggests that the effect of shifting economic activity may be higher in attainment counties. In other words, it is possible that at lower overall levels of ozone, shifting economic activity could have a larger marginal impact on reducing hourly ambient ozone concentrations. This suggests that as the NAAQS become tighter and tighter, shifting economic activity may be a more critical component for policymakers attempting to assist counties with being in attainment.

3.3.2. Air Quality Alerts

Finally, we examine differences in how places respond to the issuance of air quality alerts. Air quality alerts or action days are a form of episodic control program designed to encourage voluntary reductions in emissions from individuals and businesses through encouraging behaviors such as carpooling, telecommuting, and avoiding driving during rush hour on days forecasted to have unhealthy air quality. Local air quality agencies in many parts of the U.S. utilize air quality forecasts based on meteorological conditions to determine whether to issue an air quality alert. On days forecasted to have especially high temperatures, for example, higher rates of ozone formation may be likely. If conditions are predicted to cause air pollution to exceed a given threshold for unhealthy air quality, local agencies may issue an air quality alert.

Using data obtained from a Freedom of Information Act (FOIA) request to the U.S. EPA, we have a record of air quality alerts issued by each reporting area across the U.S. from 2004 – 2017. For our analysis, we restrict alerts to those called based on Next Day forecasts – these are the most commonly used to make alert declarations in order to allow individuals and businesses sufficient time to respond to the alert.

We estimate a modified version of Equation (2) above to examine potential differences in the responses to action day alerts, where we replace the terms for counties being in and out of attainment with indicators for whether a county called an action day alert on a given day. The results for action days and non-action days are shown in Panels A and B of Figure 10. As would be expected, the results for days in which an action day was not called are similar to our main results in Figure 7. But on those days that are projected to have the worst air quality, shifting economic activity would be expected to have the greatest impact. That is indeed what we see in Panel A, with differences of over 1.3 ppb in HE8 – HE9 and over 1ppb in HE10. Any additional actions to encourage the shifting of activity, such as issuing an air quality alert, serve to further increase the observed gap between *East* and *West*. These results provide some suggestive evidence that shifting economic activity could have its largest impact on the days where it would be most valuable.

4. Ozone By Hour – The NO_x Budget Program

In the previous section we showed that an intraday shift of economic activity can have a non-trivial effect on the intraday distribution of ambient ozone concentrations. We shift our focus from this stylized fact to an examination of how policies targeting reductions in ozone precursors affect hourly ozone. Specifically, how did the NO_x Budget Program (NBP) affect hourly ozone concentrations and how might firms have responded to the NBP?[19] Prior work analyzing the NBP has found it to be successful – Deschenes, Greenstone, and Shapiro (2017) find that the NBP significantly reduced mean summer ozone concentrations by about 6% and in turn reduced

[19] Background on the NO_x Budget Program was provided in Section 2.2.

the summer mortality rate by 0.4%.[20] In our analysis, we are interested in examining whether the NO_x Budget Program was successful at reducing ozone in peak hours. In other words, did the NO_x Budget Program alter the intraday distribution of ambient ozone concentrations?

We outline our empirical strategy in Section 4.1. Section 4.2 presents summary statistics on our sample's coverage and the average ozone levels for states that did or did not participate in the NO_x Budget Program. Our empirical results are presented and discussed in Section 4.3.

4.1. Empirical Strategy

For our analysis of the NO_x Budget Program, we restrict our sample to the months of April and May, because the pattern of ozone precursor emissions might change over the ozone season. Recall that the program took effect in warmer months only and began in May 2003; therefore we are examining the month prior to and the first month after the NO_x Budget Program took effect.[21]

We estimate the following triple-differences model:

$$\begin{aligned} P_{ihdmy} = \ & \beta_0 + \beta_1^{\tau} Treat_{idmy} * \tau + \beta_2^{\tau} Control_{idmy} * \tau + \\ & \beta_3\, NBPyear_{iy} * NBPstate_i + \beta_4 NBPmonth_{im} * NBPstate_i \\ & + \gamma_1 temp_{hdmy} + \eta_i + \delta_{dmy} + \epsilon_{ihdmy} \end{aligned} \quad (3)$$

where the dependent variable P_{ihdmy} is the hourly level of a pollutant at pollution monitor i, hour h, day d, month m, and year y. Variable *Treat* indicates a state participating in the NO_x Budget Program when the program was in effect (i.e. ozone season) in a given month-year. *Control* is an indicator for non-participating states in any month or a participating state in a month outside of the Program's ozone season. These two terms are interacted with a set of hour fixed effects τ, representing hour ending 1-23. The omitted hour in the specification is thus hour ending 24. Variable *NBPyear* is equal to 1 if it was a year when the NBP was in effect (2003-2008) and 0 otherwise; similarly *NBPmonth* is an indicator for a month when the NBP was in effect (May). *NBPstate* is an indicator variable for a state that participated in the NBP. The primary control variable, *temp*, is the contemporaneous hourly temperature from EPA's AirData database. It is

[20] The authors translate this reduction in the mortality rate into the prevention of nearly 2,000 premature fatalities.
[21] We perform a sensitivity analysis where we instead look at September and October in Section B.4 of the Appendix.

important to control for temperature in this analysis since we will be comparing ozone concentrations in April to those in the hotter month of May; results with additional control variables are presented and discussed in Section B of the Appendix. Finally, we include fixed effects for monitor (η_i) and day-by-month-by-year (δ_{dmy}) and cluster standard errors by monitor. Following Deschenes, Greenstone, and Shapiro (2017), we exclude a set of neighboring states that are downwind.[22]

The coefficients of interest from Equation (3) are β_1^τ and β_2^τ, the coefficients on treated and control observations by hour. If the NO_x Budget Program induced firms to reduce their precursor emissions during peak hours, we would expect to see statistically and economically significant differences between these coefficients in the morning and peak afternoon hours. However, if firms did not respond through shifting production across hours but instead by reducing emissions slightly across all hours, we would expect the trends in β_1^τ and β_2^τ to be similar. Since the regulation treated emissions the same irrespective of their timing (and since the ozone NAAQS is based on an 8-hour average instead of a shorter peak), our hypothesis is that we will see the latter. This is consistent with prior research on the electric generation sector suggesting that power plants generally operate their emission control equipment continuously throughout seasonal emission control programs (Martin et al., 2007).

4.2. Data and Summary Statistics

As before, the hourly pollution data comes from EPA's AirData database. We supplement the data on pollution with the contemporaneous hourly temperature from the same database. Counts of ozone monitors by year and NO_x Budget Program status (participating or non-participating states) are presented in Figure B7. The NO_x Budget Program covered parts of the East and Midwest U.S. from 2003-2008; a map of participating states and the neighboring states we exclude from our analysis following Deschenes, Greenstone, and Shapiro (2017) can be seen in Figure B8.

[22] From the authors: "The main analysis excludes Wisconsin, Iowa, Missouri, Georgia, Mississippi, Maine, New Hampshire, and Vermont. We do not exclude Arkansas or Florida because they share only small sections of border with the NBP area and because prevailing winds blow to the Northeast, away from these states. We exclude Maine even though it does not share a border with the NBP region because it is downwind and close to many NBP states. We define Alabama as an NBP state even though the southern region of the state did not participate in the market."

We plot the hourly average ambient ozone during the program period of May 2003-May 2008 in Figure 11. Panel A displays the average levels of ozone by hour for states that did not participate in the NO_x Budget Program. The hourly profile of ozone matches what we have seen in Section 3.2, with lower levels in the morning/evening and a peak in the mid-afternoon. Moving from April to May, there is little distinguishable shift in the ozone levels after the early morning hours. In Panel B, we show the same data for states that participated in the NO_x Budget Program. Recall that the NBP took effect from May–September each year, so one would expect a shift in ozone levels as we move from April to May due to the Program. We do indeed see a shift in hourly ozone, however there is actually a slight *increase* in ozone levels in peak hours in May as compared to April. Although this shift up might be due to warmer temperatures in May, this pattern also suggests that the NO_x Budget Program may not have been as effective at reducing hourly ozone levels during the hours with the highest potential marginal damage, namely the peak afternoon hours. However it should be noted that this is only suggestive, as a number of factors could explain this trend that would be separate from the effect of the Program. We will explore this trend further using our econometric model in the next subsection.

4.3. Results

Results from the estimation of our preferred specification, the triple-differences equation [Equation (3)], can be seen in Figure 12.[23] There is a slight reduction in ozone concentrations in the earlier morning hours (similar to Figure 7) due to the NO_x Budget Program that extends into the late morning. However, there is not an economically significant gap between treated and untreated observations during the peak afternoon hours of the day. In fact, there is a small but statistically significant increase in ambient ozone concentrations in treated states due to the NBP in the evening hours.[24] In summary, these results indicate that firms did not appear to shift production away from the peak ozone period in order to comply with the NO_x Budget Program. It therefore suggests that a policy targeted specifically at reducing ozone during peak hours might be necessary to achieve the greatest potential marginal benefit, since these hours have the highest ozone concentrations and thus may impose the greatest marginal damages.

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[23] These results exclude neighboring states as in Deschenes, Greenstone, and Shapiro (2017). We also estimate Equation (3) for all states; the results are unchanged and can be found in Figure B9 in the Appendix.

[24] The hourly differences between Treat and Control from estimating Equation (3) can be seen in Table B1.

Results from our analysis of the NO_x Budget Program follow closely with what we show in the analysis of ozone across time zone borders in Section 3. The raw data presented in Figure 4 shows a significant gap between east and west for a number of morning hours; however, our regression analysis in Figure 7 suggests that the shifting of activity from the time zone border causes a much smaller but significant shift of roughly 2ppb in HE6 – HE9. In this case, prior research shows that the NO_x Budget Program was successful at reducing ozone overall. However, our econometric results in Figure 12 suggest that the effect of the NBP at reducing ozone in peak hours may be minimal. While the cumulative effect of the policy across all hours may have been significant, since the NO_x Budget Program did not directly target reductions in peak hours the potential benefits to human health through reductions in these high concentration hours may have been overstated.

In Section B of the Appendix, we estimate a version of Equation (3) where we limit our analysis to states that did not participate in the NBP in order to examine whether there were significant changes to the hourly profile of ozone between April and May for non-participating states. We find no significant differences for non-participating states, and similarly find no difference for participating vs. non-participating states when we use another pollutant as our outcome variable that was not targeted by the NBP (particulate matter). The results are also qualitatively similar when controlling for whether a county is NO_x - or VOC-Limited or shifting the period of analysis to the last month of the NBP program and the 1st month after (September – October).

4.3.1. Non-Attainment Status

One could imagine that the effect we measure may vary by a county's attainment status; perhaps the Program focused predominately on non-attainment counties and caused firms to shift economic activity in these counties. Under this alternative, the results we find from estimating Equation (3) could be driven by a lack of an effect in attainment counties. To examine this potential heterogeneity, we estimate a modified version of Equation (3) where our hourly treatment and control β's are interacted with the county's attainment status.

$$P_{ichdmy} = \beta_0 + \beta_1^{\tau} Treat_{icdmy} * \tau * NonAttain + \beta_2^{\tau} Control_{icdmy} * \tau * NonAttain + \beta_3 \, NBPyear_{iy} * NBPstate_{ic} + \beta_4 NBPmonth_{im} * NBPstate_{ic} + \gamma_1 temp_{hcdmy} + \eta_i + \delta_{dmy} + \epsilon_{ichdmy} \quad (4)$$

We plot the hourly coefficients separately by attainment status in Panels A and B of Figure 13. There is no significant difference when examining counties in attainment, but we do see a more persistent difference in non-attainment counties in the late morning to early afternoon hours relative to untreated counties. However, in the early evening we see hourly ambient ozone concentrations for the treatment group shift below the levels for the untreated.

The results in Panel B of Figure 13 match with the potential heterogeneity story outlined above. But it is difficult to attribute the differences we observe for non-attainment counties as being caused by the NO_x Budget Program, particularly when we consider there is no difference in attainment counties. Instead, this could suggest that the additional regulations faced by counties that are out of attainment (through for example the state implementation plans or SIPs) are driving the observed ozone reductions, as hypothesized by Henderson (1996). Further examination of this heterogeneity is necessary to understand whether EPA regulations or the SIPs are successfully incentivizing firms to shift production.

5. Conceptual Framework for Policymaking

Findings from the analyses in Section 3 suggest that shifting economic activity can lead to reductions in hourly ozone concentrations. In Section 4, our results indicate that policies targeting reductions in ozone that disregard *when* precursor emissions are reduced may not be as effective at reducing peak ozone hours. In this section, we outline a conceptual framework for thinking about how policymakers could target reductions in peak ozone hours.

The first-best solution from standard economic theory is to price the externality, or to tax the marginal emissions of ozone precursors. Given the known hourly shape of ozone over the course of the day and forecasts about daily maximum temperatures, one could conceive of a time-varying tax that is a function of both time of day and forecasted temperature; i.e. a tax based on the potential marginal harm from ozone precursor emissions in a given hour. However, as policy has tended away from taxation of local air pollutants due to a variety of political and other reasons, we focus here on suggesting an adaptation to a type of program that has been shown to have a level of political tractability: cap-and-trade.

Section 5.1 presents a conceptual framework for a standard cap-and-trade program, and Section 5.2 illustrates our extension to allow for intra-day variation in permitting.

5.1. Conceptual Framework of Firm Production Under Cap-and-Trade

In a cap-and-trade program such as the NO_x Budget Program, there is an initial allocation of permits to firms based on a historical base-level of emissions. Fowlie and Perloff (2013) show that this initial allocation has no effect on the market outcome. Each permit is for a single unit of emissions, and firms buy and sell these permits from one another to ensure that they have sufficient permits to cover their emissions or risk facing a significant financial penalty. Once the cap-and-trade program begins, the number of permits each period is gradually reduced, thereby increasing the value of the remaining permits and enforcing a reduction in pollutants that at a minimum will not exceed the total amount of all permits in the market.

The permit in a standard cap-and-trade program is for one unit of emissions, regardless of where or when it is emitted. In this case, for a distribution of firms with heterogeneous costs of compliance, we would expect that in equilibrium firms with lower compliance or abatement costs will reduce their emissions (Rubin, 1996; Meng, 2017). They are then compensated for these reductions through the permits they can sell to firms with a higher compliance cost. If the revenue from selling their permits does not outweigh their compliance cost (i.e. the permit price is too low), then firms have insufficient incentive to make the costly investment to reduce emissions. In a well-functioning market, the permit price will be such that the marginal firm (from the perspective of achieving the policymaker's emissions reduction target) is indifferent between reducing their emissions and purchasing additional permits from other firms to comply with the regulation. The manner in which firms reduce their emissions may vary from undertaking new capital investments in pollution abatement technology to updating plant components or to running/operating at a lower level (i.e. generating lower emissions per hour at the expense of lower overall output). Decisions even among the same group of firms may vary;

in the case of electric power producers, regulated power plants were more likely to undertake the capital investment than de-regulated or public utilities under the NO_x Budget Program (Fowlie, 2010).

Fowlie and Muller (2019) tackle the first issue of *where* emissions occur, showing that under perfect information and heterogeneous damages, damage-based policy differentiation is unambiguously welfare improving.[25] We modify their approach to focus instead on the problem of *when* emissions occur. To provide firms with incentives to reduce emissions during particular hours or periods where marginal damages are likely to be highest, the price they face (e.g., the permit price) must vary. In a well-functioning market, this can be achieved by allowing the number of permits to vary by hour or peak/off-peak period; if the number of permits is lower in hours with higher marginal damages (i.e. when emissions reductions are most valuable), the permit price in these hours will be higher and provide incentives to a greater number of firms to reduce their emissions.

Henderson (1996) was the first to explore the issue of *when* emissions occur with regards to ozone. He finds suggestive evidence that firms in non-attainment counties could comply with NAAQS regulation by reducing ozone in the mid-morning hours. In Section 3 we extended his preliminary finding by examining the impact of a 1-hour shift in economic activity on ozone across the United States using data from over 35 years. In the next subsection we introduce a stylized model to illustrate how accounting for the value of when precursor emissions occur can be implemented through a cap-and-trade program.[26]

5.2. Allowing for Intra-Day Variation

Our stylized model building on the work of Fowlie and Muller (2019) is fully outlined in Appendix C. Here we discuss its main features and predictions. We extend their framework of two firms with low and high compliance costs to consider multiple program periods. For simplicity, we illustrate the two-period case with a single peak and off-peak period, denoted with

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[25] However, they find that under certain circumstances it can actually be beneficial to implement a policy that ignores the spatial differences.

[26] It should be noted that we do not currently compare the potential benefits of our cap-and-trade approach to achieving the same goals through the traditional regulatory approach of command and control. Given the simplicity of our model, we are also unable to comment on the program's impact in terms of environmental justice. For more on these important issues, we refer the reader to work examining a regional NO_x trading program in southern California (Fowlie et al., 2012).

subscripts *P* and *OP* respectively. Firms face abatement costs as a quadratic function of emissions and seek to minimize their private costs given their initial permit allocations (A_{iP}, A_{iOP}) and the permits they buy/sell from other firms. In our model, permits are valid for either the peak or off-peak period, and therefore the firm can buy or sell permits at the prevailing market prices for each period. The regulator is assumed to have full knowledge of the cost parameters of the firm, and has the objective of minimizing total social costs which are defined as the sum of private abatement costs and damages from emissions of the local pollutant. The regulator minimizes costs over the possible set of emissions ($e_{iP}, e_{iOP}\ \forall i$) to determine the optimal emission cap to set for the peak and off-peak period. This in turn informs the quantity of permits to be made available in each period.

For this program to be considered successful in our context of ozone, the resulting emissions from the time-varying cap-and-trade program during the peak period should be lower than in the standard cap-and-trade. Even if aggregate emissions were higher under the alternative program, due to the nature of ozone's risks from short-term exposure to elevated concentrations, reductions in the period with the highest hourly ambient ozone concentrations outweigh potential increases in the off-peak period. Indeed, studies from the epidemiology and economics literature suggest that exposure to ambient ozone at levels below a threshold of around 30-40 ppb are likely to have minimal effects on respiratory function (U.S. EPA 2006; Pattenden et al., 2010) or productivity (Graff Zivin and Neidell, 2012).

We compare the resulting equilibrium emission levels under the standard cap-and-trade and the peak period in the time differentiated case. The difference derived in Appendix C is: [27]

$$\mathrm{E} - \mathrm{E_P} = \frac{(\beta_H + \beta_L)(\delta_P - \delta_{OP})}{4\beta_H\, \beta_L}$$

where β_H and β_L represent the slope of the marginal abatement cost curves for the high and low compliance cost firms, respectively. Since the marginal damages are higher in the peak period (i.e. $\delta_P > \delta_{OP}$), we know that our numerator is strictly greater than zero, or $\mathrm{E} - \mathrm{E_P} > 0$. Thus, in

[27] This assumes that the cost of reducing emissions for firms does not vary by time of day, i.e. the cost function for reducing emissions in the peak period is the same as the off-peak period. Given that emission control technology is generally not operated on and off over the course of a day (Martin et al., 2007), we argue that this assumption is plausible. However, the assumption would potentially be violated if, for example, operations and/or efficiency of emission control equipment is significantly affected by higher temperatures.

our simplified case, we have shown that emissions during the peak period under the temporally differentiated cap-and-trade program will be strictly lower than the emissions during the same period under a standard cap-and-trade without differentiation.

6. Concluding Remarks

This paper examines how shifting the timing of economic activity causes shifts in ambient ozone concentrations by examining monitor-level data on ambient ozone near United States time zone borders from 1980-2017. We find that there is suggestive evidence that a time zone border shifts economic activity on either side of the border by up to 1 hour. In turn, this shift in activity leads to an increase in ambient ozone in the morning hours on the western side of a time zone border relative to the east totaling about 2 ppb driven by higher solar intensity. While the magnitude may seem small, the hourly effect is equivalent to 10% of the decrease implemented in the most recent ozone NAAQS. Our finding is robust to a series of alternative specifications with various meteorological and regional controls.

We then focus our attention on temporally-undifferentiated ozone policies and analyze a program that aimed to reduce ambient ozone concentrations by targeting its precursors – the NO_x Budget Program. Utilizing a triple-differences estimation over the period 1980-2008 and focusing on the 1st month before and after the Program's ozone season began, we find no economically significant reduction in ambient ozone concentrations during peak ozone hours due to the Program. These results indicate that while firms reduced emissions overall, they did not significantly reduce their emissions in or around peak periods. This suggests that potential benefits from the Program in terms of ozone reductions may be overstated.

Finally, we investigate and propose an alternative framework for a cap-and-trade program with time-varying permits. The stylized model allows the regulator to reduce the number of permits available for the peak period relative to the off-peak, which in turn increases the relative permit price for the peak ozone hours. This provides firms with incentives to reduce their emissions of precursors during this peak period, and encourages lower cost firms to shift their production to off-peak hours and profit from selling permits for peak hours to firms that find shifting their activity to be more costly. In the context of the electric generation sector, this would serve to further incentivize electric utilities or load serving entities to procure generation from renewables such as solar during peak hours in place of coal or natural gas. It would also provide additional incentives for the integration of large-scale energy storage that could not only take nighttime generation from wind and dispatch it in peak periods, but potentially allow for existing fossil fuels to shift generation to less harmful off-peak periods while continuing to serve load in higher demand hours.

Future work could explore the marginal willingness to pay for short-term reductions in peak ozone. Additionally, in our analyses we focused on exploring the potential benefits of shifting economic activity. We used the example of time zone borders to show that this is not only possible but can affect ambient ozone concentrations. However, an important consideration for the policymaker is whether the benefits of improved health through reduced ambient ozone exposure is offset by the increase in the firm's private costs to comply with a hypothetical time-varying permit program. Improving our understanding of the costs from shifting economic activity should be an important goal for future research.

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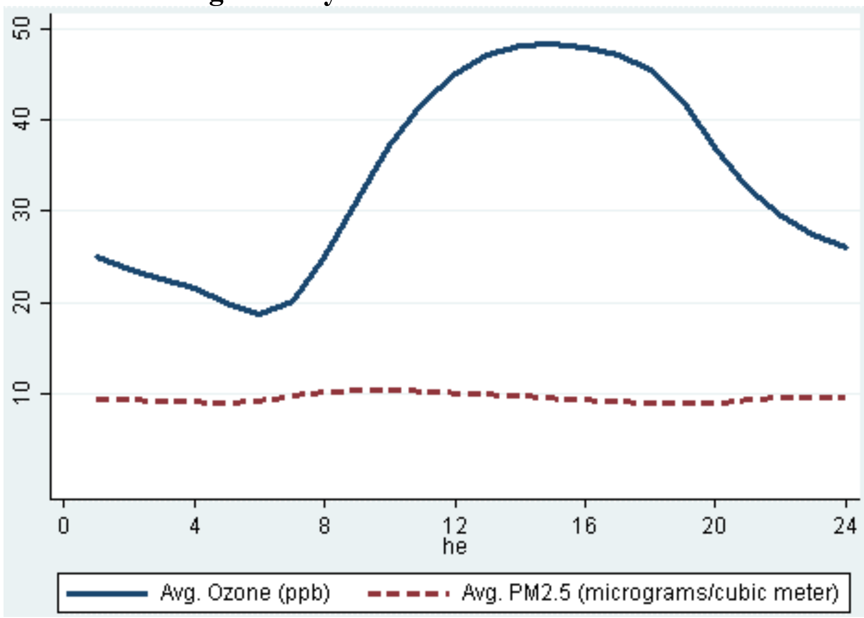
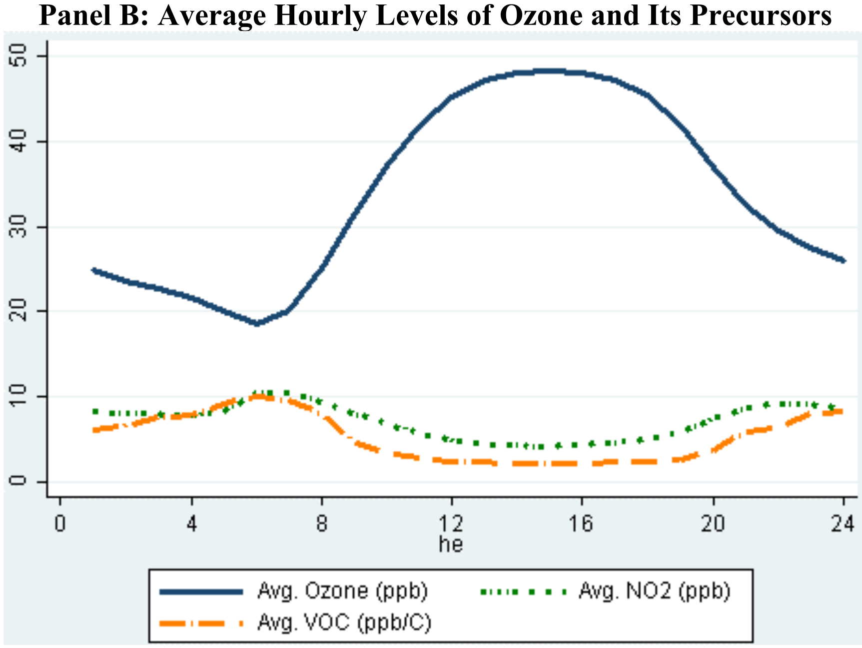
1. Figures

Figure 1 – Average Hourly Pollutant Concentrations

Panel A: Average Hourly Levels of Ozone and Particulate Matter



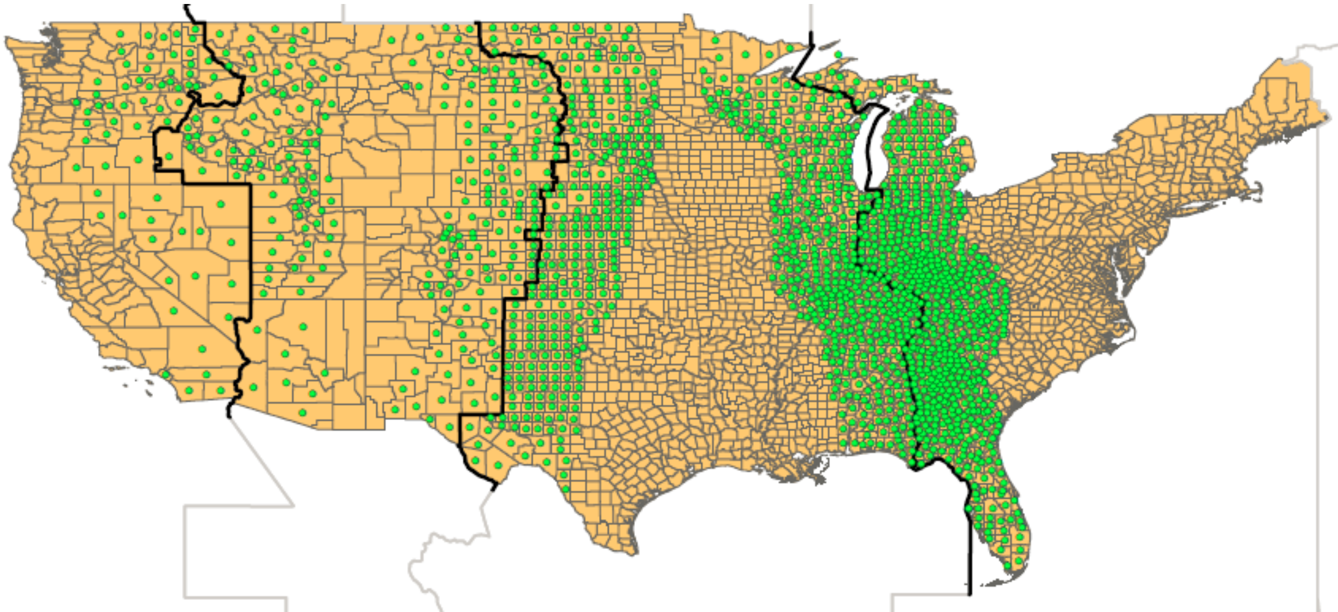
Panel B: Average Hourly Levels of Ozone and Its Precursors



Notes: Average hourly pollutant concentrations across all counties within 200 miles of a U.S. time zone border from June-August 2010. Data from EPA's AirData database, restricted to valid monitor-years.

Figure 2 – Counties and Monitors within 200 Miles of a U.S. Time Zone Border

Panel A: Counties within 200 Miles of a U.S. Time Zone Border



Panel B: Ozone Monitors within 200 Miles of a U.S. Time Zone Border

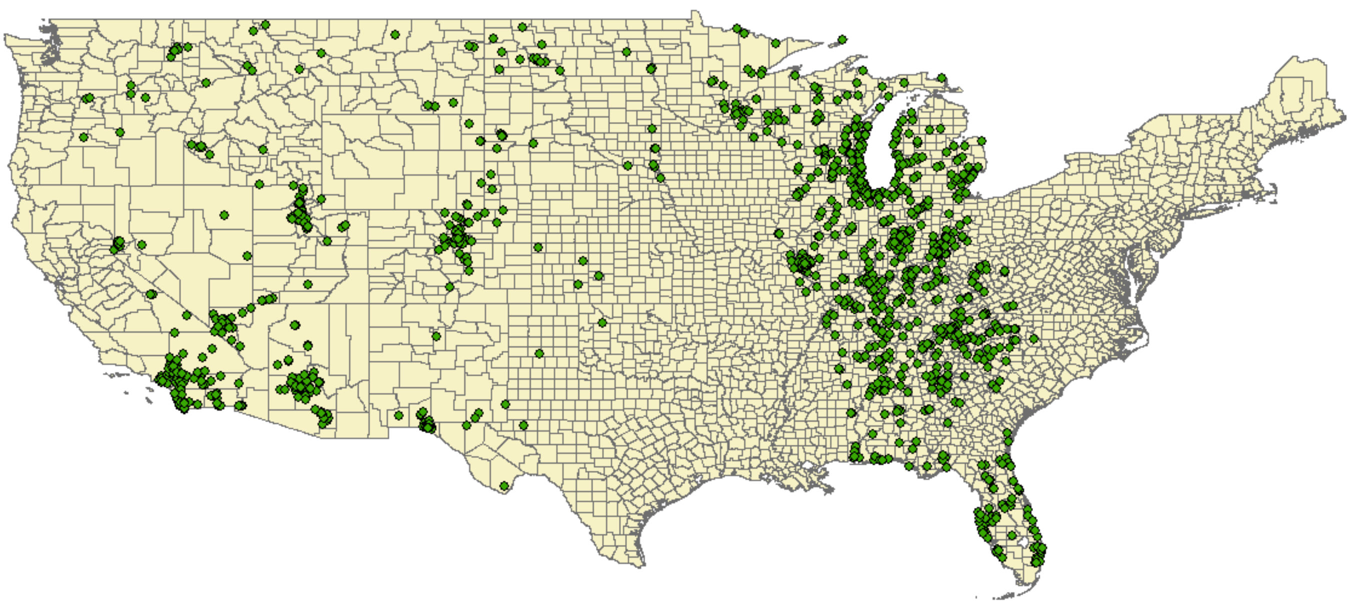
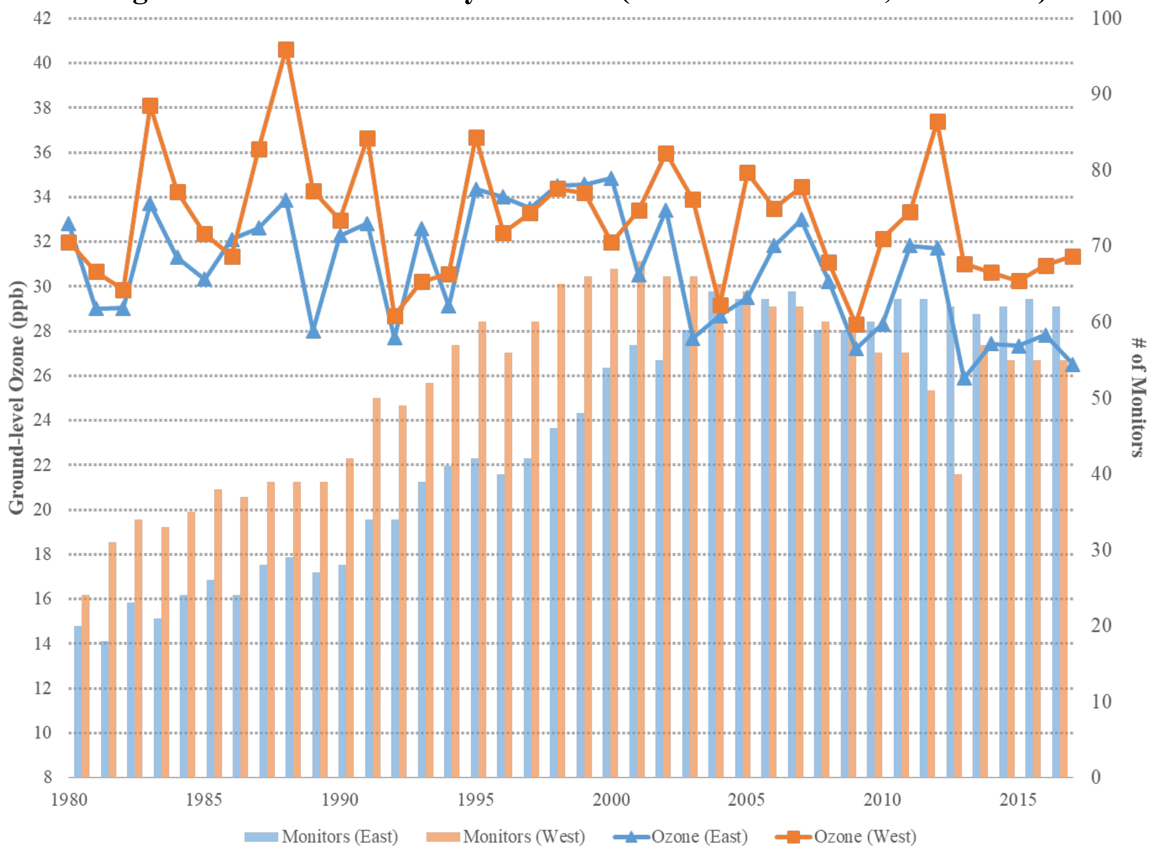
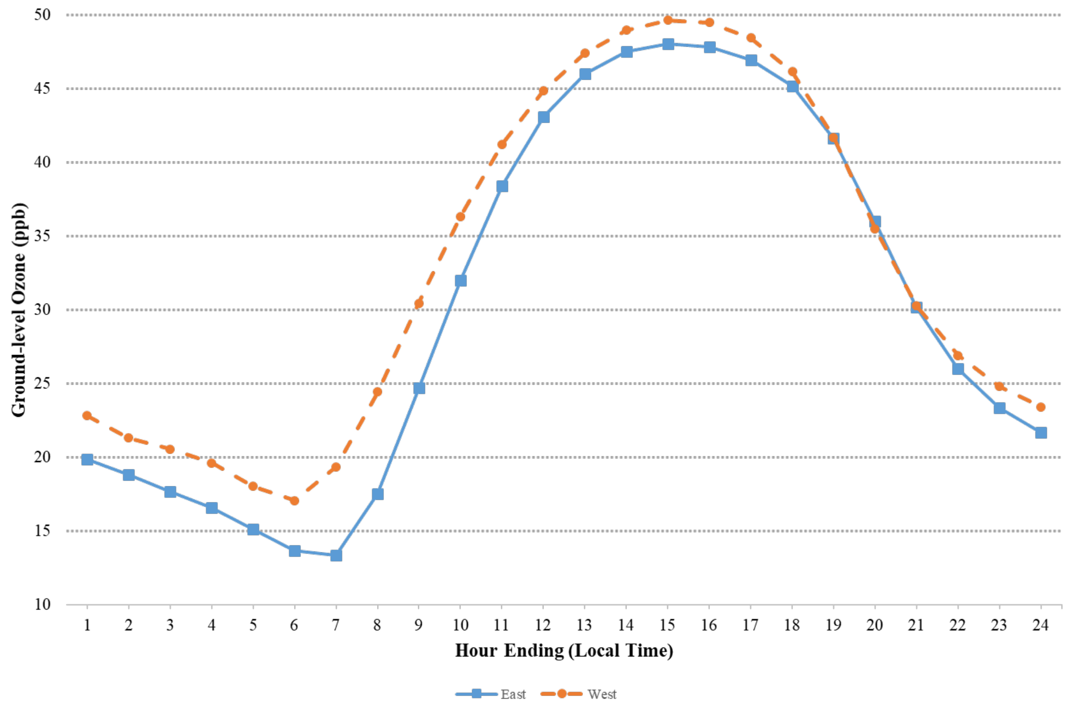


Figure 3 – Ozone Summary Statistics (Central Time zone, 1980-2017)



Notes: Average hourly ozone and monitor count across all counties within 50 miles of the Central time zone border. Data from EPA's AirData database, restricted to valid ozone monitor-years. Valid monitor-years are defined as having: 1) at least 9 hours reported between 9AM and 9PM and 2) at least 75% of hours June 1 - August 31 report an observation.

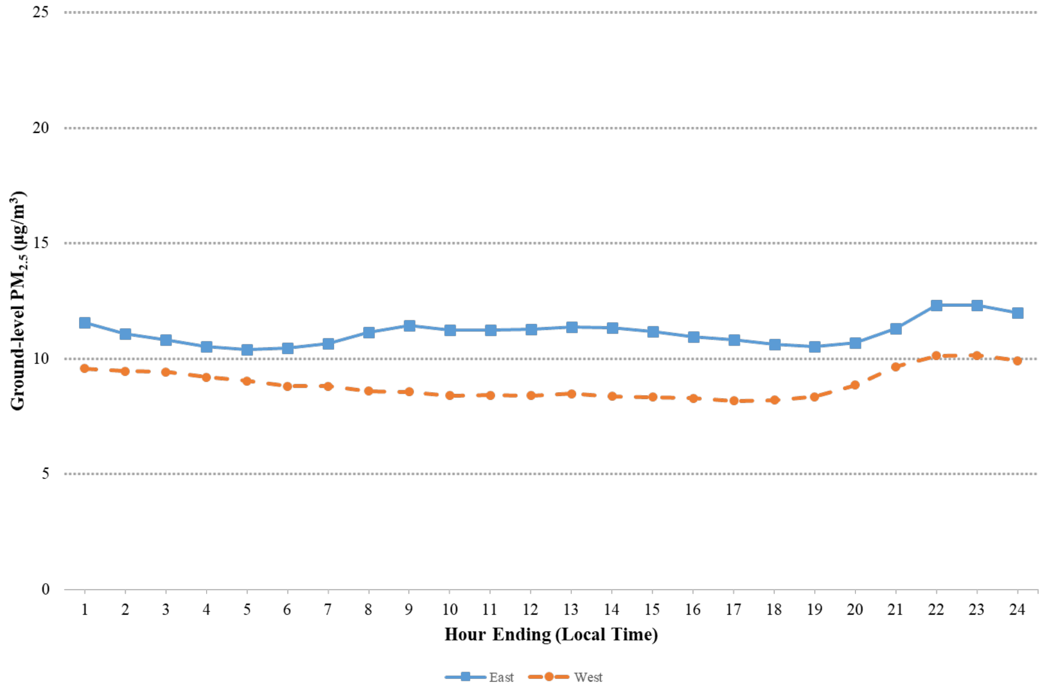
Figure 4 – Average Ozone by Hour of the Day (Central Time Zone, 1980-2017)



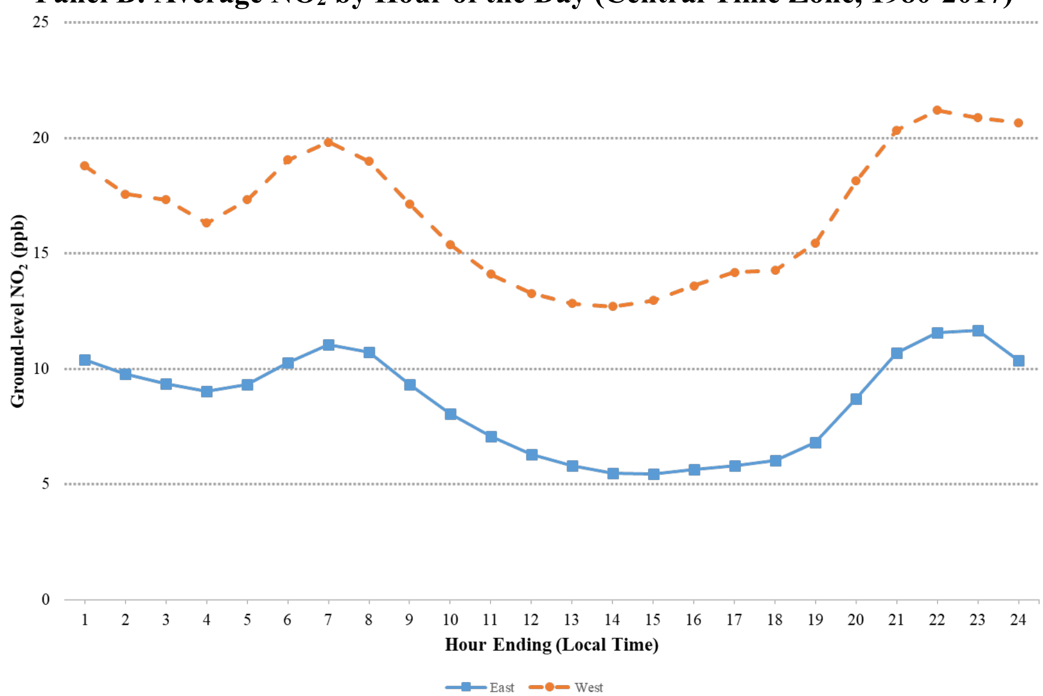
Notes: Average hourly ozone across all counties within 50 miles of the Central time zone border. Data from EPA's AirData database, restricted to valid monitor-years. Valid monitor-years are defined as having: 1) at least 9 hours reported between 9AM and 9PM and 2) at least 75% of hours June 1 – August 31 report an observation.

Figure 5 – Average NO_2 and $PM_{2.5}$ by Hour

Panel A: Average $PM_{2.5}$ by Hour of the Day (Central Time Zone, 1980-2017)



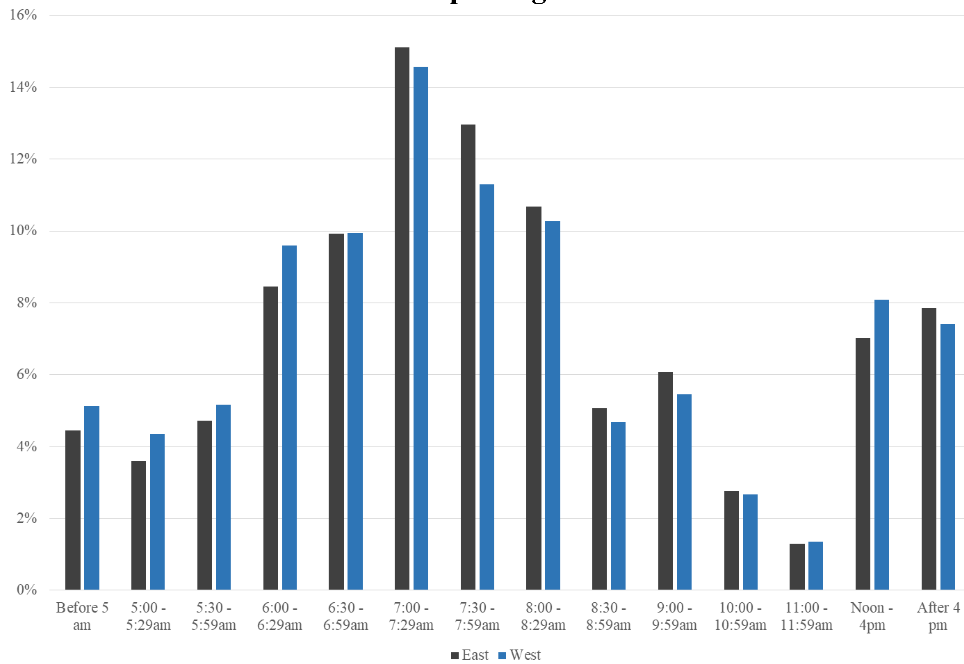
Panel B: Average NO_2 by Hour of the Day (Central Time Zone, 1980-2017)



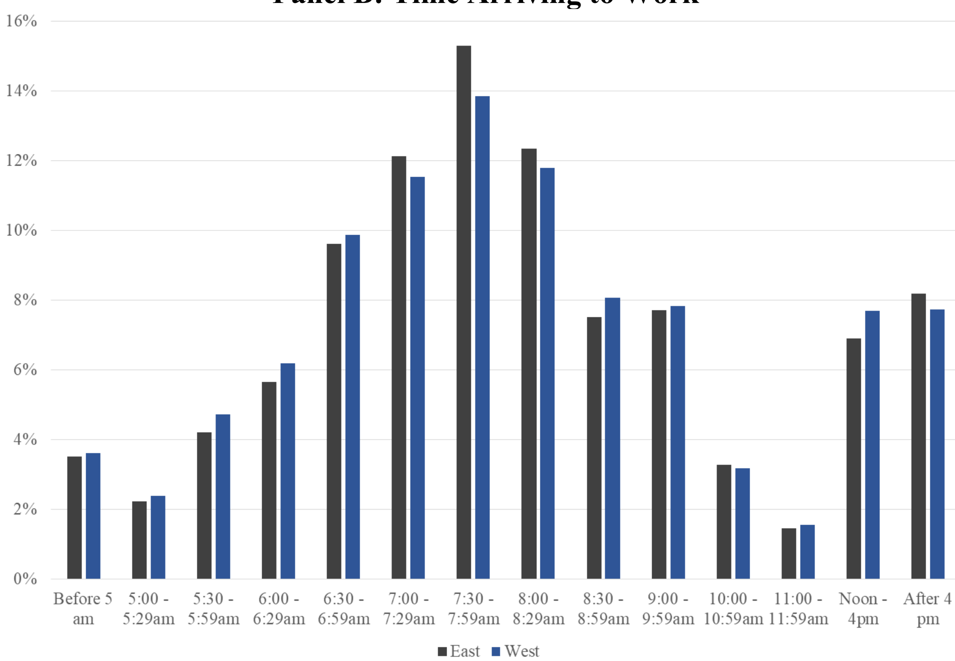
Notes: Average hourly NO_2 and $PM_{2.5}$ across all counties within 50 and 75 miles of the Central time zone border. Data from EPA's AirData database, restricted to valid monitor-years. Valid monitor-years are defined as having: 1) at least 9 hours reported between 9AM and 9PM and 2) at least 75% of hours June 1 - August 31 report an observation.

Figure 6 – Average Times Departing for and Arriving at Work (50 Miles)

Panel A: Time Departing Home for Work

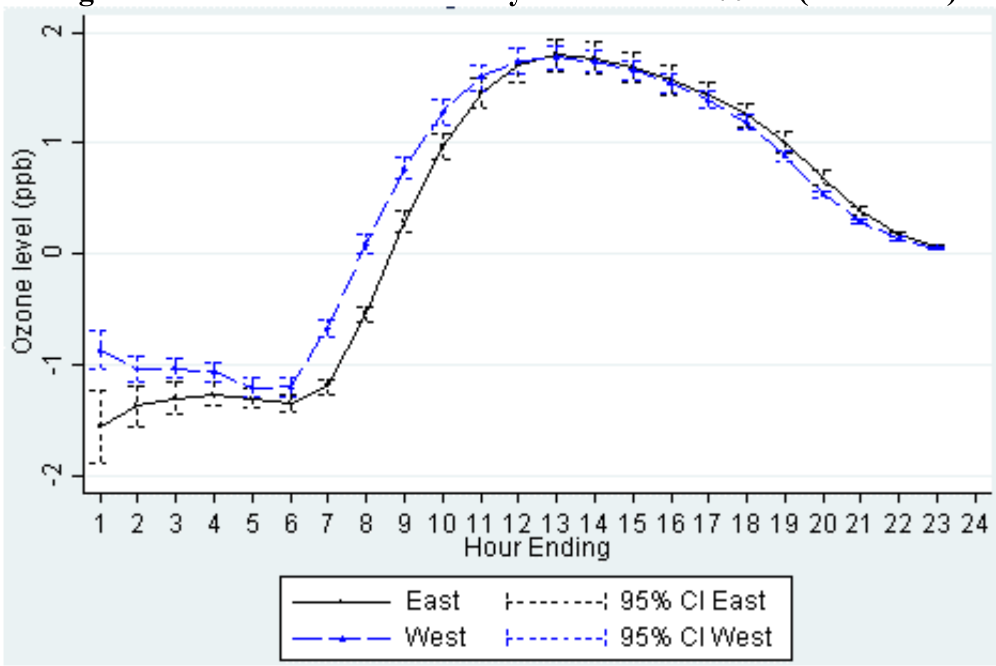


Panel B: Time Arriving to Work



Notes: From ACS 2012-2016 data, downloaded from American Fact Finder at the county -level. Restricted to counties within 50 miles of the Central time zone border.

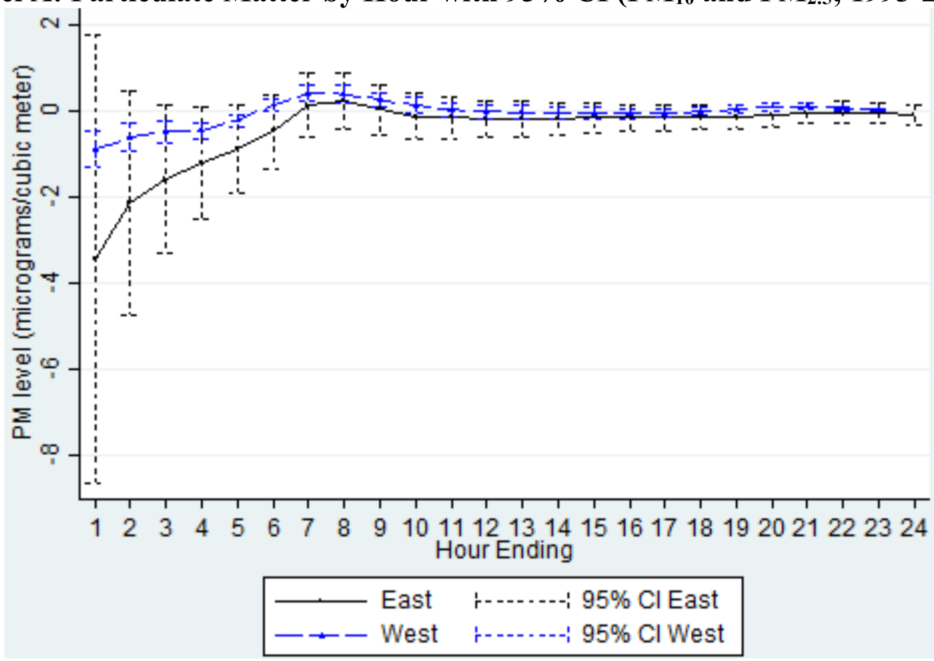
Figure 7 – Ground Level Ozone by Hour with 95% CI (1980-2017)



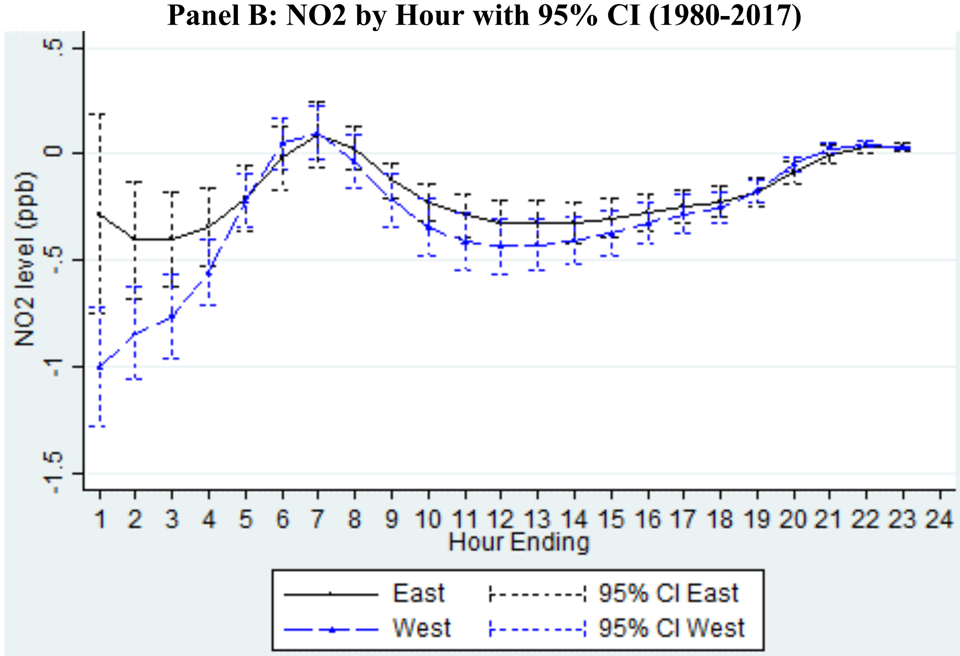
Notes: Results of estimation of Equation (1) for the period 1980-2017. Includes counties within 50 miles of a U.S. time zone border. Plot is of the β's for *East* and *West* by hour. Omitted category is hour ending 24. Standard errors clustered by monitor.

Figure 8– Particulate Matter and NO_2 by Hour with 95% CI

Panel A: Particulate Matter by Hour with 95% CI (PM_{10} and $PM_{2.5}$; 1993-2017)



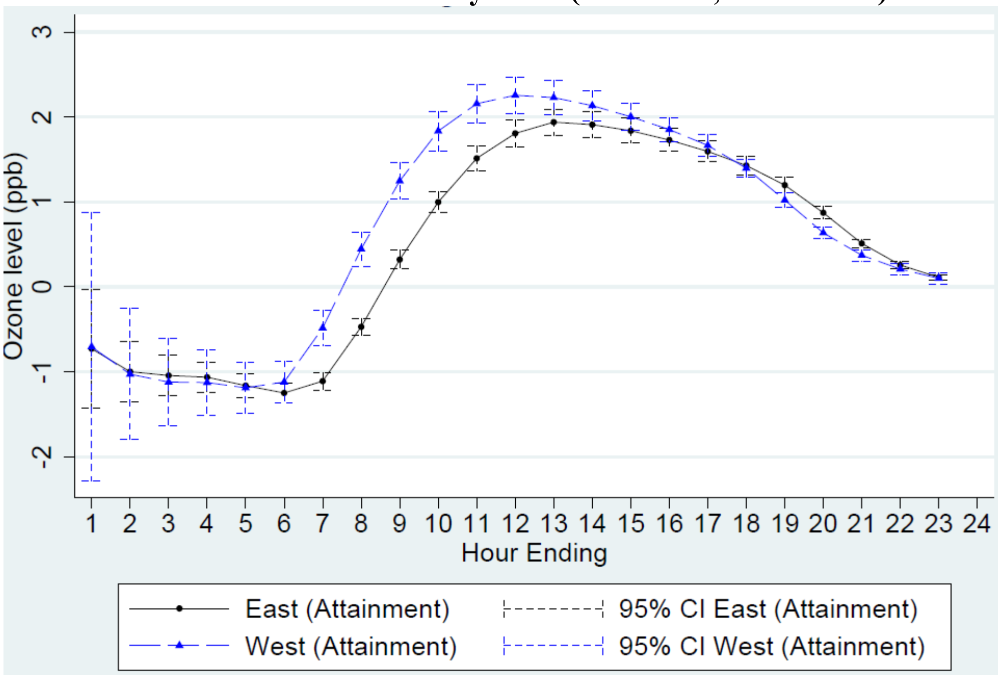
Panel B: NO2 by Hour with 95% CI (1980-2017)



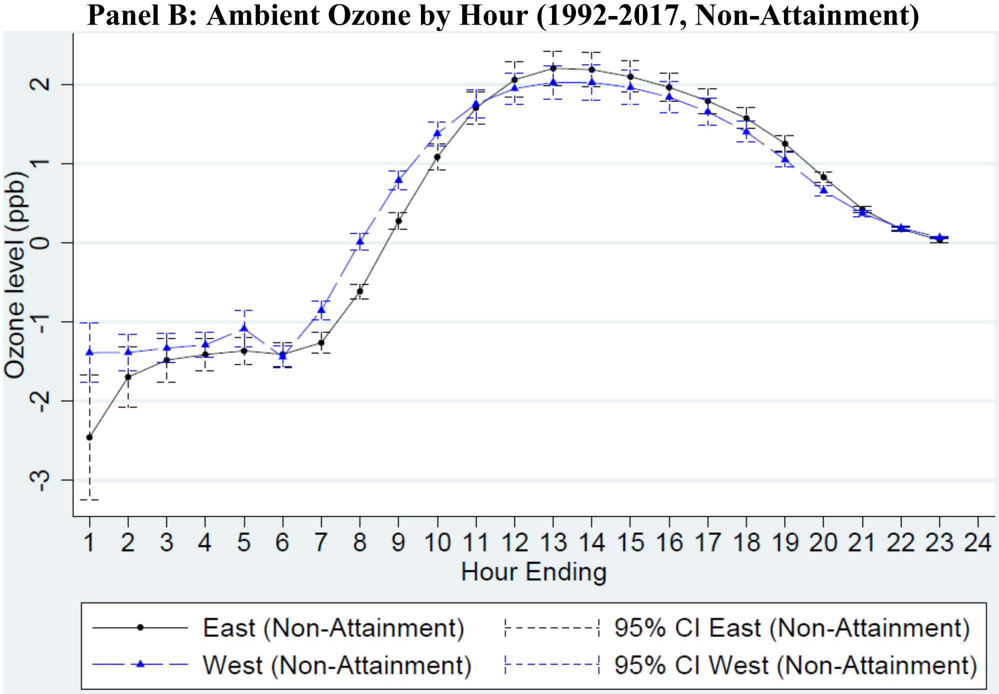
Notes: Plot is of the β's for *East* and *West* by hour. Omitted category is hour ending 24. Standard errors clustered by monitor. Panel A: Results of estimation of Equation (1) for the period 1993-2017, where the dependent variable is particulate matter. Data on both PM10 and PM2.5 are included, with a dummy variable for PM2.5. Includes counties within 75 miles of a U.S. time zone border. Panel B*:* Results of estimation of Equation (1) for the period 1980-2017, where the dependent variable is nitrogen dioxide. Includes counties within 50 miles of a U.S. time zone border.

Figure 9 - Ambient Ozone by Hour and Attainment Status

Panel A: Ambient Ozone by Hour (1992-2017, Attainment)



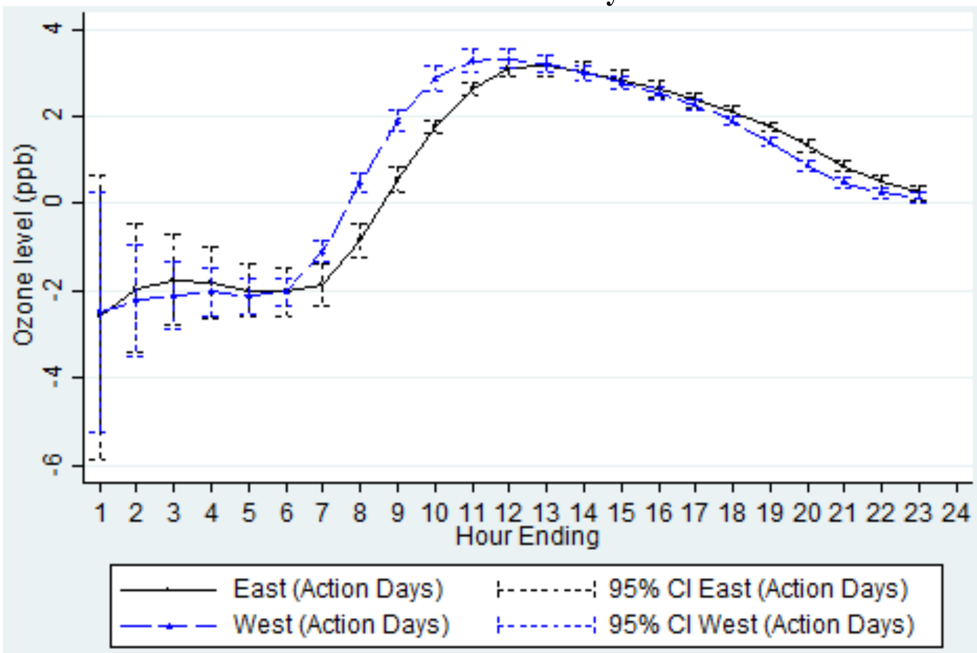
Panel B: Ambient Ozone by Hour (1992-2017, Non-Attainment)



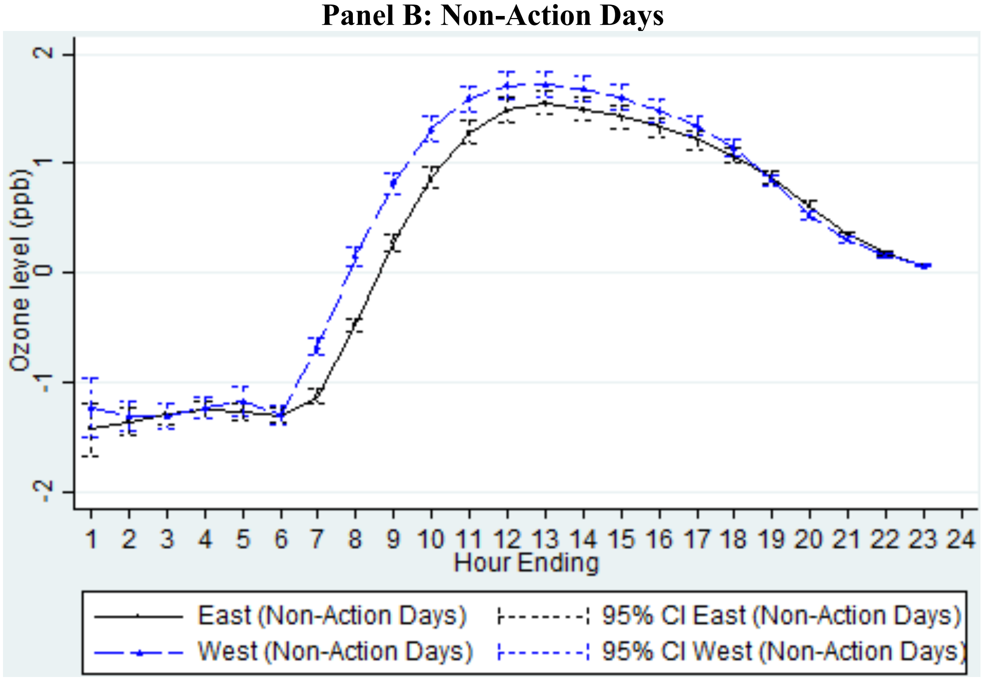
Notes: Results of estimation of Equation (2) for the period 1980-2017. Includes counties (A) in or (B) out of attainment within 100 miles of a U.S. time zone border. Plot is of the β's for *East* and *West* by hour. The omitted category is hour ending 24. Standard errors clustered by monitor.

Figure 10 – Ambient Ozone by Hour (2004-2017, Action Days)

Panel A: Action Days



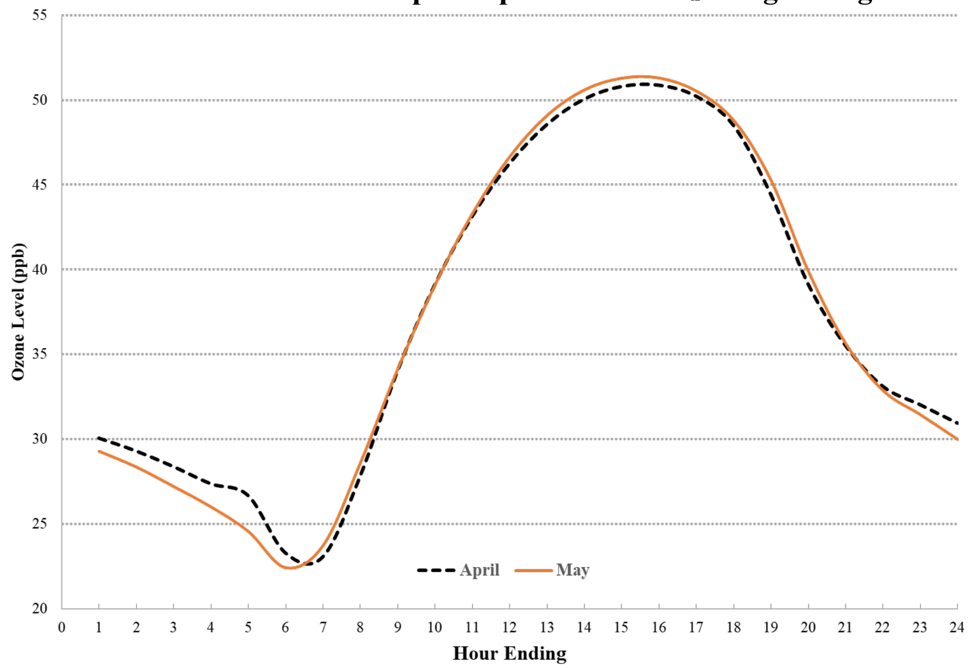
Panel B: Non-Action Days



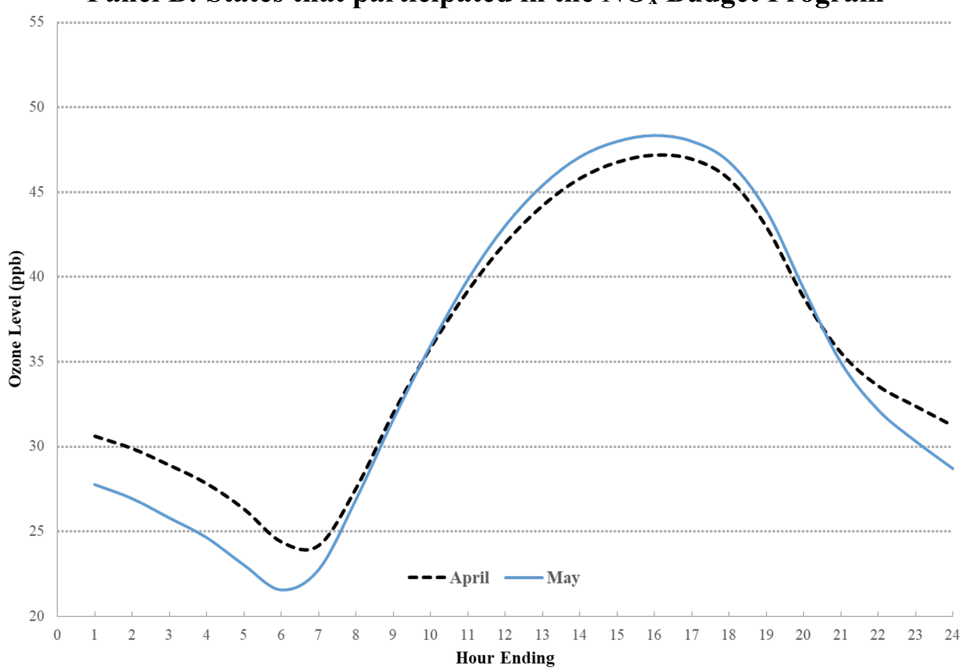
Notes: Results of estimation of a modified version of Equation (2) as described in Section 3.3.2 for the period 2004-2017. Includes counties within 100 miles of a U.S. time zone border that called an action day alert, limited to reporting areas confirmed as participating on EPA's AirNow website. Plot is of the β's for *East* and *West* by hour. The omitted category is hour ending 24. Standard errors clustered by monitor.

Figure 11 – Average Hourly Ozone (April 2003 – May 2008)

Panel A: States that did not participate in the NO_x Budget Program

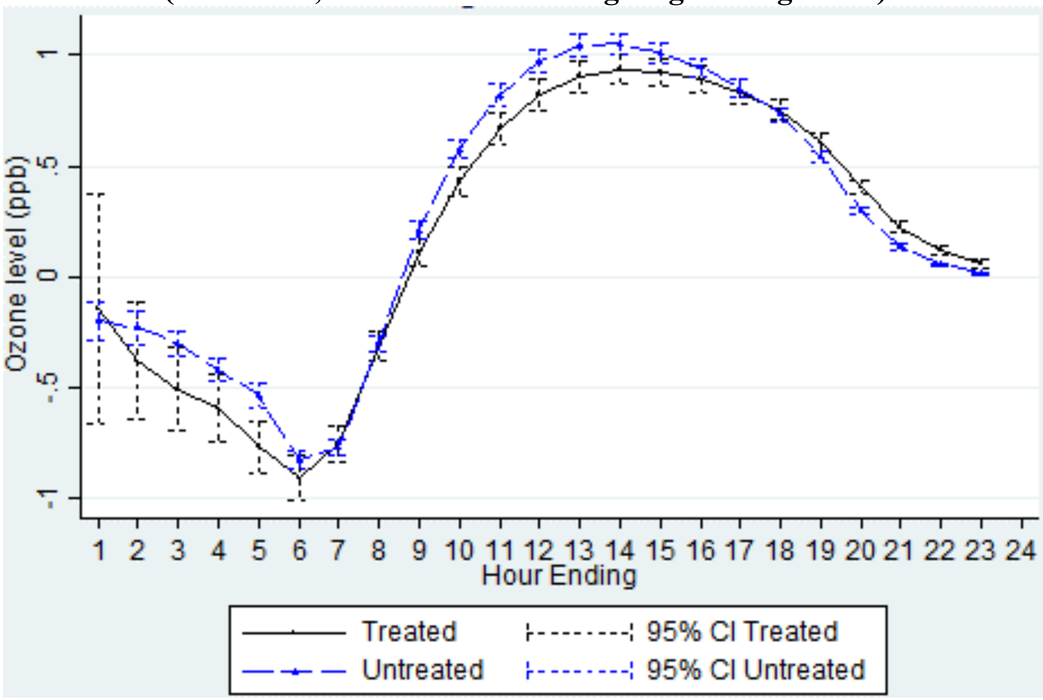


Panel B: States that participated in the NO_x Budget Program



Notes: Average hourly ozone from EPA's AirData database. Hourly ozone levels averaged across all states that did not participate (Panel A) or participated (Panel B) in the NO_x Budget Program, based on our sample of counties with ozone monitor data matched to contemporaneous hourly temperature.

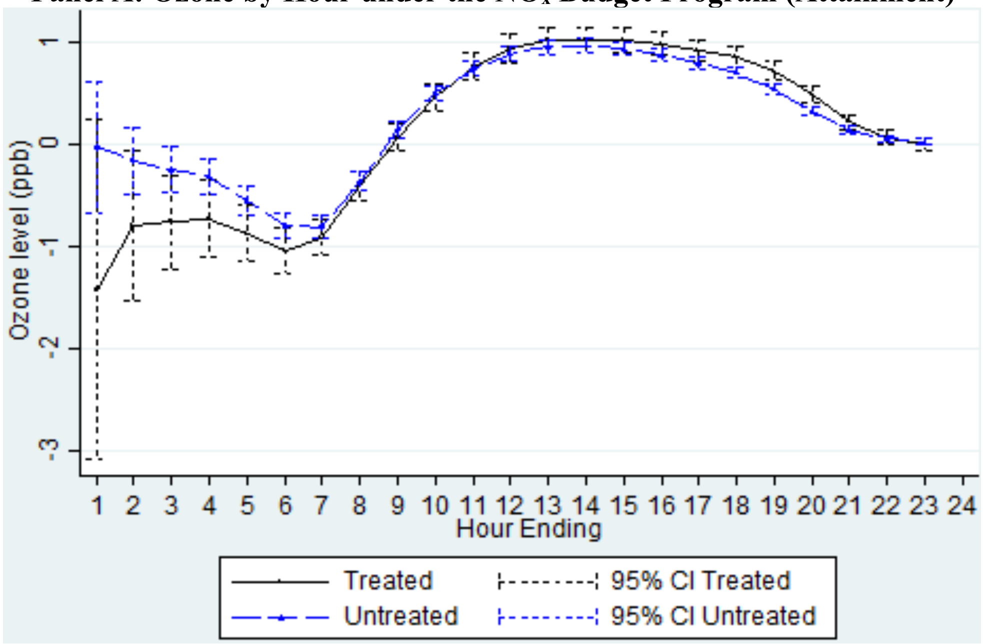
Figure 12 – Ozone by Hour under the NO_x Budget Program (1980-2008; NBP states excluding neighboring states)



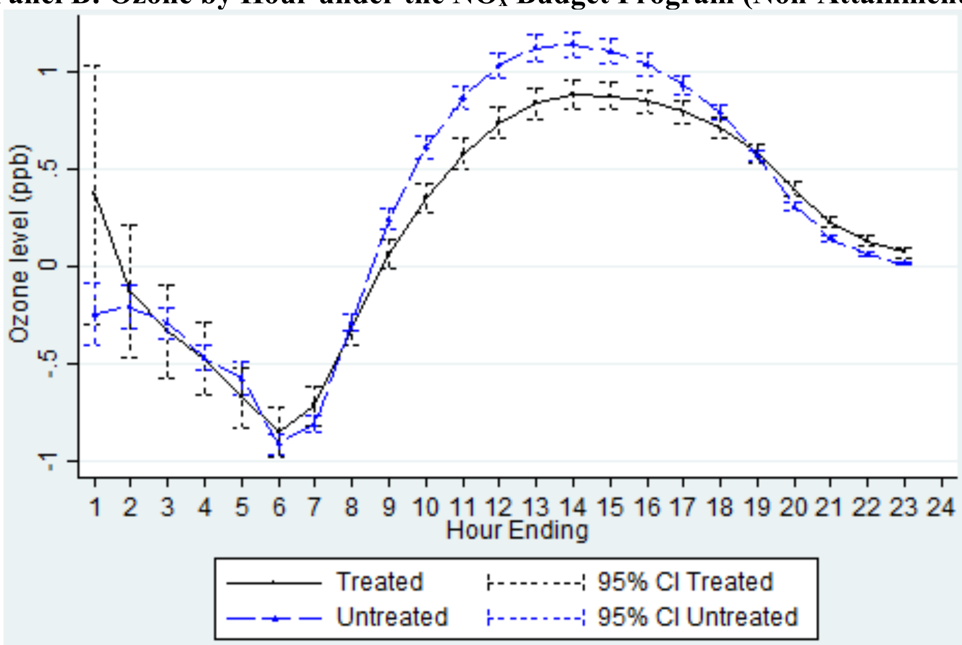
Notes: Estimation of Equation (3), our triple difference equation analyzing the NO_x Budget Program. "Treated" refers to states participating in the NO_x Budget Program during the period when the program was active (May 2003 – May 2008); "Untreated" refers to all other observations. Following Deschenes, Greenstone, and Shapiro (2017), neighboring states to those states participating in the Program are excluded. Standard errors clustered by monitor.

Figure 13 – Ozone by Hour and Attainment Status under the NO_x Budget Program (1980-2008; excluding neighboring states)

Panel A: Ozone by Hour under the NO_x Budget Program (Attainment)



Panel B: Ozone by Hour under the NO_x Budget Program (Non-Attainment)



Notes: Estimation of Equation (4). "Treated" refers to states participating in the NO_x Budget Program during the period when the program was active (May 2003 – May 2008); "Untreated" refers to all other observations. Following Deschenes, Greenstone, and Shapiro (2017), neighboring states to those states participating in the Program are excluded. Standard errors clustered by monitor.

2. Tables

Table 1 – Summary Statistics by Decade (Central Time Zone, 1980-2017)

Summary Statistics - Central Timezone				
	Concentration		# of Monitors	
Year	*East*	*West*	*East*	*West*
	Ozone (ppb)			
1980-1989	31.28	33.96	24	35
1990-1999	32.55	33.00	39	56
2000-2009	30.69	32.69	60	64
2010-2017	28.36	32.13	62	53
	NO2 (ppb)			
1980-1989	11.69	18.94	5	14
1990-1999	9.47	19.19	9	16
2000-2009	7.57	14.31	11	16
2010-2017	4.59	9.95	7	11
	VOC (ppb C)			
1990-1999	5.55	3.57	160	189
2000-2009	2.73	2.90	205	227
2010-2017	2.52	2.52	164	55
	PM_{10} (μg/m3)			
1990-1999	29.35	33.78	3	3
2000-2009	25.62	27.98	13	5
2010-2017	21.96	26.02	13	5
	$PM_{2.5}$ (μg/m3)			
2000-2009	12.97	13.21	2	1
2010-2017	11.48	10.09	17	7

Notes: Average pollutant concentration within 50 miles (Ozone, NO2) and 75 miles (VOC, PM10, PM2.5) of the Central time zone border and average number of monitors by pollutant. Data from EPA's AirData database, restricted to valid ozone monitor-years based on Auffhammer and Kellogg (2011). Monitor definition from EPA's Air Quality System of a) site (state, county, site number), b) pollutant code and c) parameter occurrence code (see: https://aqs.epa.gov/aqsweb/airdata/FileFormats.html). Large monitor counts for VOC driven by separate observations for each organic compound.

Table 2 – Demographic Shares of Workers within 50 miles of a U.S. Time Zone Border

	West	East	Difference
Male	0.537	0.519	0.0309
	(0.00227)	(0.00625)	(0.0846)
White	0.798	0.830	-0.0523
	(0.00089)	(0.00292)	(0.0772)
Black	0.099	0.124	0.0668
	(0.00218)	(0.00117)	(0.0569)
Other	0.103	0.046	-0.0145
	(0.00307)	(0.00175)	(0.0412)
Under 18	0.031	0.022	-0.0328
	(0.00078)	(0.00124)	(0.0265)
18 to 35	0.332	0.349	-0.0607
	(0.00862)	(0.00685)	(0.0540)
45 to 65	0.390	0.377	0.0591
	(0.00157)	(0.00212)	(0.0646)
Over 65	0.045	0.044	0.0217
	(0.00082)	(0.00056)	(0.0334)
Married	0.518	0.525	0.0402
	(0.01378)	(0.01282)	(0.0653)
Single	0.302	0.315	-0.0417
	(0.01011)	(0.00253)	(0.0720)
Divorced or Separated	0.153	0.143	0.00515
	(0.00433)	(0.00819)	(0.0368)
Widowed	0.028	0.017	-0.00373
	(0.00066)	(0.00211)	(0.00850)
Own Home	0.694	0.730	0.0523
	(0.02173)	(0.00717)	(0.0503)
Rent Home	0.288	0.262	-0.0601
	(0.02283)	(0.00676)	(0.0518)
Weekly earnings < $400	0.318	0.365	-0.0747
	(0.00592)	(0.00677)	(0.0583)
Weekly earnings $400-$750	0.283	0.307	0.0522
	(0.00845)	(0.00036)	(0.0574)
Weekly earnings $750-$1,000	0.142	0.105	-0.0189
	(0.00003)	(0.00342)	(0.0494)
Weekly earnings > $1,000	0.257	0.223	-1.305e+08
	(0.01434)	(0.00298)	(9.843e+07)
High School	0.310	0.282	-0.0112
	(0.00282)	(0.00272)	(0.0726)
Some College	0.212	0.165	-0.0432
	(0.00189)	(0.00325)	(0.0384)
Associate	0.092	0.111	-0.00163
	(0.00028)	(0.00435)	(0.0356)
Bachelors	0.198	0.204	0.0115
	(0.00444)	(0.00735)	(0.0541)
Grad School	0.077	0.117	0.0676
	(0.00013)	(0.00016)	(0.0512)

Notes: Average shares for workers in all counties within 50 miles of a U.S. time zone border from the 2003-2017 American Time Use Survey. Differences based on a series of regressions of each variable against an indicator for being on the Eastern side of the border. Workers defined as "employed-at work". Standard errors in parentheses. ***, **, * indicate significance at 1%, 5%, and 10%.

Online Appendix

A. Analyses of Ozone by Hour Across Time Zone Borders

A.1. Meteorological Controls

In the paper, we restrict observations to a tight window around a time zone border for our analysis of the impact of shifting activity on hourly ozone concentrations. We argue that that due to the narrow distance around a time zone border we use, counties on either side of the border face the same meteorological conditions.

Since ozone formation is driven in part by temperature, if one side of the border was persistently warmer/cooler than the other side, we could be confounding our estimates of the effect of shifting economic activity with underlying differences between eastern and western counties. Further, concentrations of ozone may not stay where they are formed, but could instead be transported across the time zone borders by wind. It is therefore important to test whether these meteorological factors have a significant effect on our results by including them in our regression analysis.

Specifically, we utilize monitor-level data on hourly temperature, wind speed, and wind direction from EPA's AirData Database. For each hour and county, we calculate the average level for each variable and interact with *east* and *west* in our regression specifications. Note that in all of the results utilizing the matched ozone monitor and meteorological data in this subsection, our subsample is just under half the size of our main dataset.

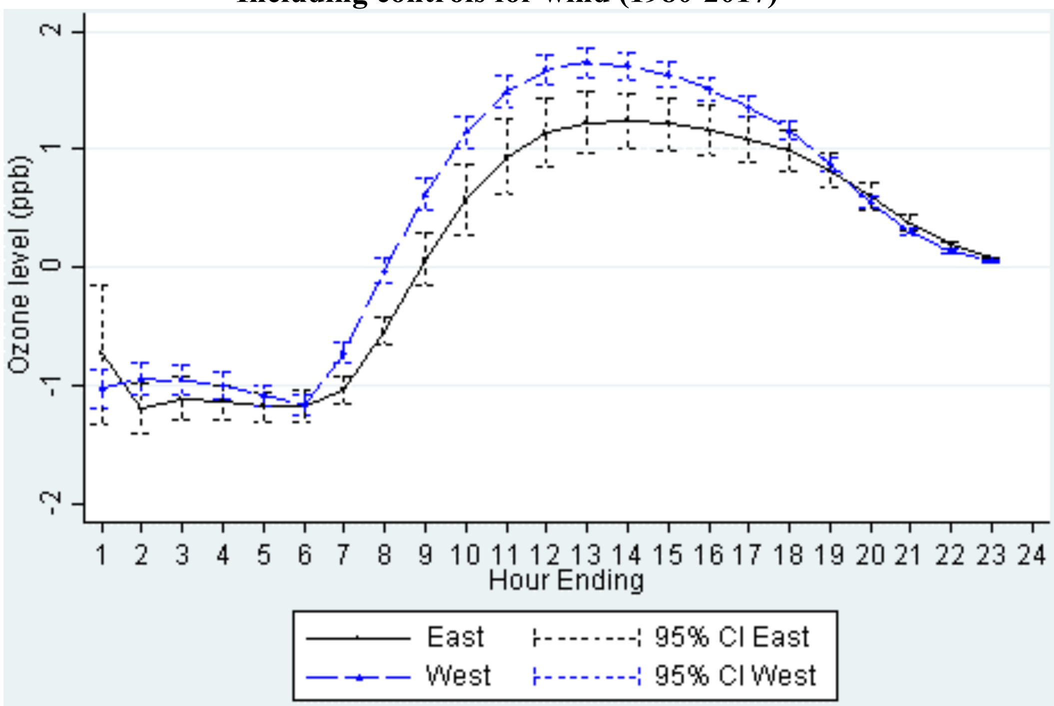
A.1.1. Wind

We extend Equation (1) to include our wind data:

$$\begin{aligned} P_{it} = {} & \beta_0 + \beta_1^E East_{i1} + \beta_1^W west_{i1} + \ldots + \beta_{23}^E East_{i23} + \beta_{23}^W West_{i23} \\ & + \gamma_1 East_i * winspeed_{ct} + \gamma_2 West_i * winspeed_{ct} + \gamma_3 East_i * windir_{ct} \\ & + \gamma_4 West_i * windir_{ct} + \eta_i + \delta_{dmy} + \epsilon_{ict} \end{aligned} \quad \text{(A1)}$$

where the variables are defined as before. The new terms are seen next to the coefficients for γ_1 through γ_4, and are the interaction between being on the eastern (western) side of a time zone border and wind speed and wind direction, respectively. Results from this estimation on our subsample can be seen in Figure A1. The results are qualitatively similar for HE6 – HE9; we see a persistent gap between ozone levels on the eastern and western sides of the border. However, in this case we actually see this gap persist into the early afternoon hours.

Figure A1 - Ground Level Ozone by Hour with 95% CI
Including controls for wind (1980-2017)



Notes: Results of estimation of Equation (A1) for the period 1980-2017. Includes counties within 50 miles of a U.S. time zone border. Plot is of the β's for *East* and *West* by hour. Omitted category is hour ending 24. Standard errors clustered by monitor.

A.1.2. Temperature

A potential concern is that by omitting temperature in our main specification, there could be underlying climatic differences between counties on either side of a time zone border. Thus, what we attribute to shifting economic activity could instead be attributed to variation in temperature. To alleviate this concern, we extend Equation (1) to include data on hourly temperature:

$$P_{it} = \beta_0 + \beta_1^E East_{i1} + \beta_1^W west_{i1} + \cdots + \beta_{23}^E East_{i23} + \beta_{23}^W West_{i23}$$
$$+\gamma_1 East_i * temp_{ct} + \gamma_2 West_i * temp_{ct} + \eta_i + \delta_{dmy} + \epsilon_{ict} \quad \text{(A2)}$$

where the variables are defined as before. The new terms, seen next to the coefficients for γ_1 and γ_2, are the interaction between being on the eastern side of a time zone border and contemporaneous hourly temperature.

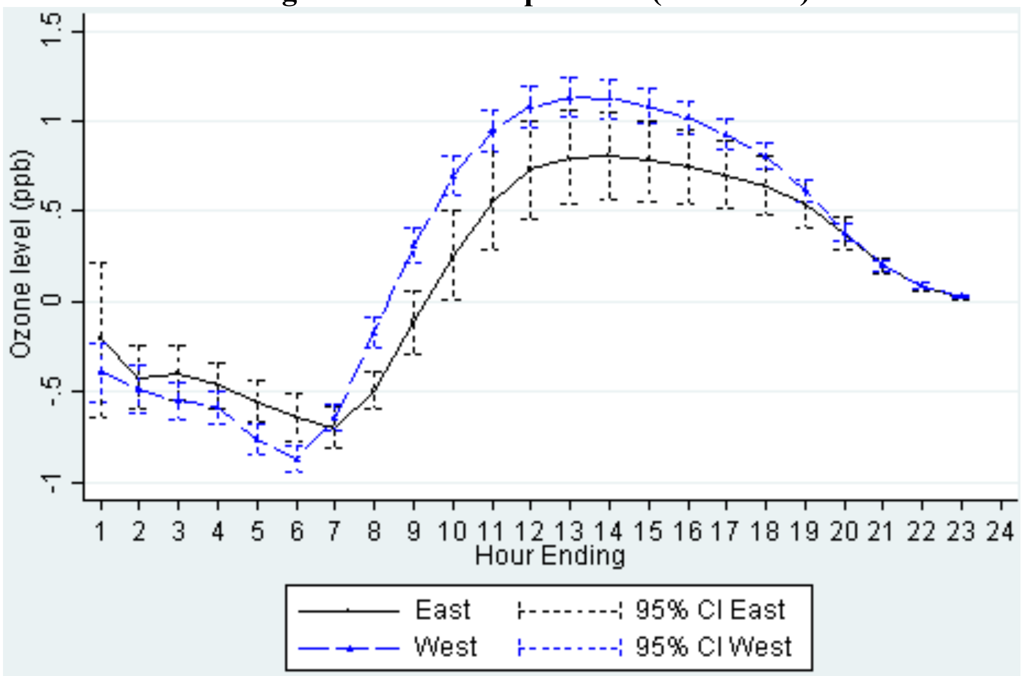
We estimate Equation (A2) on our matched subsample of counties with valid ozone monitor-years and contemporaneous hourly temperature data, and present the results in Figure A2. Reassuringly, the plot is quite similar to what is shown in Figure 7 in the main paper. Ozone levels are similar on either side of the border in the middle of the night, before becoming significantly higher for counties on the west from HE8 – HE10 when sunlight is more intense on that side of the border. The levels are not distinguishable between counties on either side during the peak afternoon hours, and this continues into the evening.

Finally, since the relationship between ozone and temperature may be nonlinear, we include a flexible polynomial form for temperature as in Equation (A3):

$$\begin{aligned} P_{it} = {} & \beta_0 + \beta_1^E East_{i1} + \beta_1^W west_{i1} + \ldots + \beta_{23}^E East_{i23} + \beta_{23}^W West_{i23} \\ & + \gamma_1 East_{ic} * temp_{ct} + \gamma_2 West_{ic} * temp_{ct} + \gamma_3 East_i * temp_{ct}^2 \\ & + \gamma_4 West_{ic} * temp_{ct}^2 + \gamma_5 East_i * temp_{ct}^3 + \gamma_6 West_i * temp_{ct}^3 \\ & + \eta_i + \delta_{dmy} + \epsilon_{ict} \end{aligned} \tag{A3}$$

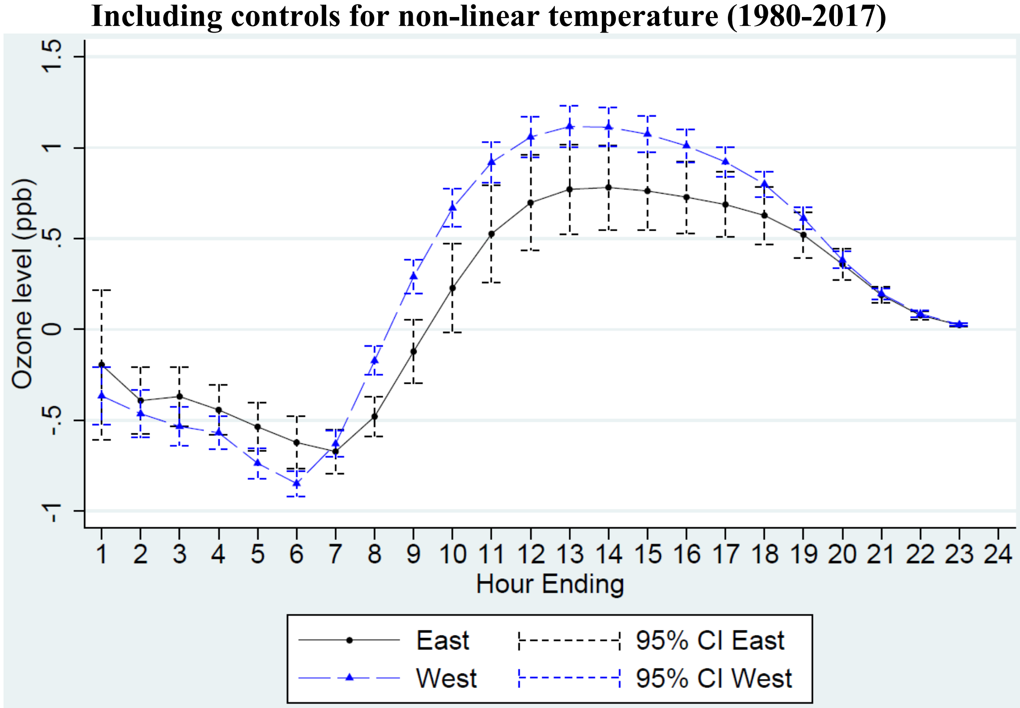
The results are plotted in Figure A3 and are virtually identical to those seen in Figure A2. In short, while there are slight differences when including temperature, the results are qualitatively similar. We choose to present the results with the largest sample of ozone monitors in the main paper, as temperature variation between counties on either side of the border is likely to be minimal given our tight radius. The results in these figures illustrate that this assumption is reasonable.

Figure A2 - Ground Level Ozone by Hour with 95% CI
Including controls for temperature (1980-2017)



Notes: Results of estimation of Equation (A2) for the period 1980-2017. Includes counties within 50 miles of a U.S. time zone border. Plot is of the β's for *East* and *West* by hour. Omitted category is hour ending 24. Standard errors clustered by monitor.

Figure A3 - Ground Level Ozone by Hour with 95% CI
Including controls for non-linear temperature (1980-2017)



Notes: Results of estimation of Equation (A3) for the period 1980-2017. Includes counties within 50 miles of a U.S. time zone border. Plot is of the β's for *East* and *West* by hour. Omitted category is hour ending 24. Standard errors clustered by monitor.

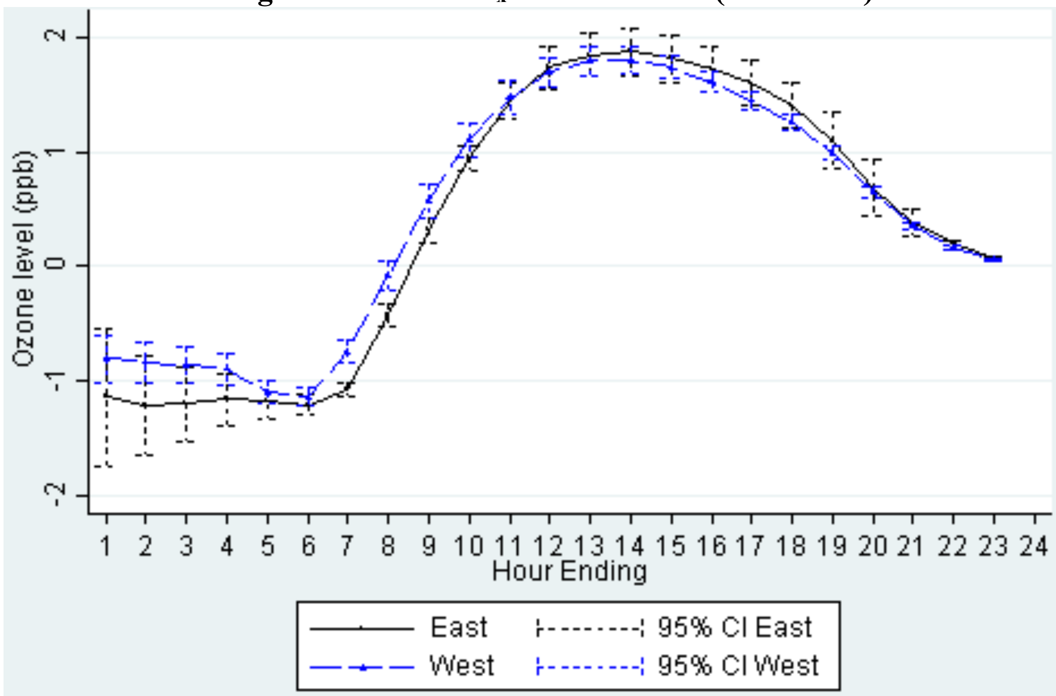
A.2. NO_x/VOC-Limited Status

First, we take daily measures of both ambient NO_x and VOC from EPA's AirData database for 1980-2017. For each county-day, we calculate the ratio of VOCs to NO_x and classify a day as either 1) NO_x -Limited, 2) VOC-Limited, or 3) Neutral.[28] Counties are identified as being NO_x - or VOC-limited in a year based on which category has the largest tally of days in a given year. Since these statuses are fairly stable year-to-year, we fill in missing years as NO_x -Limited, VOC-Limited, or Neutral by the total count of days in each category across a 5-year period.

We estimate a modified version of Equation (1) as in in Section A.1.1 above, where we replace the terms for wind speed and direction with controls for counties that are NO_x - or VOC-limited. Results from this estimation can be seen in Figure A4. The results are qualitatively similar to the main results in the paper; we see a significant gap between ozone levels on the eastern and western sides of the border in the morning hours (HE7-HE8). Moving into the afternoon, the ozone concentration on the west dips slightly below the levels on the east as would be expected, but this difference is not statistically significant.

[28] Following NRC (1991), days with a ratio of VOCs to NO_x of 4 or below are identified as VOC-Limited and 15 or above as NO_x -Limited; the remainder are Neutral.

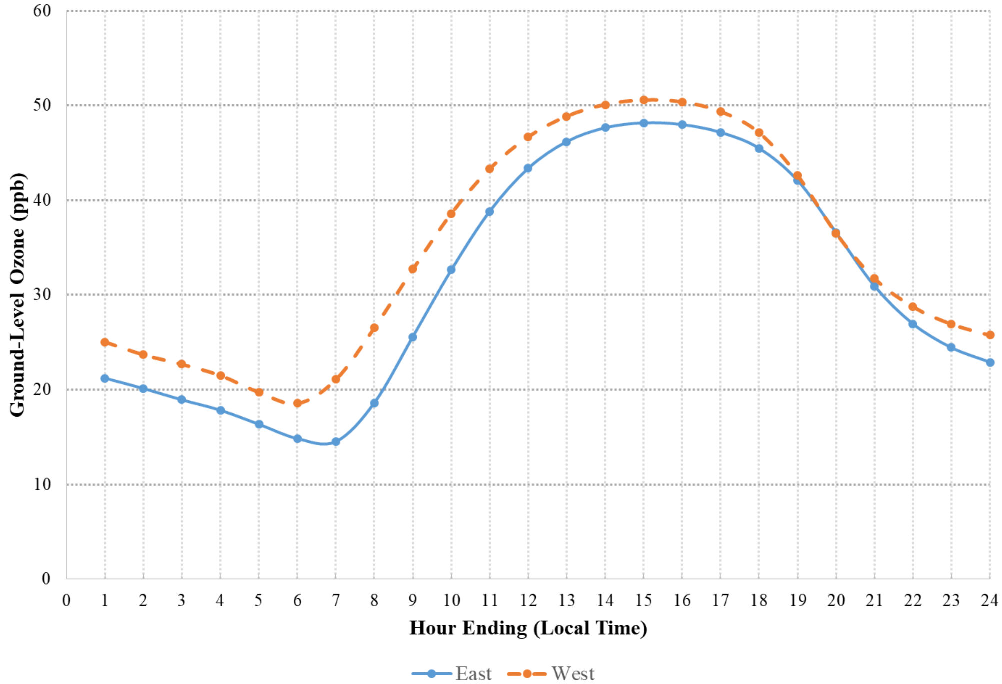
Figure A4 - Ground Level Ozone by Hour with 95% CI
Including controls for NO_x/VOC-Limited (1980-2017)



Notes: Results of estimation of modified Equation (A1) for the period 1980-2017. Includes counties within 50 miles of a U.S. time zone border. Plot is of the β's for *East* and *West* by hour. The omitted category is hour ending 24. Standard errors clustered by monitor.

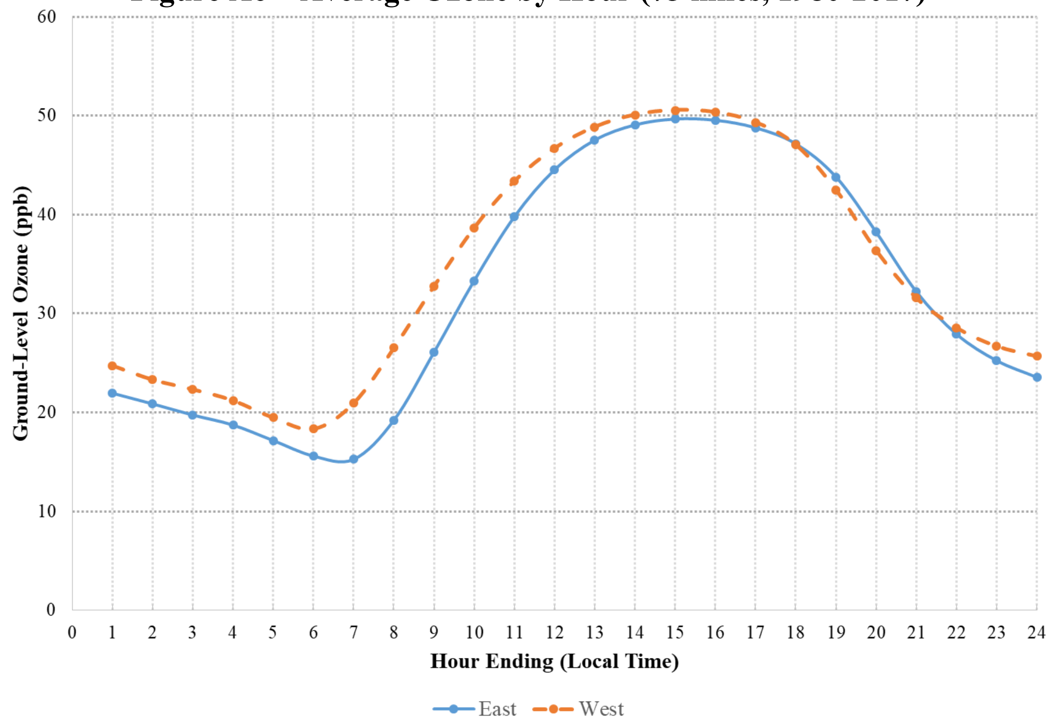
A.3. Figures and Tables by Hour – Time Zone Borders

Figure A5 – Average Ozone by Hour (50 miles, 1980-2017)



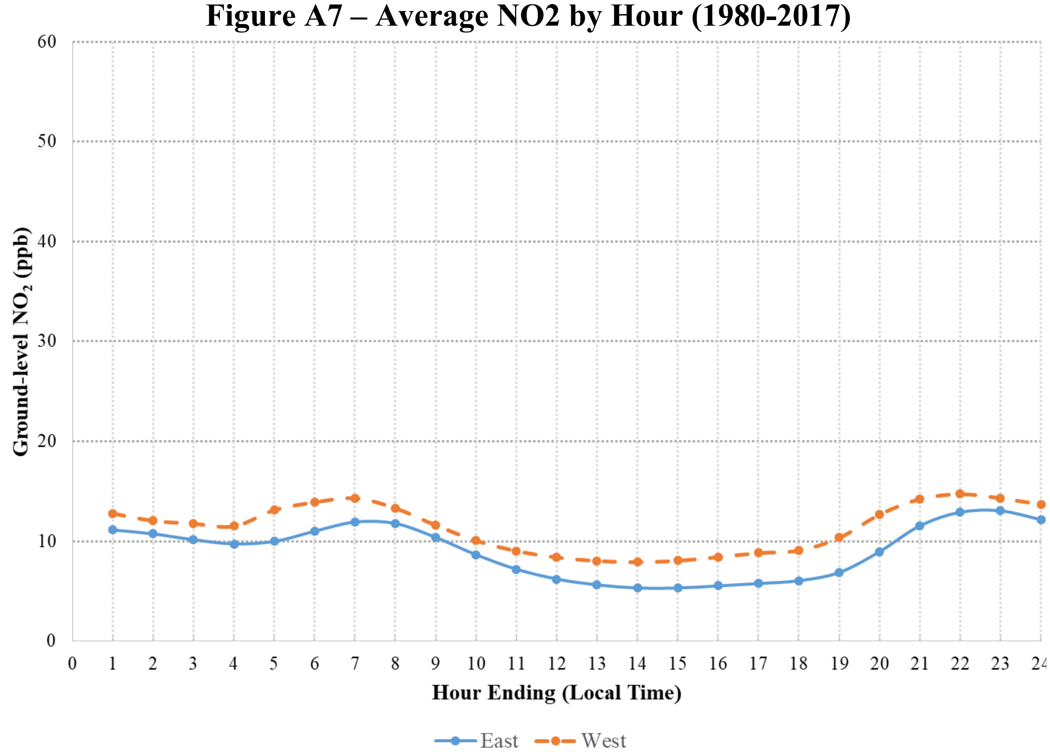
Notes: Average hourly ozone across all counties within 50 miles of a U.S. time zone border. Data from EPA's AirData database, restricted to valid monitor-years. Valid monitor-years are defined as having: 1) at least 9 hours reported between 9AM and 9PM and 2) at least 75% of hours June 1 - August 31 report an observation.

Figure A6 – Average Ozone by Hour (75 miles, 1980-2017)



Notes: Average hourly ozone across all counties within 75 miles of a U.S. time zone border. Data from EPA's AirData database, restricted to valid monitor-years.

Figure A7 – Average NO2 by Hour (1980-2017)



Notes: Average hourly NO2 across all counties within 75 miles of a U.S. time zone border. Data from EPA's AirData database, restricted to valid monitor-years.

Table A1 – Hourly Differences between West and East (1980-2017, Summer)

Hour Ending	West - East
1	0.694***
	(0.191)
2	0.340**
	(0.109)
3	0.272**
	(0.0847)
4	0.201**
	(0.0707)
5	0.0980
	(0.0643)
6	0.146*
	(0.0602)
7	0.534***
	(0.0546)
8	0.641***
	(0.0572)
9	0.485***
	(0.0715)
10	0.315***
	(0.0844)
11	0.149
	(0.0914)
12	0.0391
	(0.0938)
13	-0.0141
	(0.0923)
14	-0.0292
	(0.0882)
15	-0.0294
	(0.0826)
16	-0.0292
	(0.0767)
17	-0.0385
	(0.0704)
18	-0.0673
	(0.0623)
19	-0.122*
	(0.0515)
20	-0.146***
	(0.0374)
21	-0.0955***
	(0.0215)
22	-0.0473***
	(0.0111)
23	-0.0159*
	(0.00624)

Note: Difference in estimated hourly coefficients for east and west from Equation (1).

A.4. Travel Time and Occupations Across Time Zone Borders

Table A2 – Average Times Arriving and Departing for Work (50 miles)

	Time Departing Home for Work		*Time Arriving to Work*			*Travel Time to Work*	
	% of Total		*% of Total*			*% of Total*	
	East	West	East	West		East	West
Before 5 am	4.4%	5.1%	3.5%	3.6%	<5 mins	2.9%	2.6%
5 - 5:29am	3.6%	4.4%	2.2%	2.4%	5 - 9 mins	9.9%	8.9%
5:30 - 5:59am	4.7%	5.2%	4.2%	4.7%	10 - 14 mins	14.4%	12.7%
6 - 6:29am	8.5%	9.6%	5.7%	6.2%	15 - 19 mins	16.7%	13.9%
6:30 - 6:59am	9.9%	9.9%	9.6%	9.9%	20 - 24 mins	15.8%	13.5%
7 - 7:29am	15.1%	14.6%	12.1%	11.5%	25 - 29 mins	6.6%	6.0%
7:30 - 7:59am	13.0%	11.3%	15.3%	13.9%	30 - 34 mins	13.4%	14.4%
8 - 8:29am	10.7%	10.3%	12.3%	11.8%	35 - 39 mins	2.9%	3.2%
8:30 - 8:59am	5.1%	4.7%	7.5%	8.1%	40 - 44 mins	3.4%	4.6%
9 - 9:59am	6.1%	5.5%	7.7%	7.8%	45 - 59 mins	7.5%	9.7%
10 - 10:59am	2.8%	2.7%	3.3%	3.2%	60 - 89 mins	4.6%	7.8%
11 - 11:59am	1.3%	1.4%	1.5%	1.6%	>90 mins	2.0%	2.7%
Noon - 4pm	7.0%	8.1%	6.9%	7.7%			
After 4 pm	7.9%	7.4%	8.2%	7.7%			

Notes: From ACS 2012-2016 data, downloaded from American Fact Finder at the county-level. Restricted to counties within 50 miles of the Central time zone border.

Table A3 – Average Times Arriving and Departing for Work (200 miles)

	Time Departing Home for Work		*Time Arriving to Work*			*Travel Time to Work*	
	% of Total		*% of Total*			*% of Total*	
	East	West	East	West		East	West
Before 5 am	4.2%	5.0%	3.2%	3.6%	<5 mins	2.8%	3.2%
5 - 5:29am	3.5%	4.3%	2.0%	2.4%	5 - 9 mins	9.7%	10.5%
5:30 - 5:59am	4.5%	5.6%	4.0%	5.0%	10 - 14 mins	14.1%	14.1%
6 - 6:29am	8.5%	9.6%	5.6%	6.5%	15 - 19 mins	16.2%	15.3%
6:30 - 6:59am	9.8%	10.8%	9.6%	10.7%	20 - 24 mins	15.7%	14.4%
7 - 7:29am	14.8%	14.9%	11.8%	12.3%	25 - 29 mins	6.8%	6.5%
7:30 - 7:59am	12.8%	12.3%	15.0%	15.0%	30 - 34 mins	13.7%	13.3%
8 - 8:29am	10.9%	9.3%	12.4%	11.3%	35 - 39 mins	3.1%	3.1%
8:30 - 8:59am	5.3%	4.3%	7.8%	6.8%	40 - 44 mins	3.6%	3.9%
9 - 9:59am	6.1%	5.0%	8.0%	6.7%	45 - 59 mins	7.6%	8.1%
10 - 10:59am	2.9%	2.5%	3.4%	2.9%	60 - 89 mins	4.6%	5.6%
11 - 11:59am	1.3%	1.2%	1.5%	1.4%	>90 mins	2.0%	2.2%
Noon - 4pm	7.5%	7.8%	7.3%	7.6%			
After 4 pm	8.0%	7.4%	8.3%	7.7%			

Notes: From ACS 2012-2016 data, downloaded from American Fact Finder at the county-level. Restricted to counties within 200 miles of the Central time zone border.

Table A4 – Regressions of the Share of Workers by Occupation within 50 Miles of a U.S. Time Zone Border against being on the East

	(1)	(2)	(3)	(4)	(5)
Manufacturing and Production					
East	0.0767	0.0861	0.0633	0.0793	0.0471
	(0.0693)	(0.0656)	(0.0661)	(0.0736)	(0.0683)
Constant	0.299***	0.445***	0.0273	0.295	-0.259
	(0.0610)	(0.0898)	(0.293)	(0.261)	(0.338)
Service					
East	-0.0773	-0.0685*	-0.0546	-0.0475	-0.0340
	(0.0460)	(0.0400)	(0.0410)	(0.0441)	(0.0437)
Constant	0.240***	0.376***	0.486**	0.165	0.430*
	(0.0404)	(0.0548)	(0.182)	(0.156)	(0.216)
Sales and Office					
East	-0.0517	-0.0519	-0.0423	-0.0782	-0.0614
	(0.0517)	(0.0527)	(0.0518)	(0.0584)	(0.0532)
Constant	0.255***	0.253***	-0.0675	0.340	0.278
	(0.0455)	(0.0722)	(0.229)	(0.207)	(0.263)
Farming, Fishing, and Forestry					
East	-0.0102*	-0.0101*	-0.00897	-0.0109	-0.00952
	(0.00548)	(0.00558)	(0.00585)	(0.00646)	(0.00657)
Constant	0.0112**	0.0126	0.0329	0.00847	0.0418
	(0.00482)	(0.00765)	(0.0259)	(0.0229)	(0.0325)
Construction and Maintenance					
East	-0.0139	-0.0149	0.00364	-0.00148	0.00780
	(0.0352)	(0.0358)	(0.0343)	(0.0374)	(0.0382)
Constant	0.0951***	0.0791	0.109	-0.120	-0.0288
	(0.0310)	(0.0490)	(0.152)	(0.133)	(0.189)
Production and Transportation of Materials					
East	0.0764	0.0594	0.0390	0.0587	0.0500
	(0.0721)	(0.0561)	(0.0429)	(0.0523)	(0.0455)
Constant	0.0998	-0.165**	0.412**	0.312	0.538**
	(0.0635)	(0.0768)	(0.190)	(0.185)	(0.225)
N	31	31	31	31	31
Male		Y	Y	Y	Y
White or Black			Y		Y
Age Dummies				Y	Y

Notes: Results from a series of regressions where the dependent variable is the share of workers by occupation category from the 2003-2017 American Time Use Survey within 50 miles of a U.S. time zone border against an indicator for being on the eastern side of the border. Demographic controls represent the share of the population by county. Age controls for under 18, 18-35, 45-65, and over 65. Workers defined as "employed-at work".

Table A5 – Average Time Leaving for Work within 50 Miles of a U.S. Time Zone Border

	East	West
Avg. Hour of Time Leaving for Work	7.9	8.1
	(0.0132)	(0.0452)
Avg. Minutes of Time Leaving for Work	23.7	21.2
	(0.2265)	(0.1977)
Avg. Time Leaving for Work	8:17 AM	8:24 AM
95% CI	(8:14 AM, 8:19 AM)	(8:18 AM, 8:30 AM)

Notes: Average hour and minute of departure time to work from the 2003-2017 American Time Use Survey within 50 miles of a U.S. time zone border for full-time workers that are "employed-at-work".

A.5. History of NAAQS

Table A6 – Historical Ambient Ozone NAAQS

Year	Final Rule	Indicator	Averaging Time	Level	Form
1971	36 FR 8186	Total photochemical oxidants	1 hour	80 ppb	Not to be exceeded more than one hour per year
1979	44 FR 8202	O_3	1 hour	120 ppb	Attainment is defined when the expected number of days per calendar year, with maximum hourly average concentration greater than 0.12 ppm, is equal to or less than 1
1997	62 FR 38856	O_3	8 hours	80 ppb	Annual fourth-highest daily maximum 8-hour average concentration, averaged over 3 years
2008	73 FR 16483	O_3	8 hours	75 ppb	Annual fourth-highest daily maximum 8-hour average concentration, averaged over 3 years
2015	80 FR 65292	O_3	8 hours	70 ppb	Annual fourth-highest daily maximum 8-hour average concentration, averaged over 3 years

Source: https://www.epa.gov/ozone-pollution/table-historical-ozone-national-ambient-air-quality-standards-naaqs. The 1997 standard was not put into place until 2004 due to lawsuits.

Table A7 – Historical Particulate Matter NAAQS

Year	Final Rule	Primary/Secondary	Indicator	Averaging Time	Level ($\mu g/m^3$)	Form
1971	36 FR 8186	Primary	TSP	24 hour	260	Not to be exceeded more than once per year
1971	36 FR 8186	Primary	TSP	Annual	75	Annual geometric mean
1971	36 FR 8186	Secondary	TSP	24 hour	150	Not to be exceeded more than once per year
1971	36 FR 8186	Secondary	TSP	Annual	60	Annual geometric mean
1987	52 FR 24634	Primary and secondary	PM_{10}	24 hour	150	Not to be exceeded more than once per year on average over a 3-year period
1987	52 FR 24634	Primary and secondary	PM_{10}	Annual	50	Annual arithmetic mean, averaged over 3 years
1997	62 FR 38652	Primary and secondary	$PM_{2.5}$	24 hour	65	98th percentile, averaged over 3 years
1997	62 FR 38652	Primary and secondary	$PM_{2.5}$	Annual	15	Annual arithmetic mean, averaged over 3 years
2006	71 FR 61144	Primary and secondary	$PM_{2.5}$	24 hour	35	98th percentile, averaged over 3 years
2006	71 FR 61144	Primary and secondary	$PM_{2.5}$	Annual	15	Annual arithmetic mean, averaged over 3 years
2006	71 FR 61144	Primary and secondary	PM_{10}	24 hour	150	Not to be exceeded more than once per year on average over a 3-year period
2012	78 FR 3085	Primary	$PM_{2.5}$	Annual	12	annual mean, averaged over 3 years
2012	78 FR 3085	Secondary	$PM_{2.5}$	Annual	15	annual mean, averaged over 3 years
2012	78 FR 3085	Primary and secondary	$PM_{2.5}$	24 hour	35	98th percentile, averaged over 3 years
2012	78 FR 3085	Primary and secondary	PM_{10}	24 hour	150	Not to be exceeded more than once per year on average over 3 years

Source: https://www.epa.gov/pm-pollution/table-historical-particulate-matter-pm-national-ambient-air-quality-standards-naaqs

Table A8 – Historical Nitrogen Dioxide NAAQS

Year	Final Rule	Primary/Secondary	Indicator	Averaging Time	Level	Form
1971	36 FR 8186	Primary and secondary	NO_2	Annual	53 ppb	Annual arithmetic average
2010	75 FR 6474	Primary	NO_2	1 hour	100 ppb	98th percentile, 1-hour daily maximum, averaged over 3 years
2010	75 FR 6474	Primary and secondary	NO_2	Annual	53 ppb	Prior standard retained without revision

Source: https://www.epa.gov/no2-pollution/table-historical-nitrogen-dioxide-national-ambient-air-quality-standards-naaqs

B. Analyses of Ozone by Hour from the NO_x Budget Program

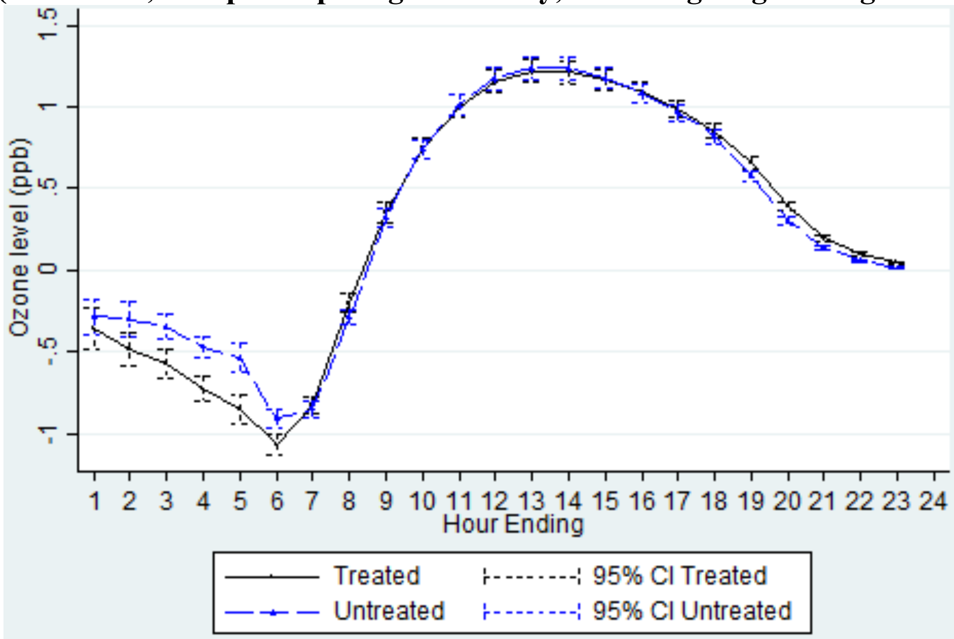
B.1. Non-Participants

In the main paper, when we first examine the NO_x Budget Program and its effect on hourly ozone concentrations by estimating Equation (3) we find some differences in the hourly ozone profile for treated vs. untreated states. However, in this estimating equation all states are included in the analysis, and therefore we are comparing states that participated in the Program to states that both did and did not participate in the Program. It is therefore conceivable that a portion of the change we find is attributable to changes in the hourly ozone profile of non-participating states between April and May that should be otherwise unaffected by the introduction of the NO_x Budget Program.

As a robustness check, we can thus re-estimate Equation (3) by limiting our sample to only states that did not participate in the NO_x Budget Program, where now *treat* is defined as equal to 1 if the NO_x Budget Program was in effect (May 2003 – May 2008), and zero otherwise.[29] The results are presented in Figure B1, and show the hourly shape we would expect without any significant differences between April and May for non-participating states. This suggests that non-participating states operated the same (in terms of productions and/or their use of emission control technology) across both months.

[29] Following Deschenes, Greenstone, and Shapiro (2017), we exclude neighboring states that could potentially be affected by the NO_x Budget Program.

Figure B1 – Ozone by Hour under the NO_x Budget Program
(1980-2008; non-participating states only, excluding neighboring states)

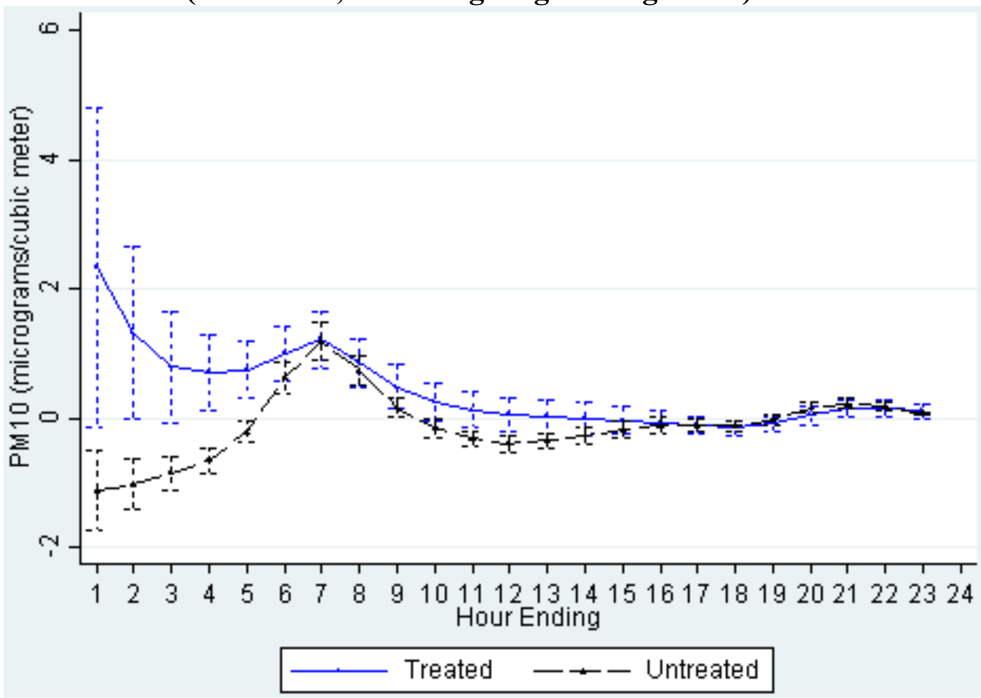


Notes: Results of estimation of Equation (3) for the period 1980-2008, limited to states that did not participate in the NOx Budget Program and were not neighboring participating states (following Deschenes, Greenstone, and Shapiro, 2017). Plot is of the β's for *Treat* and *Untreat* by hour. Omitted category is hour ending 24. Standard errors clustered by monitor.

B.2. Other Pollutants

As we did for our analysis across time zone borders in Figure 8, we can check for unobservable differences between our treatment and control groups by looking at pollutants without a known hourly shape. Thus, we estimate Equation (3) where our dependent variable is particulate matter; the results are shown in Figure B2. As can be seen in the Figure, aside from the first few hours in the middle of the night the trends in particulate matter are largely the same amongst both the treated and control groups. Additionally, both trends are centered on zero during the day, providing suggestive evidence that Equation (3) is well specified.

Figure B2 – Particulate Matter by Hour under the NOx Budget Program (1980-2008; excluding neighboring states)



Notes: Estimation of Equation (3), our triple difference equation analyzing the NO_x Budget Program, where PM_{10} is our dependent variable. "Treated" refers to states participating in the NO_x Budget Program during the period when the program was active (May 2003 – May 2008); "Untreated" refers to all other observations. Following Deschenes, Greenstone, and Shapiro (2017), neighboring states to those states participating in the Program are excluded. Standard errors clustered by monitor.

B.3. NO_x/VOC-Limited

We perform an additional robustness check to our estimation of the impact of the NO_x Budget Program on intraday emissions from Equation (3). This sensitivity allows for estimation of our treatment effect relative to a county's background levels of other pollutants. It is possible that the effect we measure may vary by whether a county is NO_x - or VOC-limited. Therefore, we estimate a modified version of Equation (3) where our hourly treatment and control β's are interacted with the county's NO_x-limited/VOC-limited status.

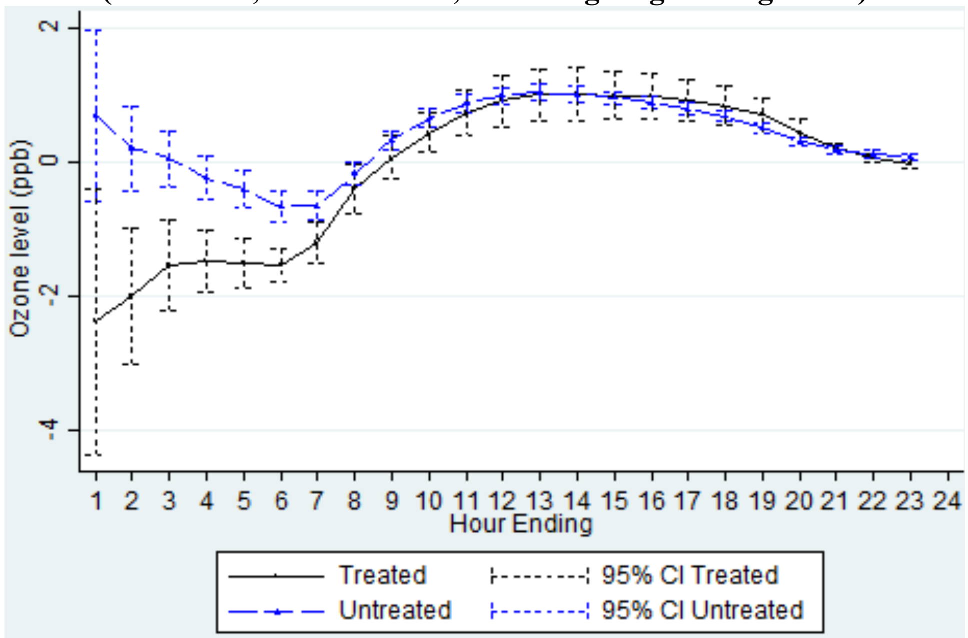
$$P_{ichdmy} = \beta_0 + \beta_1^{\tau} Treat_{icdmy} * \tau * Limited + \beta_2^{\tau} Control_{icdmy} * \tau * Limited + \beta_3 \, NBPyear_{iy} * NBPstate_{ic} + \beta_4 NBPmonth_{im} * NBPstate_{ic} + \gamma_1 temp_{hcdmy} + \eta_i + \delta_{dmy} + \epsilon_{ichdmy} \quad \text{(B1)}$$

where the variables are defined as in Equation (3), with the new term *Limited* representing a series of dummy variables for a county being 1) NO_x-Limited, 2) VOC-Limited, and 3) Neutral.[30]

Results are presented separately for each group – NO_x-Limited, VOC-Limited, and Neutral in Figure B3, Figure B4, and Figure B5, respectively. We observe some heterogeneity in the differences between treated and untreated hours across the three figures. Namely, we see no significant difference due to the Program in NO_x-Limited counties, while the small differences we observe in Figure 12 in the main paper appear to be driven by Neutral or VOC-Limited counties. NO_x-Limited counties are the counties with the highest marginal cost of NO_x emissions in terms of ozone formation, and thus NO_x emissions abatement in these counties provides the largest marginal benefit. Yet it these counties here where we find no significant difference in the change in hourly ambient ozone concentrations caused by the Program. In the areas where it mattered most, the NO_x Budget Program did not incentivize firms to shift their production away from the harmful peak ozone hours.

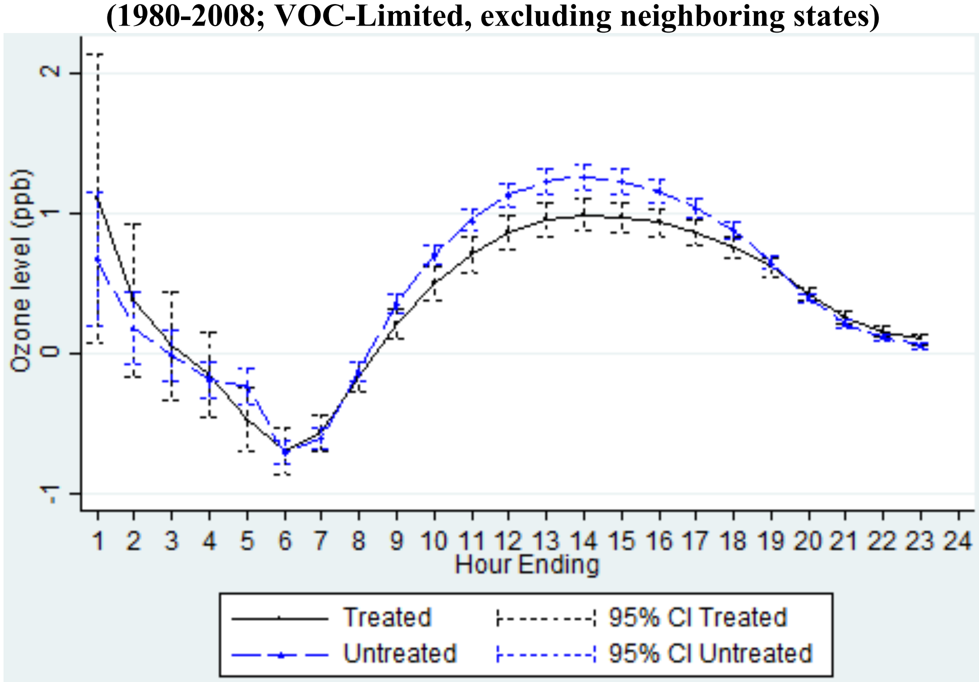
[30] See Appendix Section A.2 for more detail on how these variables were constructed.

Figure B3 – Ozone by Hour under the NOx Budget Program
(1980-2008; NOx-Limited, excluding neighboring states)



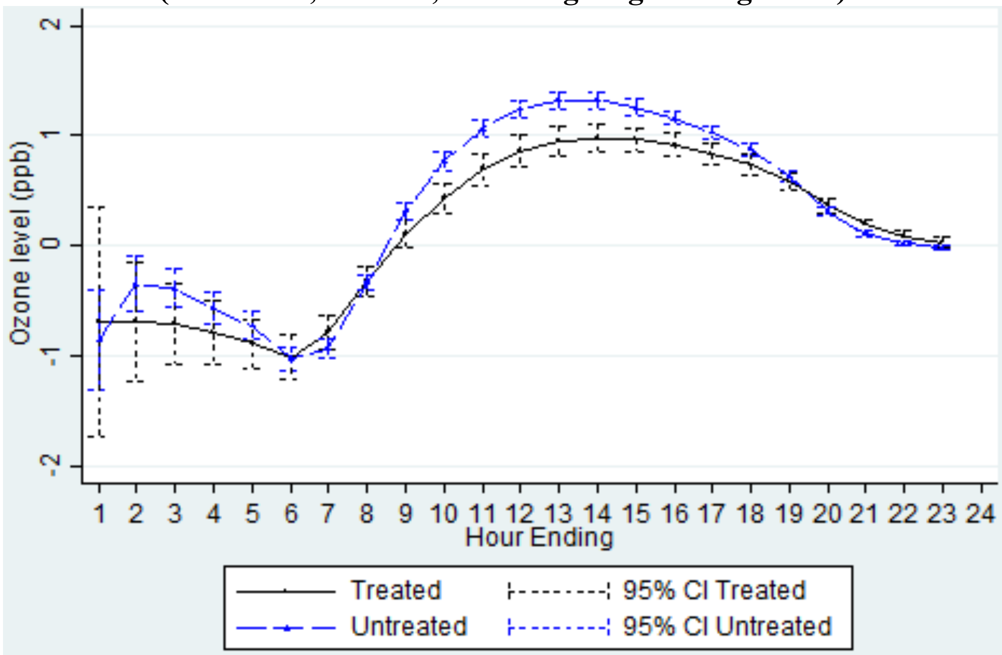
Notes: Estimation of Equation (B1). "Treated" refers to states participating in the NO_x Budget Program during the period when the program was active (May 2003 – May 2008); "Untreated" refers to all other observations. Following Deschenes, Greenstone, and Shapiro (2017), neighboring states to those states participating in the Program are excluded. Standard errors clustered by monitor.

Figure B4 – Ozone by Hour under the NO_x Budget Program
(1980-2008; VOC-Limited, excluding neighboring states)



Notes: Estimation of Equation (B1). "Treated" refers to states participating in the NO_x Budget Program during the period when the program was active (May 2003 – May 2008); "Untreated" refers to all other observations. Following Deschenes, Greenstone, and Shapiro (2017), neighboring states to those states participating in the Program are excluded. Standard errors clustered by monitor.

Figure B5 – Ozone by Hour under the NO_x Budget Program (1980-2008; Neutral, excluding neighboring states)

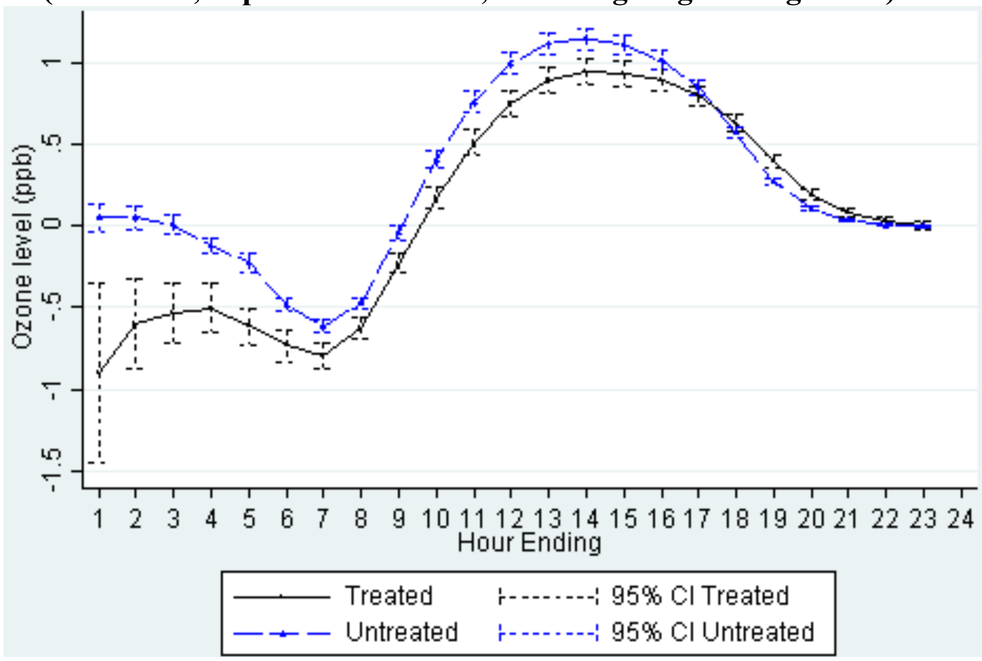


Notes: Estimation of Equation (B1). "Treated" refers to states participating in the NO_x Budget Program during the period when the program was active (May 2003 – May 2008); "Untreated" refers to all other observations. Following Deschenes, Greenstone, and Shapiro (2017), neighboring states to those states participating in the Program are excluded. Standard errors clustered by monitor.

B.4. Timing Sensitivity: September/October

Finally, we estimate Equation (3) where we shift the period of analysis from the 1st month before and after the NBP was in effect (April, May) to the last month the NBP was in effect and the 1st month after (September, October). It is worth noting that our sample size is smaller in October relative to April/May since the typical ozone season runs from April 1 – September 30th and ozone monitoring is therefore unavailable in some locations. Nonetheless, the results in Figure B6 are qualitatively similar to our main estimation in Figure 12.

Figure B6 – Ozone by Hour under the NOx Budget Program (1980-2008; September-October, excluding neighboring states)



Notes: Estimation of Equation (3), our triple difference equation analyzing the NO_x Budget Program for the months of September and October. "Treated" refers to states participating in the NO_x Budget Program during the period when the program was active (Sept. 2003 – Sept. 2008); "Untreated" refers to all other observations. Following Deschenes, Greenstone, and Shapiro (2017), neighboring states to those states participating in the Program are excluded. Standard errors clustered by monitor.

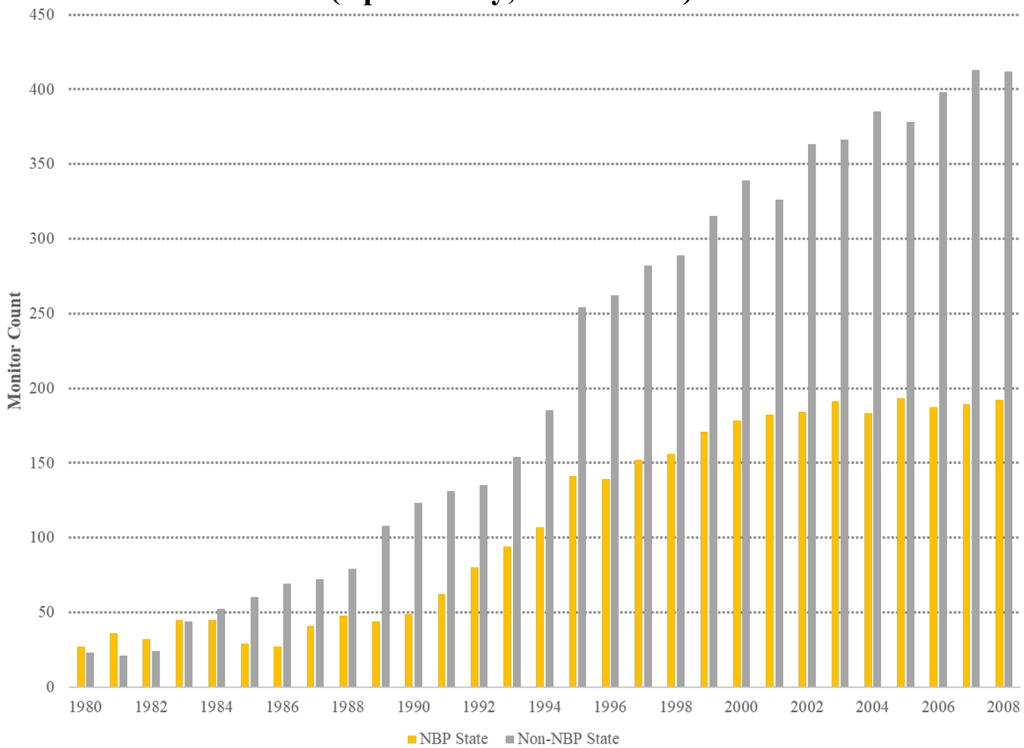
B.5. Additional Tables and Figures

Table B1 – Hourly Differences between Treat and Control for the NOx Budget Program (1980-2008, April-May)

Hour Ending	Treat - Untreat
1	0.0538
	(0.278)
2	-0.148
	(0.142)
3	-0.206*
	(0.0976)
4	-0.172*
	(0.0789)
5	-0.236***
	(0.0618)
6	-0.0832
	(0.0526)
7	0.0171
	(0.0411)
8	-0.0110
	(0.0315)
9	-0.103***
	(0.0297)
10	-0.147***
	(0.0318)
11	-0.153***
	(0.0340)
12	-0.150***
	(0.0343)
13	-0.137***
	(0.0330)
14	-0.114***
	(0.0314)
15	-0.0864**
	(0.0291)
16	-0.0533*
	(0.0267)
17	-0.0169
	(0.0238)
18	0.0191
	(0.0207)
19	0.0717***
	(0.0173)
20	0.112***
	(0.0141)
21	0.0883***
	(0.0118)
22	0.0610***
	(0.0111)
23	0.0387***
	(0.0110)

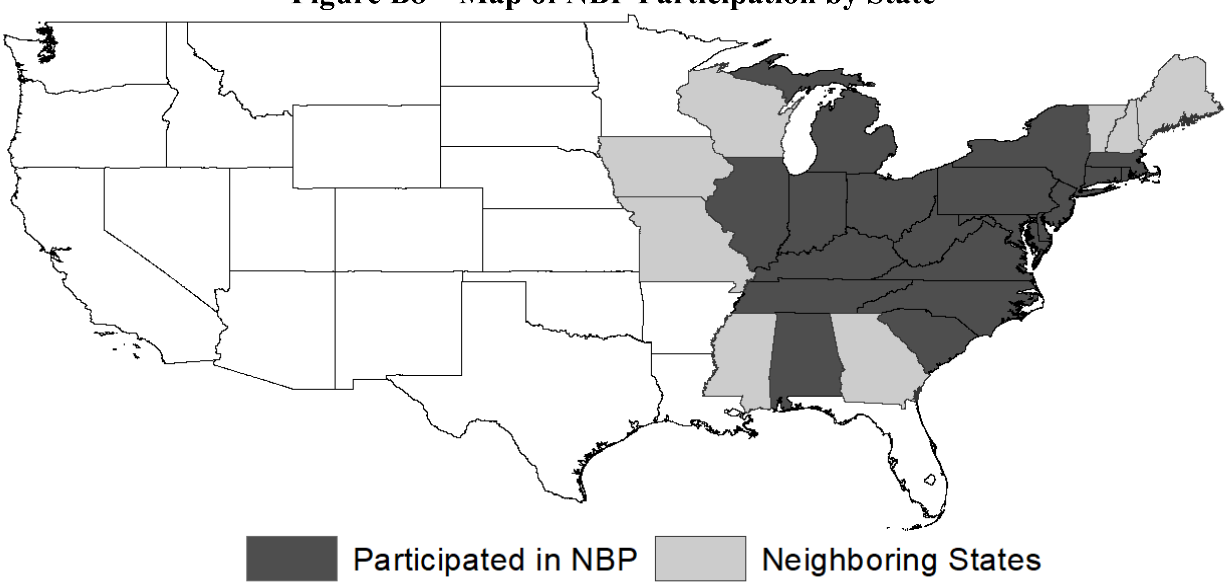
Notes: Differences in estimated hourly coefficients for Treat and Control from estimation of Equation (3) as shown in Figure 12.

Figure B7 – Count of Ozone Monitors by Year
(April – May, 1980 – 2008)



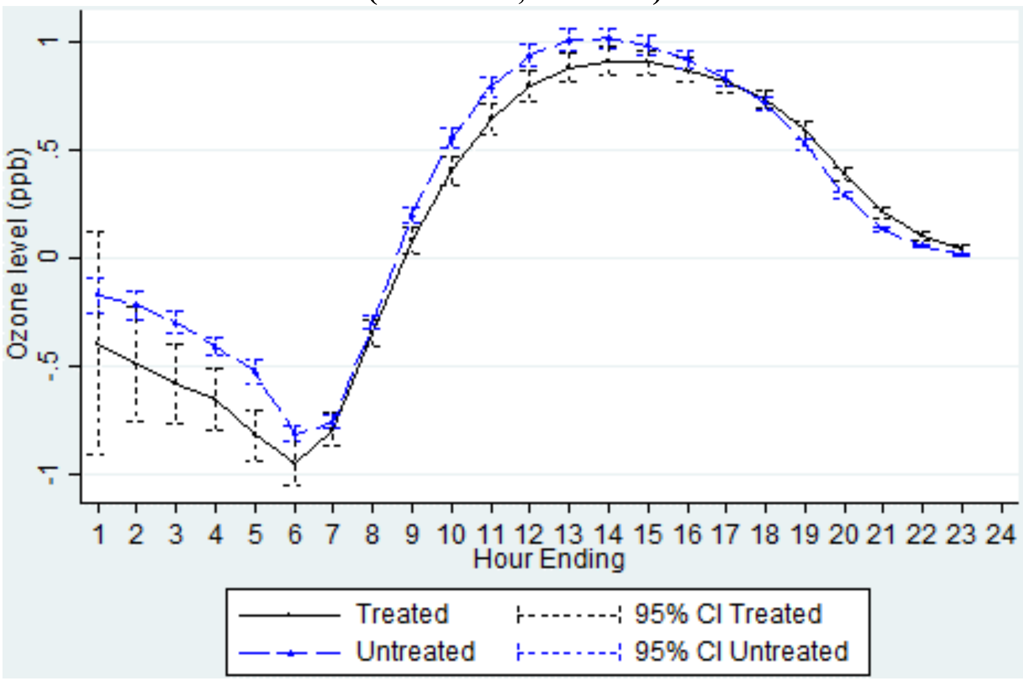
Notes: Count of monitor-year observations for April-May of each calendar year from our dataset of hourly ozone levels matched with contemporaneous hourly temperature. Counts are separated by whether a state did or did not participate in the NO_x Budget Program. Data from EPA's AirData database.

Figure B8 – Map of NBP Participation by State



Notes: Adopted from Deschenes, Greenstone, and Shapiro (2017).

Figure B9 – Ozone by Hour under the NO_x Budget Program (1980-2008; all states)



Notes: Estimation of Equation (3), our triple difference equation analyzing the NO_x Budget Program. "Treated" refers to states participating in the NO_x Budget Program during the period when the program was active (May 2003 – May 2008); "Untreated" refers to all other observations. Standard errors clustered by monitor.

C. Stylized Model

Below is our illustrative model for the time-varying cap-and-trade program. We follow the model presented in Fowlie and Muller (2019), first presenting the results from their undifferentiated case and then extending the model to include time-varying permits.

Firms are indexed by i =1, 2, …, N. Firm's abatement costs are assumed to be a quadratic function of abatement, with

$$C_i(e_i) = \alpha_{\{0i\}} - \alpha_{\{1i\}}e_i + \beta_i e_1^2.$$

The regulator's objective is to minimize total social costs, which are defined as the sum of damages from emissions and the cost of abatement: $TSC = D_i(e_i) + C_i(e_i)$. The marginal damage parameter is defined as $\delta_i = D_i'(e_i)$. Finally, the initial allocation of permits is A_i, and $\{A_{\{sij\}}, A_{\{bij\}}\}$ are permits sold by firm i and bought by firm i.

For the following, we assume for simplicity two firm types: low and high cost (L, H).

C.1. Undifferentiated Case from Fowlie and Muller (2019)

The firm's problem is given by:

$$\min TC_L = \alpha_{0L} - \alpha_{1L}e_L + \beta_L e_L^2 + \tau(A_{bLH} - A_{sLH})$$
$$\text{s.t. } e_L \leq A_L + A_{bLH} - A_{sLH}$$

The Lagrangian for this problem is:

$$L_L = \alpha_{\{oL\}} - \alpha_{1L}e_L + \beta_L e_L^2 + \tau(A_{bLH} - A_{sLH}) - \lambda_L(A_L + A_{bLH} - A_{sLH} - e_L)$$

Taking FOCs and solving for the permit price τ, we have:

$$\alpha_{1L}e_L - 2\beta_L e_L = \tau$$

or the marginal cost = permit price at the optimum emission level.

The regulator's problem is:

$$\min_{\{e_L, e_H\}} = (\alpha_{oL} - \alpha_{1L}e_L + \beta_L e_L^2) + (\alpha_{oH} - \alpha_{1H}e_H + \beta_H e_H^2)$$
$$\text{s.t. } e_L + e_H \leq E$$

where E is the emissions cap.

In Fowlie and Muller (2019), the authors show that the optimal emissions levels are:

$$e_L^U = \frac{\alpha_{1L} - (\frac{1}{\beta_H + \beta_L})(\beta_H\delta + \delta\beta_L)}{2\beta_L}$$

$$e_H^U = \frac{\alpha_{1H} - (\frac{1}{\beta_H + \beta_L})(\beta_H\delta + \delta\beta_L)}{2\beta_H}$$

and aggregate are then:

$$E = \frac{\alpha_{1L} - \left(\frac{1}{\beta_H + \beta_L}\right)(\beta_H\delta + \delta\beta_L)}{2\beta_L} + \frac{\alpha_{1H} - \left(\frac{1}{\beta_H + \beta_L}\right)(\beta_H\delta + \delta\beta_L)}{2\beta_H}$$

$$= \frac{\beta_H\alpha_{1L} - \beta_H\delta - \delta\beta_L + \alpha_{1H}\beta_L}{2\beta_H\beta_L}$$

For comparison with the temporal differentiation case that follows, we define δ above as $\delta = \frac{\delta_P + \delta_{OP}}{2}$.

C.2. Firms with Temporal Differentiation

Here (again for simplicity) we assume 2 different time periods (P, OP). The below assumes that firms face different cost functions for the peak and off-peak period. In this differentiated context,

$$\min TC_L = \alpha_{0LP} - \alpha_{1L}e_{LP} + \beta_{LP}e_{LP}^2 + \tau_P(A_{bLHP} - A_{sLHP})$$
$$+ \alpha_{0LOP} - \alpha_{1L}e_{LOP} + \beta_{LOP}e_{LOP}^2 + \tau_{OP}(A_{bLHOP} - A_{sLHOP})$$
$$\text{s.t. } e_{LP} \leq A_{LP} + A_{bLHP} - A_{sLHP}$$
$$\text{s.t. } e_{LOP} \leq A_{LOP} + A_{bLHOP} - A_{sLHOP}$$

where τ_P and τ_{OP} are the permit prices for the peak and off-peak period, respectively. Similarly, as compared to the undifferentiated case the allocations are separate for each period (A_{LP} and A_{LOP}) with the number of allocations lower in the peak period (i.e. $A_{LP} \ll A_{LOP}$).

The Lagrangian for the firm's problem is:

$$L_L = \alpha_{0LP} - \alpha_{1L}e_{LP} + \beta_{LP}e_{LP}^2 + \tau_P(A_{bLHP} - A_{sLHP})$$
$$+ \alpha_{0LOP} - \alpha_{1L}e_{LOP} + \beta_{LOP}e_{LOP}^2 + \tau_{OP}(A_{bLHOP} - A_{sLHOP})$$
$$- \lambda_{\mathrm{LP}}(A_{LP} + A_{bLHP} - A_{sLHP} - e_{LP})$$
$$+ \lambda_{LOP}(A_{LOP} + A_{bLHOP} - A_{sLHOP} - e_{LOP})$$

Taking FOCs and solving for the optimal permit prices τ_P and τ_{OP}, we have:

$$\frac{\partial}{\partial e_{LP}}: \lambda_{LP} - \alpha_{1LP} + 2\beta_{LP} = 0$$

$$\frac{\partial}{\partial A_{bLHP}}: \tau_P - \lambda_{LP} = 0$$

$$\frac{\partial}{\partial A_{sLHP}}: \lambda_{LP} - \tau_P = 0$$

$$\frac{\partial}{\partial e_{LOP}}: \lambda_{LOP} - \alpha_{1LOP} + 2\beta_{LOP} = 0$$

$$\frac{\partial}{\partial A_{bLHOP}}: \tau_{OP} - \lambda_{LOP} = 0$$

$$\frac{\partial}{\partial A_{sLHOP}}: \lambda_{LOP} - \tau_{OP} = 0$$

$$\rightarrow\rightarrow \tau_P = \alpha_{1LP} - 2\beta_{LP}e_{LP}$$

$$\tau_{OP} = \alpha_{1LOP} - 2\beta_{LOP}e_{LOP}$$

or the marginal cost equals the permit price at the optimal emission level in each period.

The regulator's problem is to minimize total social costs, or:

$$\min_{e_{LP},e_{LOP},e_{HP},e_{HOP}} = (\alpha_{0LP} - \alpha_{1L}e_{LP} + \beta_{LP}e_{LP}^2) + \alpha_{0LOP} - \alpha_{1L}e_{LOP} + \beta_{LOP}e_{LOP}^2$$

$$+ (\alpha_{0HP} - \alpha_{1H}e_{HP} + \beta_{HP}e_{HP}^2) + \alpha_{0HOP} - \alpha_{1H}e_{HOP} + \beta_{HOP}e_{HOP}^2$$

$$\bar{D} \geq \delta_P(e_{LP} + e_{HP}) + \delta_{OP}(e_{LOP} + e_{HOP})$$

where we modify the regulator's problem following Muller and Mendelsohn (2009) and Fowlie and Muller (2019) to replace the emissions cap with a damage cap ($\bar{D}$).

The Lagrangian for the regulator's problem is:

$$L = (\alpha_{0LP} - \alpha_{1L}e_{LP} + \beta_{LP}e_{LP}^2) + \alpha_{0LOP} - \alpha_{1L}e_{LOP} + \beta_{LOP}e_{LOP}^2$$

$$+ (\alpha_{0HP} - \alpha_{1H}e_{HP} + \beta_{HP}e_{HP}^2) + \alpha_{0HOP} - \alpha_{1H}e_{HOP} + \beta_{HOP}e_{HOP}^2$$

$$-\phi[\delta_P(e_{LP} + e_{HP}) + \delta_{OP}(e_{LOP} + e_{HOP}) - \bar{D}]$$

FOCs:

$$\frac{\partial}{\partial e_{LP}}: - \alpha_{1LP} + 2\beta_{LP} + \phi\delta_P = 0$$

$$\frac{\partial}{\partial e_{LOP}}: - \alpha_{1LOP} + 2\beta_{LOP} + \phi\delta_{OP} = 0$$

$$\frac{\partial}{\partial e_{HP}}: - \alpha_{1HP} + 2\beta_{HP} + \phi\delta_P = 0$$

$$\frac{\partial}{\partial e_{HOP}}: - \alpha_{1HOP} + 2\beta_{HOP} + \phi\delta_{OP} = 0$$

Following Fowlie and Muller (2019) Appendix 1.4, we solve for the optimal emissions levels by period that set our FOCs equal to zero.

$$e_{LP}^{D} = \frac{\alpha_{1LP} - \phi\delta_{P}}{2\beta_{LP}}$$

$$e_{LOP}^{D} = \frac{\alpha_{1LOP} - \phi\delta_{OP}}{2\beta_{LOP}}$$

$$e_{HP}^{D} = \frac{\alpha_{1HP} - \phi\delta_{P}}{2\beta_{HP}}$$

$$e_{HOP}^{D} = \frac{\alpha_{1HOP} - \phi\delta_{OP}}{2\beta_{HOP}}$$

Next, we solve for the optimal value of φ by taking the partial derivative of ΔTSC with respect to φ and solve for φ (to minimize ΔTSC).

If $\phi^{*} = 1$, then we have:

$$e_{LP}^{D} = \frac{\alpha_{1LP} - \delta_{P}}{2\beta_{LP}}$$

$$e_{LOP}^{D} = \frac{\alpha_{1LOP} - \delta_{OP}}{2\beta_{LOP}}$$

$$e_{HP}^{D} = \frac{\alpha_{1HP} - \delta_{P}}{2\beta_{HP}}$$

$$e_{HOP}^{D} = \frac{\alpha_{1HOP} - \delta_{OP}}{2\beta_{HOP}}$$

Aggregate emissions in each period are then:

$$E_{P} = \frac{\alpha_{1LP} - \delta_{P}}{2\beta_{LP}} + \frac{\alpha_{1HP} - \delta_{P}}{2\beta_{HP}}$$

$$= \frac{\beta_{HP}(\alpha_{1LP} - \delta_{P})}{2\beta_{LP}\beta_{HP}} + \frac{\beta_{LP}(\alpha_{1HP} - \delta_{P})}{2\beta_{HP}\beta_{LP}}$$

$$= \frac{\beta_{HP}\alpha_{1LP} - \beta_{HP}\delta_{P} + \beta_{LP}\alpha_{1HP} - \beta_{LP}\delta_{P})}{2\beta_{LP}\beta_{HP}}$$

$$E_{OP} = \frac{\alpha_{1LOP} - \delta_{OP}}{2\beta_{LOP}} + \frac{\alpha_{1HOP} - \delta_{OP}}{2\beta_{HOP}}$$

$$= \frac{\beta_{HOP}\alpha_{1LOP} - \beta_{HOP}\delta_{OP} + \beta_{LOP}\alpha_{1HOP} - \beta_{LOP}\delta_{OP})}{2\beta_{LOP}\beta_{HOP}}$$

We can now compare emissions in the peak period in the differentiated case, E_P, to emissions in the undifferentiated case:

$$E = \frac{\beta_H \alpha_{1L} - \beta_H \delta - \delta \beta_L + \alpha_{1H} \beta_L}{2\beta_H \beta_L}$$

$$E_P = \frac{\beta_{HP} \alpha_{1LP} - \beta_{HP} \delta_P + \beta_{LP} \alpha_{1HP} - \beta_{LP} \delta_P)}{2\beta_{LP} \beta_{HP}}$$

If we assume the firm's cost to reduce emissions in the peak and off-peak periods are the same [in other words, let $C_i(e_{iP}) = C_{i(e_{iOP})} = C_i(e_i)$], we can calculate the difference between aggregate emissions in the differentiated and undifferentiated case:

$$E - E_P = \frac{\beta_H \alpha_{1L} - \beta_H \delta - \delta \beta_L + \alpha_{1H} \beta_L}{2\beta_H \beta_L}$$

$$- \frac{\beta_H \alpha_{1L} - \beta_H \delta_P + \beta_L \alpha_{1H} - \beta_L \delta_P)}{2\beta_L \beta_H}$$

$$= \frac{\beta_H \delta_P - \beta_H \delta + \beta_L \delta_P - \beta_L \delta}{2\beta_H \beta_L}$$

$$= \frac{\beta_H (\delta_P - \delta) + \beta_L (\delta_P - \delta)}{2\beta_H \beta_L}$$

Since marginal damages from emissions in the peak period are greater than average marginal damages, this expression is strictly greater than zero. To show this explicitly, we plug in for δ:

$$E - E_P = \frac{\beta_H (\delta_P - \delta) + \beta_L (\delta_P - \delta)}{2\beta_H \beta_L}$$

$$= \frac{\beta_H (\delta_P - \frac{\delta_P + \delta_{OP}}{2}) + \beta_L (\delta_P - \frac{\delta_P + \delta_{OP}}{2})}{2\beta_H \beta_L}$$

$$= \frac{(\beta_H + \beta_L)(\delta_P - \delta_{OP})}{4\beta_H \beta_L}$$

Again, since $\delta_P > \delta_{OP}$, we know that emissions are reduced in the peak period relative to the undifferentiated case.