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TIMING MATTERS: INTRA-DAY SHIFTS OF ECONOMIC ACTIVITY AND AMBIENT  
OZONE CONCENTRATIONS

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### **ABSTRACT**

Ground-level ozone has been shown to have significant negative health externalities from short-term exposure, and as such has been regulated by the U.S. Clean Air Act since the 1970s. Ozone is not emitted directly; instead formation occurs due to a complex Leontief-like combination of air pollutants, under sunlight and warm temperatures, that results in high levels mid-day and low levels at night. Despite this known relationship, EPA regulations mostly 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 in certain hours 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 the timing of those emissions. We conclude by outlining a possible policy approach to account for the time-varying value of reductions in ozone precursor emissions.

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## 1. Introduction

Efficient taxes for an externality would equate the marginal costs and benefits of pollution (Pigou 1920). In reality, the marginal damages of many pollutants vary over space and time, so policies that reflected those differences would thus increase efficiency. Recent studies have explored spatial variation in efficient pollution regulation, but largely abstracted from fine-grained temporal variation.<sup>3</sup> Similarly, U.S. standards regulating pollution concentrations are usually based on temporally uniform thresholds. In this study, we examine whether policies that would incentivize intra-day shifts in economic activity while holding constant the daily level of activity would be effective in reducing daily ambient ozone concentrations. Ground-level ozone is among the many pollutants whose damages potentially vary over time.

Tropospheric or ground-level ozone is not emitted directly, but instead forms through a Leontief-like complex combination of nitrous oxides (NO<sub>x</sub>) and volatile organic compounds (VOCs), under sunlight and warm temperatures. Due to the role of sunlight, ozone forms over the course of the day and peaks in the early afternoon before largely dissipating overnight. This leads to significantly higher ozone concentrations in a set of peak hours during the day when many adults and children may be outside. Short-term exposure to ambient ozone has been shown to decrease lung function (Lippman, 2009; U.S. EPA, 2015a) 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 local pollutants, ambient ozone may impose differential externalities over the course of the day.

The ideal experiment to address our research question would randomly assign locations to forcefully conduct their daily activities in different hours of the day while holding constant the daily level of economic activity. Indeed, that would allow us to investigate whether changes in hourly activities conditional on daily economic output would alter the daily pattern of ambient ozone concentrations. The ideal experiment is infeasible for obvious reasons. Instead, we propose leveraging the quasi-experiment arising from the time zone borders. Because the information is salient and binding – e.g., employees must show up for work on time, parents must drop off their children at school at the scheduled time – individuals are likely to comply

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<sup>3</sup> The literature has focused on critical topics including firm relocation decisions, emissions leakage, and marginal damages that vary by location. See, for example, Henderson (1996), Baylis, Fullerton and Karney (2014), Holland et al. (2016, 2019), Callaway, Fowlie and McCormick (2018), Fowlie and Muller (2019), and Gibson (2019).

with the policy. In fact, we provide descriptive evidence using data from the American Time Use Survey and the American Community Survey that individuals leave to work at similar times in their local time. Thus, economic activity should shift considerably across the border when we look at the same Greenwich Mean Time (GMT).<sup>4</sup>

There are two ways to harness the geographic quasi-experiment provided by the time zone borders. First, one could hold constant the level of economic activity across the border by leveraging the similarity of routine activities in local time, but exploit differences in the intensity of solar radiation and other non-anthropogenic determinants of ozone formation for the same level of emissions (given the same timing of economic activity). Second, one could exploit different levels of economic activity across the border at the same GMT while holding constant solar radiation and other non-anthropogenic determinants of ozone.

To provide a concrete example, let us consider two cities in the State of Tennessee that are on opposite sides of the time zone border. The city of Kingston is the county seat of Roane County, and Crossville is the seat of Cumberland County, as highlighted in Figure 1. Kingston and Crossville are only 34 miles apart, but Kingston is in Eastern Time (ET) and Crossville in Central Time (CT). Thus, for the first approach, we would compare 8am ET in Kingston with 8am CT in Crossville, so they will be in different GMT, but at the same local time. The level of economic activity should be similar, but the intensity of the solar radiation will be different. For the second approach, we would compare 8am ET in Kingston with 7am CT in Crossville, because those different local times correspond to the same GMT. The level of economic activity will be different in those different local times, but solar radiation should be the same.

We use these two approaches to analyze the hourly profile of ambient ozone concentration on either side of a time zone border in the United States from 1980-2017. For the same local hour, our findings indicate that ozone levels on the western side of the time zone border are higher for the morning hours (6:00–9:59am local time) relative to the eastern side. This is particularly the case for the counties in compliance with the National Ambient Air Quality Standards (NAAQS) for ambient ozone, where the constraints on emissions of ozone precursors might not be binding.

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<sup>4</sup> Alternative policies that could generate intra-day shifts of economic activity such as episodic control programs for ozone pollution may be less suitable to tackle our research question. In the case of ozone alerts, for example, not every individual might be well-informed about the alerts, and even conditional on awareness individuals might choose to not change their behavior.

For the same GMT, because school and work schedules start earlier on the eastern side, it is not surprising that ozone levels are usually higher there in most of the hours of the day.

These empirical results may shed light on counterfactual policies that would hold constant the overall level of daily economic activity while reallocating activities across different hours of the day, when solar radiation and other non-anthropogenic determinants of ozone may differ. For instance, suppose a hypothetical policy change scenario in which the school district in Kingston considers changing the time students start classes from 8am to 9am ET. One could evaluate the impact of this potential policy change on ozone concentrations, as parents and/or buses would drop off students at schools one hour later, therefore emitting more when the sunlight is more intense. It is as if the counterfactual for Kingston at 9am ET was Crossville at 8am CT, so the time zone border analysis would allow for this potential policy evaluation. Another hypothetical scenario that could be addressed using our quasi-experiment is manufacturing plants considering reallocating production from the middle to the end of the day to minimize emissions at mid-day – when ozone formation is at its peak – as alluded to by Henderson (1996, Figure 3, for example).

Having shown that an intra-day shift in economic activity can indeed affect hourly ambient ozone concentrations in certain hours of the day, we then consider how to incentivize firms to shift production away from the hours with the highest social cost. We introduce a simple conceptual framework building on Fowlie and Muller (2019) to illustrate how policymakers could modify a standard cap-and-trade program to incentivize firms to reduce ozone precursor emissions around peak ozone hours.<sup>5</sup>

Finally, we examine whether recent U.S. policies to reduce ozone precursor emissions have taken advantage of shifting activity to reduce peak ambient ozone concentrations. Our focus is the NO<sub>x</sub> Budget Program, a cap-and-trade program that was in effect during the ozone season (May – September) from 2003–2008. Although the Program did not distinguish between intra- or inter-day emissions in that period, affected locations might still be out of attainment with the

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<sup>5</sup> There are several ways in which firms or consumers could shift activity throughout the day. The one most analogous to our analysis around time zone borders would be to delay the start of the workday to change the timing of driving and production activity. The increased prevalence of teleworking and telecommuting provide an opportunity to shift the timing of precursor emission producing activities away from harmful periods. This strategy has already been encouraged through episodic control policies that target reductions in activities on the days that are expected to have the highest levels of air pollution. Alternatively, one can reduce exposure to elevated levels by reducing production in the peak ozone hours of early to mid-afternoon and shifting this later. We have seen some of this shifting on the individual level in response to high temperatures, such as with construction workers in Arizona (see [nytimes.com/interactive/2019/climate/phoenix-heat.html](https://www.nytimes.com/interactive/2019/climate/phoenix-heat.html)).

ozone NAAQS. To the extent that a nonattainment designation penalizes counties for reaching relatively high maximum ozone concentrations, it could indirectly incentivize NBP participants to affect the hourly ozone distribution.<sup>6</sup> 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 activity over the course of the day.<sup>7</sup> This finding suggests that without changes in policy design, as laid out in our conceptual framework, further peak ozone concentration reductions may not be accomplished.

This study makes two main contributions to the literature and policy design. *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, 2014; 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, such as health and productivity (Neidell, 2009; Moretti and Neidell, 2011; Graff Zivin and Neidell, 2012; Deschenes, Greenstone and Shapiro, 2017). Additionally, the EPA estimated that the cost of attaining the recent revision to the ozone NAAQS from 75 to 70 ppb nationally would be \$1.4 billion per year (U.S. EPA, 2015b); time-specific adjustments could provide an additional compliance method, perhaps a cheaper one relying primarily on peak hours.

*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 and show how much timing matters. In their setting, reductions in energy consumption during

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<sup>6</sup> This 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).

<sup>7</sup> In the Appendix we perform a robustness check where we restrict the sample to the last effective month of the Program (September) and the 1<sup>st</sup> month after (October); the results are qualitatively similar.

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 approach arising from our conceptual framework 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) and time zone borders. Several recent studies have found significant negative health and productivity effects from DST or changes in the timing of sunlight due to time zones (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). Although our goal is not to evaluate the welfare implications of the time zones – in which the counterfactual would be their elimination – our analysis reveals changes in ambient ozone concentrations due to intra-day shifts of 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<sub>x</sub> Budget Program. Section 3 presents results from our analysis of ozone levels by hour across U.S. time zone borders, while Section 4 outlines a conceptual framework for a policy that could make use of this hourly profile of ozone. Section 5 examines a recent policy that has been shown to reduce ozone, the NO<sub>x</sub> Budget Program, in the context of our findings. 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.<sup>8</sup> 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.<sup>9</sup> Ground-level ozone forms through a Leontief-like combination of two other pollutants: oxides of

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<sup>8</sup> When we refer to ozone in this paper we mean ground-level or ambient ozone, unless otherwise noted.

<sup>9</sup> 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>).

nitrogen (NO<sub>x</sub>) and volatile organic compounds (VOCs).<sup>10</sup> The ozone formation process is a complex, non-linear combination of NO<sub>x</sub>, VOCs, sunlight, and temperature. Due to the role of sunlight and temperature in this relationship, ozone is generally highest in the hot summer months.

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<sub>2</sub> and VOCs – in Figure 2. 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<sub>2.5</sub>, NO<sub>2</sub>, 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 2 Panel A), while concentrations of NO<sub>2</sub> 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 2 Panel B).<sup>11</sup>

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, 2015a). 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).

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<sup>10</sup> This Leontief-like relationship between the ozone precursors in the formation of ozone is illustrated in Figure A22.

<sup>11</sup> Ozone formation involves the destruction of NO<sub>2</sub> 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.

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 2<sup>nd</sup> 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 4<sup>th</sup> highest daily maximum ozone level (based on an 8-hour average) over a 3-year period.<sup>12</sup> The standard has subsequently been reduced to the current standard of 70 ppb based on the same 4<sup>th</sup> highest daily 8-hour average methodology.<sup>13</sup> 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<sub>x</sub> Budget Program**

Efforts in addition to the NAAQS have thus been undertaken to try and reduce ozone pollution, such as the NO<sub>x</sub> Budget Program that targeted ozone precursor emissions. The NO<sub>x</sub> 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 1<sup>st</sup> through September 30<sup>th</sup>, 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.<sup>14</sup>

Allowances under the NO<sub>x</sub> Budget Program were for emissions of a single ton of NO<sub>x</sub> during the ozone season (May 1 – September 30<sup>th</sup>). 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<sub>x</sub>

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<sup>12</sup> 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).

<sup>13</sup> 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.

<sup>14</sup> 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.

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).

### **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). The policy approach in Section 4 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 and its induced variation in the timing of sunlight (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<sub>2</sub>) and particulate matter (PM<sub>10</sub> and PM<sub>2.5</sub>).

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:

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

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.<sup>15</sup> Standard errors are clustered at the monitor level. The omitted hour in 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.<sup>16</sup>

The coefficients of interest from Equation (1) are the series of  $\beta$ '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  $\beta_t^E$  and  $\beta_t^W$  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  $\beta$ '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 of the border at the same local time are similar.<sup>17</sup> As an example, we argue (and provide evidence in Section 3.3 and the Appendix) that individuals on either side of the border leave for work or school and return home at the same local times within our narrow window of analysis. In this sense the time zone border is inducing a one-hour shift in activity (in terms of GMT) for counties on the western versus eastern side of the time zone border. 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 (in GMT) due to the time zone border will cause changes in

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<sup>15</sup> 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 DST by altering the start and end dates, but for our analysis of ozone near time zone borders 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).

<sup>16</sup> 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.

<sup>17</sup> We use the term 'same local time' to mean the identical clock hour in two time zones - for instance 8:00am in the Central time zone and 8:00am in the Eastern. These two periods are not contemporaneous, but rather occur one hour apart in Greenwich Mean Time.

concentrations of ambient ozone through the mechanism of differing levels of solar intensity interacting with precursor emissions 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 A16 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<sub>2</sub>, VOC, and particulate matter by decade for a 50- or 75-mile radius around the Central time zone border are presented in Table 1.<sup>18</sup> 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 A17 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 3 and Figure 4, we plot the hourly average level for ozone, PM<sub>2.5</sub>, and NO<sub>2</sub> on the eastern and western sides of the border, averaging across all years in the sample.<sup>19</sup>

Figure 3 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), and continues to shrink further into the evening.<sup>20</sup> Putting these differences in the context of the recent 5ppb revisions to the ozone NAAQS, they

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<sup>18</sup> As discussed below, we use a 75-mile radius for particulate matter due to insufficient coverage at the 50-mile level.

<sup>19</sup> An analogous figure presenting the summary for ozone across all time zone borders can be seen in Figure A19 in the Appendix.

<sup>20</sup> We include an analogous figure for the maximum radius in our sample of 200 miles as Figure A18. The trends are the same until the evening, when the relatively higher sunlight on the east leads to the eastern side reporting levels around 2ppb higher than the western side of the border.

make up 40% - 100% of the change in the non-attainment standards. 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 NO<sub>2</sub>, 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<sub>2.5</sub> and plot the results in Panel A of Figure 4.<sup>21</sup> It should be noted that we have more observations for our main dataset of ambient ozone as compared to both the particulate matter and the NO<sub>2</sub> 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<sub>2</sub> levels that are up to 4ppb higher than the eastern side across all hours.<sup>22</sup> 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.

Figure 5 compares maximum daily ozone concentration between the two sides of the time zone boundary. It does not matter which time (local vs. GMT) we pick to display the patterns in the data because the comparison is at the daily level instead of hourly levels. These descriptive histograms reveal ozone levels in the western side of the time zone boundary are usually higher. This pattern indicates that intra-day shifts of economic activity, *while maintaining the same daily level of economic activity*, might not be innocuous in terms of daily ozone levels. Interestingly, this is the same pattern of ozone concentration that we will uncover based on the analysis using our approach. In fact, according to the main estimates from our approach, ozone levels in the morning are higher in the western side to the boundary, but the differences are not offset by late afternoon and early evening, when the hourly pattern inverts.

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<sup>21</sup> For comparison's sake, we created versions of Figure 3 and Panel B of Figure 4 with a 75 mile radius instead of 50; these results can be seen in Figure A20 and Figure A21 in the Appendix. There are no substantive differences between the 50 and 75mile radii versions of each Figure.

<sup>22</sup> On either side of the time zone border, we see a pattern of lower NO<sub>2</sub> levels in both the middle of the day and the middle of the night. These may be due to NO<sub>2</sub> being used up in ozone formation during hours of peak sunlight and a relative lack of production activity, respectively (NRC, 1991).

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.<sup>23</sup> 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 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  $\beta$ '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

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<sup>23</sup> The ACS data used was presented at the county-level and accessed through the U.S. Census Bureau's American FactFinder.

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 HE7 - HE10 (i.e. 6:00am–9:59am) between the western and eastern sides of a time zone border, averaging 0.5 ppb per hour or 10% of the latest changes to the ozone standard.<sup>24</sup> The difference between the western and eastern sides of the border switches from positive to negative beginning in HE13, consistent with the typical daily peak of solar intensity and thus when we would expect the gap to reverse, although it is not statistically significant. As compared to the data plotted in Figure 3, 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.

Alternatively, we estimate a version of Equation (1) where the hours are defined in terms of GMT and present the results in Figure 7, Panel B. In this case, the level of solar radiation on either side of the time zone border should be the same, but the levels of economic activity will be different. Since we are using GMT, we omit HE5 instead of HE24 to be consistent with our omission of 11:00PM EDT in the main specification. Because school and work schedules start earlier in GMT on the eastern side of the border, it is not surprising that ozone levels are usually higher there in most of the hours of the day in Figure 7, Panel B. The pattern in the evening, however, is somewhat unexpected. Although sunlight is similar in GMT across the border, economic activity should wind down earlier in GMT on the eastern side. One potential explanation comes from Giuntella and Mazzonna (2019). They show that individuals living on the late sunset side of the time zone border tend to go to bed later than those living on the opposite side of the border, but do not fully compensate by waking up later in the morning. Therefore, it is possible that for several hours of the early evening ozone levels remain high because individuals are still active; hence, still emitting ozone precursors under fading sunlight.

One potential concern is that the trends we find for ozone in our preferred specification using local time 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<sub>10</sub> and PM<sub>2.5</sub>) and NO<sub>2</sub> as our dependent variables do not demonstrate the same hourly

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<sup>24</sup> The hourly differences between east and west from estimating Equation (1) can be seen in Table 3.

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.<sup>25</sup>

The results for particulate matter in Figure 8 are noteworthy as more than just a placebo test of our preferred specification in Equation (1).<sup>26</sup> Emissions of particulate matter can be both primary and secondary: sources of PM<sub>10</sub> and PM<sub>2.5</sub> 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. Or there could be differences in the baseline levels of solar intensity, causing higher rates of ozone formation on one side versus the other that are not attributable to the one-hour shift in economic activity due to the time zone border. Therefore, we perform a series of sensitivity analyses where we explicitly include controls for meteorological variables – hourly temperature, wind direction, and wind speed; hourly solar irradiance; and whether a county is NO<sub>x</sub> - or VOC-Limited. The results

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<sup>25</sup> 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<sub>2</sub> we see a pattern of lower NO<sub>2</sub> 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<sub>2</sub> being converted to ozone in the afternoon, respectively (NRC, 1991).

<sup>26</sup> 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).

remain qualitatively similar across all of these alternative specifications. Finally, it is possible that our arbitrary choice of a narrow radius around the time zone border to minimize confounding factors may contribute to our findings. We allow for the distance from the time zone border to vary up to a 200 mile radius; again, our results remain qualitatively similar. Further discussion of all of these results can be found in Section A of the Appendix.

Of particular note are the results with controls for wind direction and wind speed in Figure A1. Since the wind is typically stronger at night, it may have a larger effect on our estimates in the night hours (including on our omitted category of HE24). Not only do we see no differences in ozone concentrations in the late night hours (HE1 – HE4) between east and west after controlling for wind in Figure A1, but we also see a significant and persistent difference in ozone concentrations from the morning to the mid-afternoon (HE7 – HE16). Unfortunately our wind data is only available for a subsample of our main sample, so we present the results utilizing our full sample here and in the following subsections. Nonetheless, these results provide suggestive evidence that we may be underestimating the effect of shifting activity on ambient ozone concentrations.

### 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 4<sup>th</sup> highest daily 8-hour maximum over a 3-year period.<sup>27</sup> We examine potential differences for counties in- and out- of attainment in Equation (2):

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

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<sup>27</sup> See Table A6 in the Appendix for a history of the changes to the NAAQS standard over time.

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 A14, 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 A14, 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 A14 collectively suggest a few interesting points. First, due to their similarities our main results in Figure 7 appear to be driven by non-attainment counties (Figure A14, Panel B), 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 A14 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 predicted 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

to mitigate the unhealthy levels of pollution by encouraging individuals and business to reduce their emissions.

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 A15. 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 due to high forecasted temperatures, shifting economic activity could potentially have the greatest impact on reducing ozone concentrations. 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* compared to our main results in Figure 7. 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. Conceptual Framework for Assessing Policy Options**

In Section 3 we showed that policies that would incentivize intra-day shifts in economic activity, while holding constant the daily level of activity, could be effective in reducing daily ozone concentrations. We next turn our focus from this stylized fact to an examination of how policies targeting reductions in ozone precursors affect hourly ozone. Findings from the analyses in the previous section suggest that shifting economic activity can lead to reductions in hourly ozone concentrations. Given the known deleterious health effects of ozone, this suggests implications for corrective policies. There are generally two options, either (or both) of regulation and market-based approaches.

Regulation typically targets the peak, and has been implemented by the EPA for air quality regulation in the National Ambient Air Quality Standards (NAAQS). The initial standard for ozone would classify a county as out of attainment if it exceeded the maximum threshold in an hour more than once in a given year. The standard was substantially revised in 1997, when it was redefined based on the 4<sup>th</sup> highest daily maximum ozone level (based on an 8-hour average) over a 3-year period. The EPA claimed at the time that this new standard was equivalent to the prior 1-hour standard.<sup>28</sup> Henderson (1996) theorized that the NAAQS would induce firms to shift activity over the course of the day, in order to avoid hitting the non-attainment threshold.

Market-based approaches tend to incentivize the lowest cost reductions overall, rather than focusing on the peak. 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 an adaptation to a type of program that has been shown to have a level of political tractability: cap-and-trade.

In this section, we outline a conceptual framework for thinking about how policymakers could target reductions in peak ozone hours using a market-based approach. A cap-and-trade program has previously been shown to affect concentrations of ambient ozone (Deschenes, Greenstone and Shapiro, 2017), which we will examine further in Section 5. But does this market-based approach reduce ozone at the peak, comparable to the target of regulation such as the NAAQS? With the differential externalities imposed by ozone over the course of the day, it is important to consider what might constitute an ideal or desirable policy design for a market based approach in this setting. Something as granular as an hourly cap-and-trade market is unlikely to be administratively tractable, but allowing for separate permits for peak and off-peak periods may be feasible.

Section 4.1 presents a conceptual framework for a standard cap-and-trade program, and Section 4.2 illustrates our extension to allow for intra-day variation in permitting.

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<sup>28</sup> U.S. EPA, 1997, p.38868; U.S. EPA, 2004, p. 23970.

#### **4.1. Conceptual Framework of Firm Production Under Cap-and-Trade**

In a cap-and-trade program such as the NO<sub>x</sub> Budget Program, there is an initial allocation of permits to firms based on a historical base-level of emissions. Fowlie and Perloff (2013) examine this initial allocation and do find any significant evidence of an 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<sub>x</sub> 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.<sup>29</sup> We modify their approach to focus instead on the problem of *when* emissions occur. To provide firms with incentives to reduce emissions during particular 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 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.<sup>30</sup>

#### **4.2. 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 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

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<sup>29</sup> However, they find that under certain circumstances it can actually be beneficial to implement a policy that ignores the spatial differences.

<sup>30</sup> 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<sub>x</sub> trading program in southern California (Fowlie et al., 2012).

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:<sup>31</sup>

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

where  $\beta_H$  and  $\beta_L$  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  $E - E_P > 0$ . Thus, in 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.

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<sup>31</sup> 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.

## 5. Ozone By Hour – The NO<sub>x</sub> Budget Program

We outlined in the previous section how a theoretical cap-and-trade program with time-varying permits could affect the distribution of emissions. Recall that ozone is not emitted directly, but forms from a complex, Leontief-like production function of precursor emissions NO<sub>x</sub> and VOCs. In this section, we examine a real-world policy targeting emissions of an ozone precursor: the NO<sub>x</sub> Budget Program (NBP). Specifically, how did the NBP affect hourly ozone concentrations and how might firms have responded to it?<sup>32</sup> Although the NBP was not designed to address damages that vary within a day directly, counties could still be under nonattainment with the ozone NAAQS. To the extent that a nonattainment designation penalizes counties for reaching relatively high maximum ozone concentrations, it could indirectly incentivize NBP participants to change the hourly ozone distribution.

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 the summer mortality rate by 0.4%.<sup>33</sup> In our analysis, we are interested in examining whether the NO<sub>x</sub> Budget Program was successful at reducing ozone in harmful peak hours.<sup>34</sup> In other words, did the NO<sub>x</sub> Budget Program alter the intraday distribution of ambient ozone concentrations?

We outline our empirical strategy in Section 5.1. Section 5.2 presents summary statistics on our sample's coverage and the average ozone levels for states that did or did not participate in the NO<sub>x</sub> Budget Program. Our empirical results are presented and discussed in Section 5.3.

### 5.1. Empirical Strategy

For our analysis of the NO<sub>x</sub> 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<sub>x</sub> Budget Program took effect.<sup>35</sup>

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<sup>32</sup> Background on the NO<sub>x</sub> Budget Program was provided in Section 2.2.

<sup>33</sup> The authors translate this reduction in the mortality rate into the prevention of nearly 2,000 premature fatalities.

<sup>34</sup> In this paper we are focusing on the impacts of the NO<sub>x</sub> Budget Program on ozone concentrations. However, it is worth noting that NO<sub>x</sub> is a harmful pollutant on its own and is regulated as a criteria air pollutant by the U.S. EPA.

<sup>35</sup> We perform a sensitivity analysis where we instead look at September and October in Section B.4 of the Appendix.

We estimate the following triple-differences model:

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

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<sub>x</sub> 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  $\tau$ , 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 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 ( $\eta_i$ ) and day-by-month-by-year ( $\delta_{dmy}$ ) and cluster standard errors by monitor. Following Deschenes, Greenstone, and Shapiro (2017), we exclude a set of neighboring states that are downwind.<sup>36</sup>

The coefficients of interest from Equation (3) are  $\beta_1^{\tau}$  and  $\beta_2^{\tau}$ , the coefficients on treated and control observations by hour. If the NO<sub>x</sub> Budget Program induced firms to reduce their precursor emissions during those hours affecting peak ozone concentrations, 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

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<sup>36</sup> 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."

production across hours but instead by reducing emissions slightly across all hours, we would expect the trends in  $\beta_1^\tau$  and  $\beta_2^\tau$  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).

## 5.2. 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<sub>x</sub> Budget Program status (participating or non-participating states) are presented in Figure B9. The NO<sub>x</sub> 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 B11.

We plot the hourly average ambient ozone during the program period of May 2003-May 2008 in Figure B10. Panel A displays the average levels of ozone by hour for states that did not participate in the NO<sub>x</sub> 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<sub>x</sub> 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<sub>x</sub> 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.

### 5.3. Results

Results from the estimation of our preferred specification, the triple-differences equation [Equation (3)], can be seen in Figure 9.<sup>37</sup> There is a slight reduction in ozone concentrations in the earlier morning hours (similar to Figure 7) due to the NO<sub>x</sub> 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.<sup>38</sup> In summary, these results indicate that firms did not appear to shift production away from those hours affecting the peak ozone period in order to comply with the NO<sub>x</sub> 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 with the highest ozone concentrations impose the greatest marginal damages.

Results from our analysis of the NO<sub>x</sub> 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 3 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 0.5 ppb per hour in HE7 – HE10. In this case, prior research shows that the NO<sub>x</sub> Budget Program was successful at reducing ozone overall. However, our econometric results in Figure 9 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<sub>x</sub> 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

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<sup>37</sup> 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 B12 in the Appendix.

<sup>38</sup> The hourly differences between Treat and Control from estimating Equation (3) can be seen in Table B1.

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<sub>x</sub> - or VOC-Limited, shifting the period of analysis to the last month of the NBP program and the 1<sup>st</sup> month after (September – October), or estimated using a version of the two-way fixed effects estimation presented in Deschenes, Greenstone, and Shapiro (2017).

### 5.3.1. 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 in these counties to shift economic activity. 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  $\beta$ ’s are interacted with the county’s attainment status.

$$\begin{aligned}
 P_{ichdmy} = & \beta_0 + \beta_1^t Treat_{icdmy} * \tau * NonAttain + \beta_2^c Control_{icdmy} * \tau * NonAttain + \\
 & \beta_3 NBPyear_{iy} * NBPstate_{ic} + \beta_4 NBPmonth_{im} * NBPstate_{ic} \\
 & + \gamma_1 temp_{hcdmy} + \eta_i + \delta_{dmy} + \epsilon_{ichdmy}
 \end{aligned} \tag{4}$$

We plot the hourly coefficients separately by attainment status in Panels A and B of Figure B7. 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 B7 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<sub>x</sub> 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.

## 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 revision of the ozone NAAQS. Our finding is robust to a series of alternative specifications with various meteorological and regional controls.

We then 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.

Finally, we 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<sub>x</sub> Budget Program. Utilizing a triple-differences estimation over the period 1980-2008 and focusing on the 1<sup>st</sup> 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.

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. Firm abatement costs are likely non-trivial, and may vary by time of day – it is possible that the costs of abatement could be highest in the hours with the largest potential marginal benefit from reductions. Improving our understanding of the costs from shifting economic activity should be an important goal for future research.

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## 1. Tables

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

<b>Summary Statistics - Central Timezone</b>				
<b>Year</b>	<b>Concentration</b>		<b># of Monitors</b>	
	<i>East</i>	<i>West</i>	<i>East</i>	<i>West</i>
<b>Ozone (ppb)</b>				
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
<b>NO2 (ppb)</b>				
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
<b>VOC (ppb C)</b>				
1990-1999	5.55	3.57	160	189
2000-2009	2.73	2.90	205	227
2010-2017	2.52	2.52	164	55
<b>PM<sub>10</sub> (µg/m<sup>3</sup>)</b>				
1990-1999	29.35	33.78	3	3
2000-2009	25.62	27.98	13	5
2010-2017	21.96	26.02	13	5
<b>PM<sub>2.5</sub> (µg/m<sup>3</sup>)</b>				
2000-2009	12.97	13.21	2	1
2010-2017	11.48	10.09	17	7

*Notes:* Average pollutant concentration within 50 miles (Ozone, NO<sub>2</sub>) and 75 miles (VOC, PM<sub>10</sub>, PM<sub>2.5</sub>) 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 (0.00227)	0.519 (0.00625)	0.0309 (0.0846)
White	0.798 (0.00089)	0.830 (0.00292)	-0.0523 (0.0772)
Black	0.099 (0.00218)	0.124 (0.00117)	0.0668 (0.0569)
Other	0.103 (0.00307)	0.046 (0.00175)	-0.0145 (0.0412)
Under 18	0.031 (0.00078)	0.022 (0.00124)	-0.0328 (0.0265)
18 to 35	0.332 (0.00862)	0.349 (0.00685)	-0.0607 (0.0540)
45 to 65	0.390 (0.00157)	0.377 (0.00212)	0.0591 (0.0646)
Over 65	0.045 (0.00082)	0.044 (0.00056)	0.0217 (0.0334)
Married	0.518 (0.01378)	0.525 (0.01282)	0.0402 (0.0653)
Single	0.302 (0.01011)	0.315 (0.00253)	-0.0417 (0.0720)
Divorced or Separated	0.153 (0.00433)	0.143 (0.00819)	0.00515 (0.0368)
Widowed	0.028 (0.00066)	0.017 (0.00211)	-0.00373 (0.00850)
Own Home	0.694 (0.02173)	0.730 (0.00717)	0.0523 (0.0503)
Rent Home	0.288 (0.02283)	0.262 (0.00676)	-0.0601 (0.0518)
Weekly earnings < \$400	0.318 (0.00592)	0.365 (0.00677)	-0.0747 (0.0583)
Weekly earnings \$400-\$750	0.283 (0.00845)	0.307 (0.00036)	0.0522 (0.0574)
Weekly earnings \$750-\$1,000	0.142 (0.00003)	0.105 (0.00342)	-0.0189 (0.0494)
Weekly earnings > \$1,000	0.257 (0.01434)	0.223 (0.00298)	-1.305e+08 (9.843e+07)
High School	0.310 (0.00282)	0.282 (0.00272)	-0.0112 (0.0726)
Some College	0.212 (0.00189)	0.165 (0.00325)	-0.0432 (0.0384)
Associate	0.092 (0.00028)	0.111 (0.00435)	-0.00163 (0.0356)
Bachelors	0.198 (0.00444)	0.204 (0.00735)	0.0115 (0.0541)
Grad School	0.077 (0.00013)	0.117 (0.00016)	0.0676 (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%.

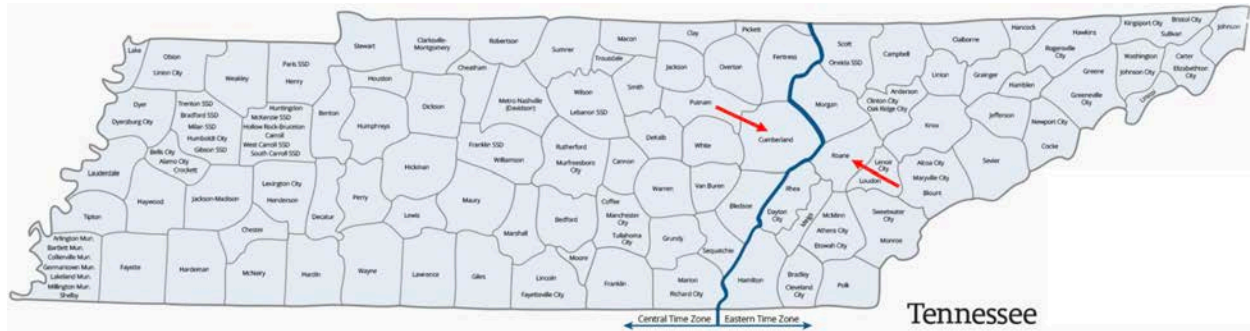
**Table 3 – Hourly Differences between West and East (1980-2017, Summer)**

Hour Ending	West - East (Local) [1]	West - East (GMT) [2]
1	0.694*** (0.191)	-1.998* (0.910)
2	0.340** (0.109)	1.311** (0.418)
3	0.272** (0.0847)	1.326*** (0.216)
4	0.201** (0.0707)	0.619*** (0.0854)
5	0.0980 (0.0643)	- -
6	0.146* (0.0602)	-0.446*** (0.0514)
7	0.534*** (0.0546)	-0.655*** (0.0785)
8	0.641*** (0.0572)	-0.779*** (0.0901)
9	0.485*** (0.0715)	-0.744*** (0.0917)
10	0.315*** (0.0844)	-0.777*** (0.0901)
11	0.148 (0.0914)	-0.825*** (0.0904)
12	0.0390 (0.0938)	-0.918*** (0.0923)
13	-0.0142 (0.0923)	-1.017*** (0.0876)
14	-0.0292 (0.0882)	-1.096*** (0.0790)
15	-0.0294 (0.0826)	-0.984*** (0.0662)
16	-0.0292 (0.0767)	-0.778*** (0.0566)
17	-0.0385 (0.0704)	-0.624*** (0.0521)
18	-0.0673 (0.0623)	-0.526*** (0.0484)
19	-0.122* (0.0515)	-0.458*** (0.0481)
20	-0.146*** (0.0374)	-0.432*** (0.0485)
21	-0.0955*** (0.0215)	-0.399*** (0.0476)
22	-0.0473*** (0.0111)	-0.390*** (0.0468)
23	-0.0159* (0.00625)	-0.345*** (0.0427)
24	- -	-0.252*** (0.0385)

*Notes:* Difference in estimated hourly coefficients for *East* and *West* from [1] Equation (1) and [2] a modified version of Equation (1) using GMT.

## 2. Figures

**Figure 1: Time Zone Border in Tennessee**

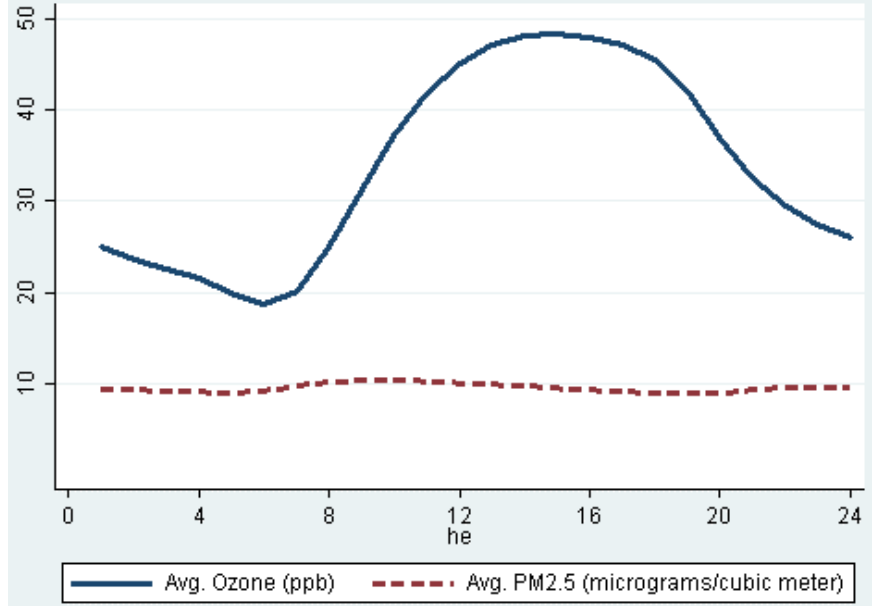


*Notes:* This map of the State of Tennessee highlights the two counties used in the example in the text: Roane County in the Eastern Time Zone and Cumberland County in the Central Time Zone.

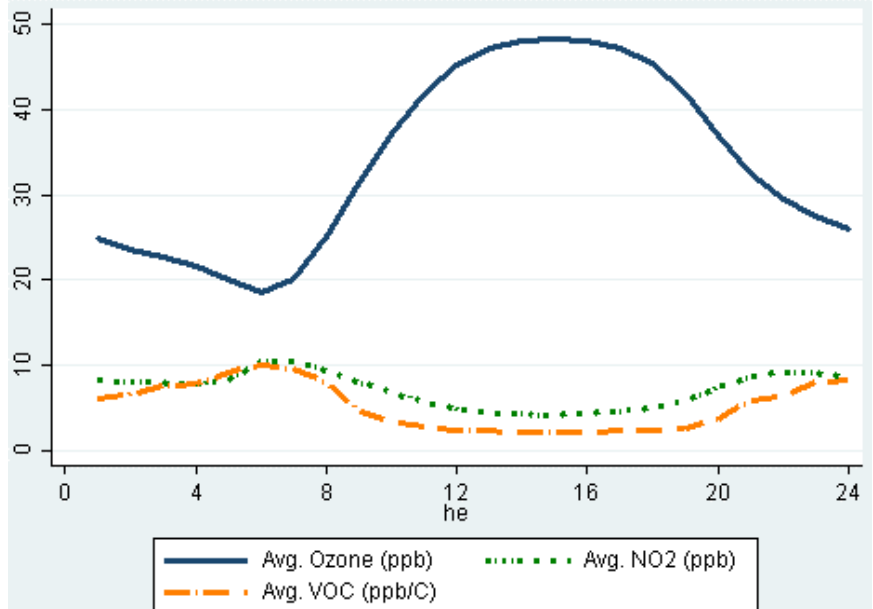
*Source:* <https://www.quora.com/What-is-the-time-zone-for-Tennessee>.

**Figure 2 – Average Hourly Pollutant Concentrations**

**Panel A: Average Hourly Levels of Ozone and Particulate Matter**

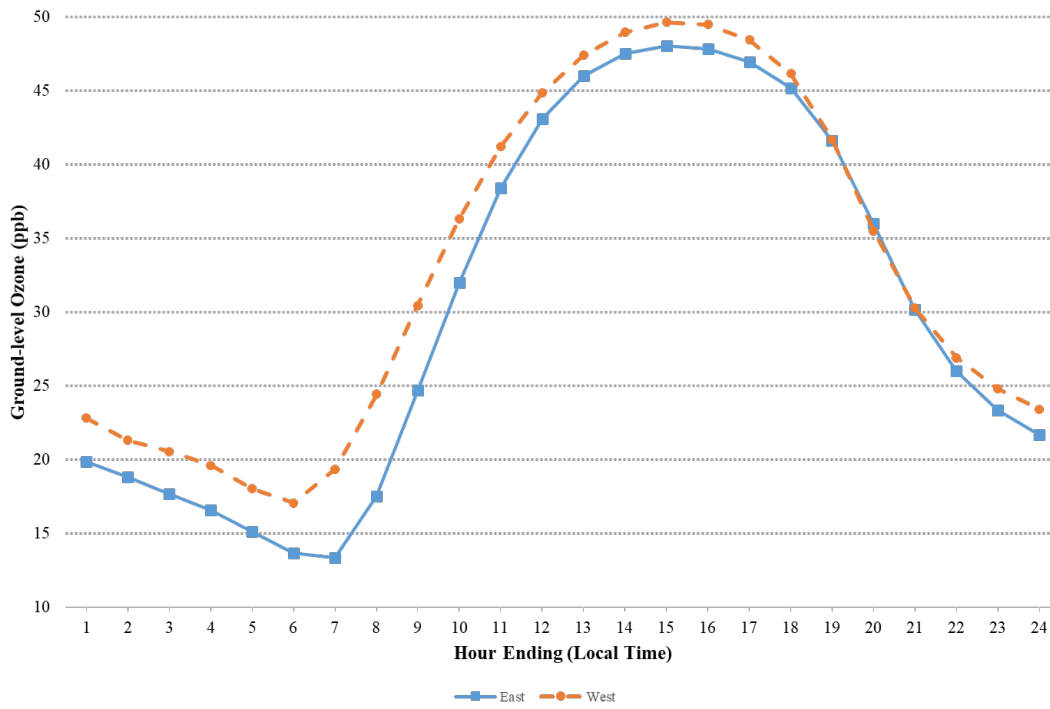


**Panel B: Average Hourly Levels of Ozone and Its Precursors**



*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.

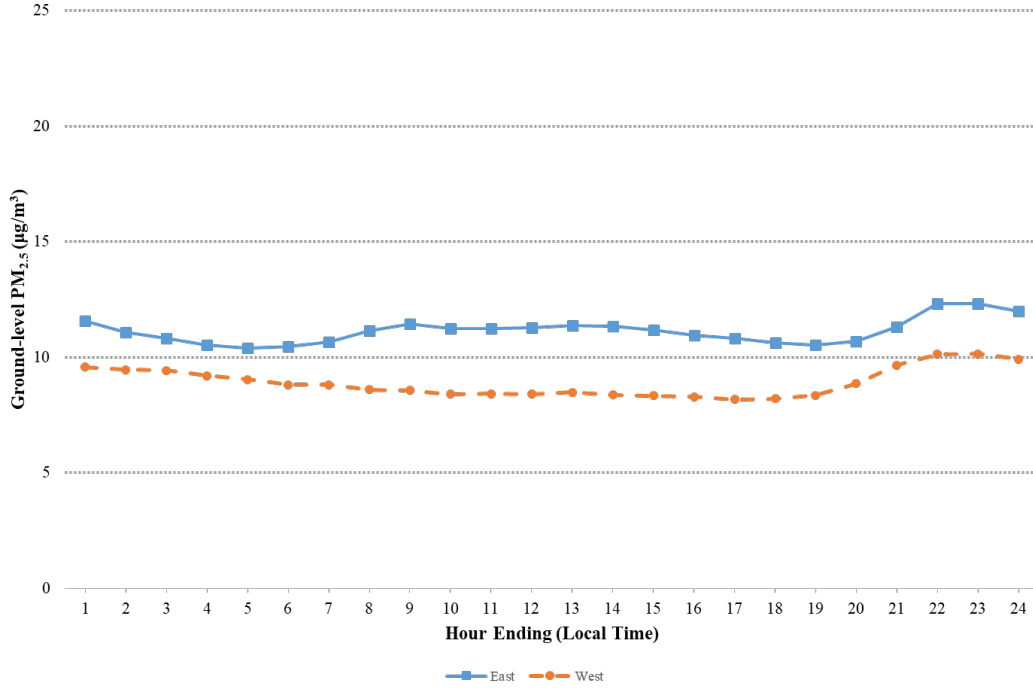
**Figure 3 – Average Ozone by Hour of the Day (Central Time Zone, 1980-2017)**



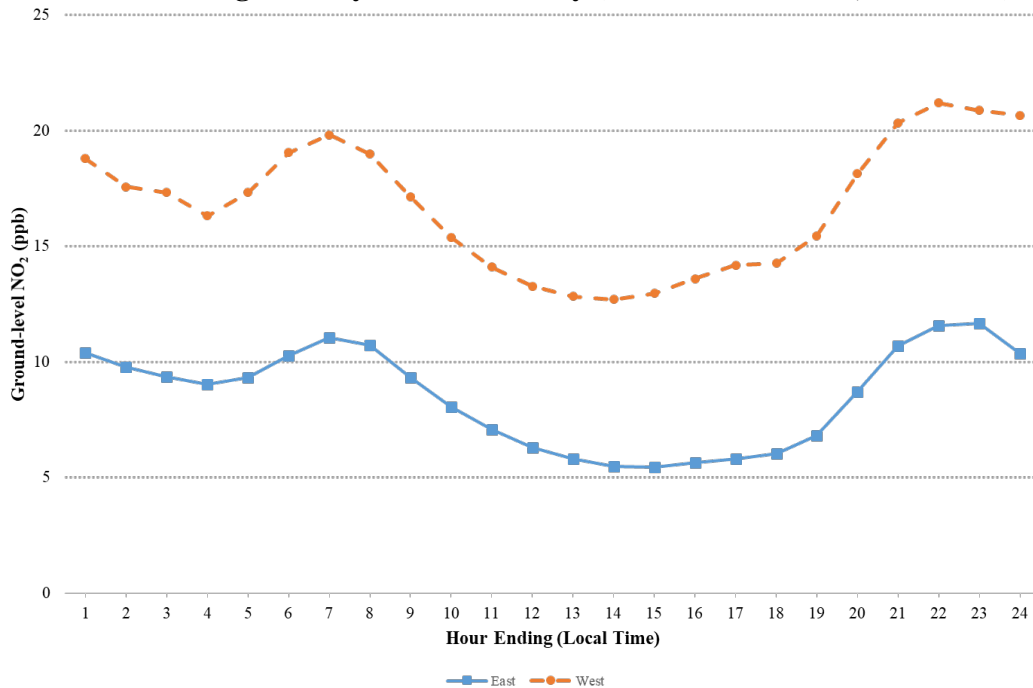
*Notes:* Average hourly ozone across all counties within 50 miles of the Central time zone border. Data from EPA’s AirData database, restricted to valid monitor-years. Valid monitor-years are defined as having: 1) at least 9 hours reported between 9AM and 9PM and 2) at least 75% of hours June 1 – August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

**Figure 4 – Average NO<sub>2</sub> and PM<sub>2.5</sub> by Hour**

**Panel A: Average PM<sub>2.5</sub> by Hour of the Day (Central Time Zone, 1980-2017)**

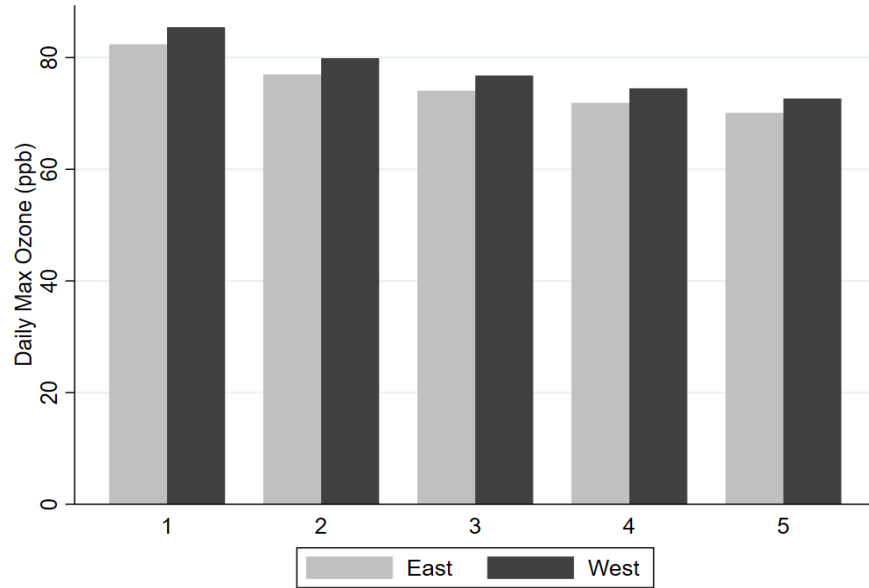


**Panel B: Average NO<sub>2</sub> by Hour of the Day (Central Time Zone, 1980-2017)**

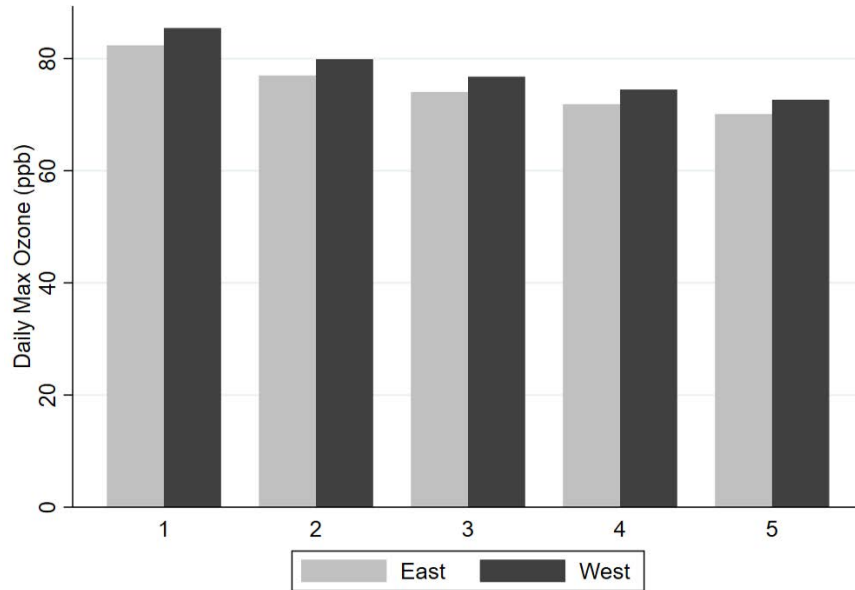


*Notes:* Average hourly NO<sub>2</sub> and PM<sub>2.5</sub> across all counties within 50 and 75 miles of the Central time zone border. Data from EPA’s AirData database, restricted to valid monitor-years. Valid monitor-years are defined as having: 1) at least 9 hours reported between 9AM and 9PM and 2) at least 75% of hours June 1 - August 31 report an observation.

**Figure 5 – Highest Annual 8-Hour Ozone Concentration, by Rank (1980-2017, 50 miles)**  
**Panel A: Local Time**



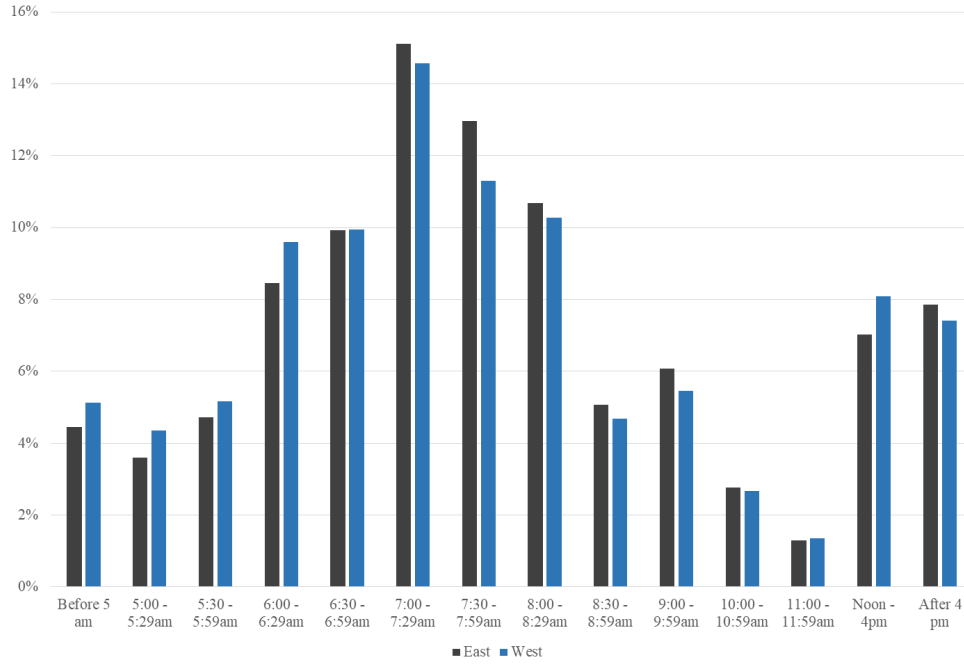
**Panel B: Greenwich Mean Time**



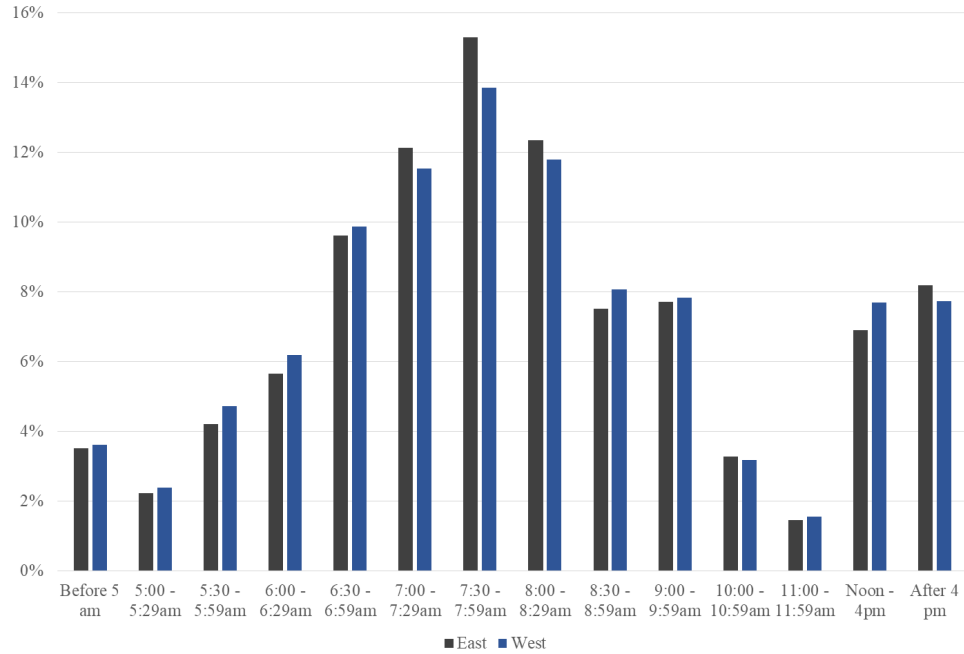
*Notes:* This figure compares daily maximum 8-hour ozone concentration across the time zone border. The comparison is made for the highest, 2<sup>nd</sup> highest, 3<sup>rd</sup>, 4<sup>th</sup>, and 5<sup>th</sup> highest 8-hour average concentration in a day by year, averaged across all years in the sample (1980 – 2017).

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

**Panel A: Time Departing Home for Work**

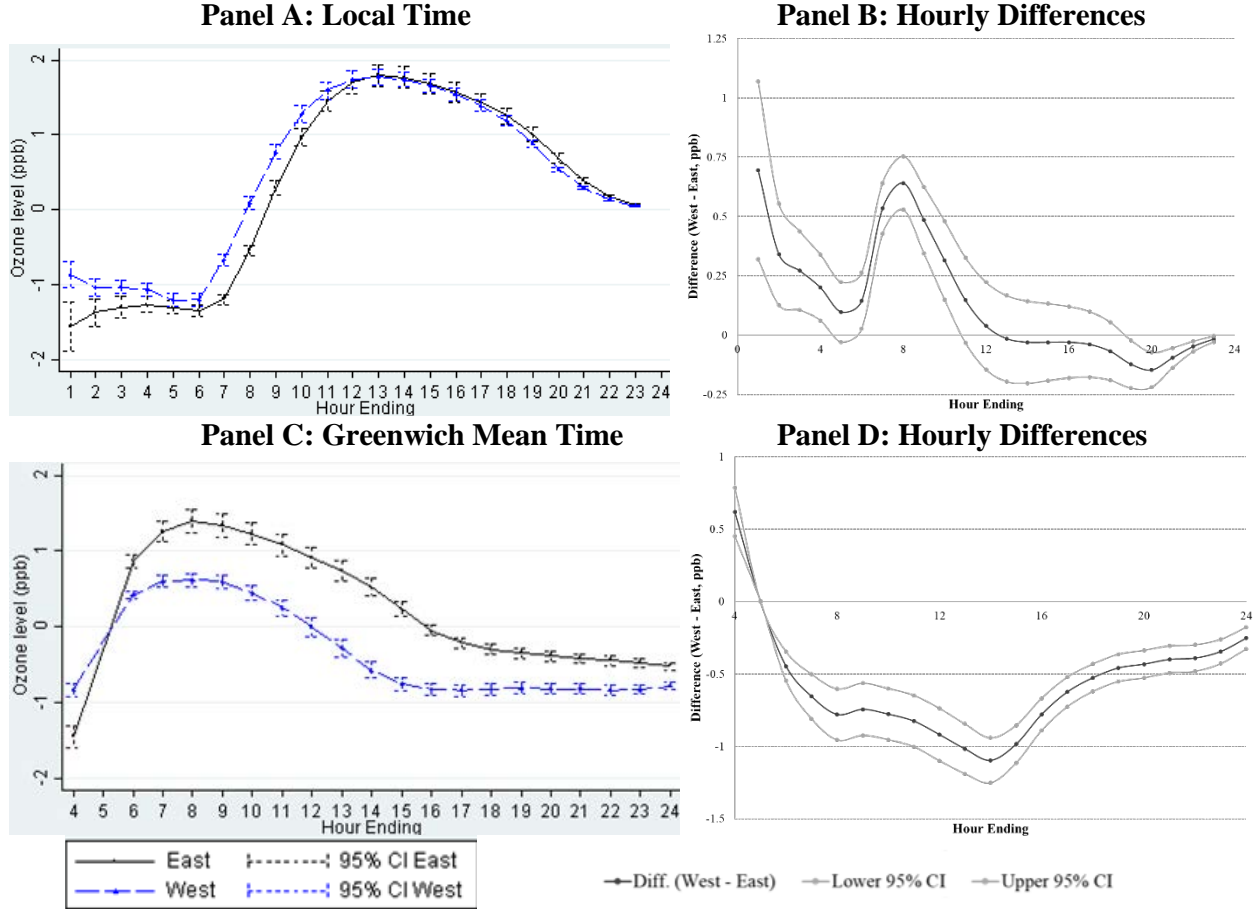


**Panel B: Time Arriving to Work**



*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.

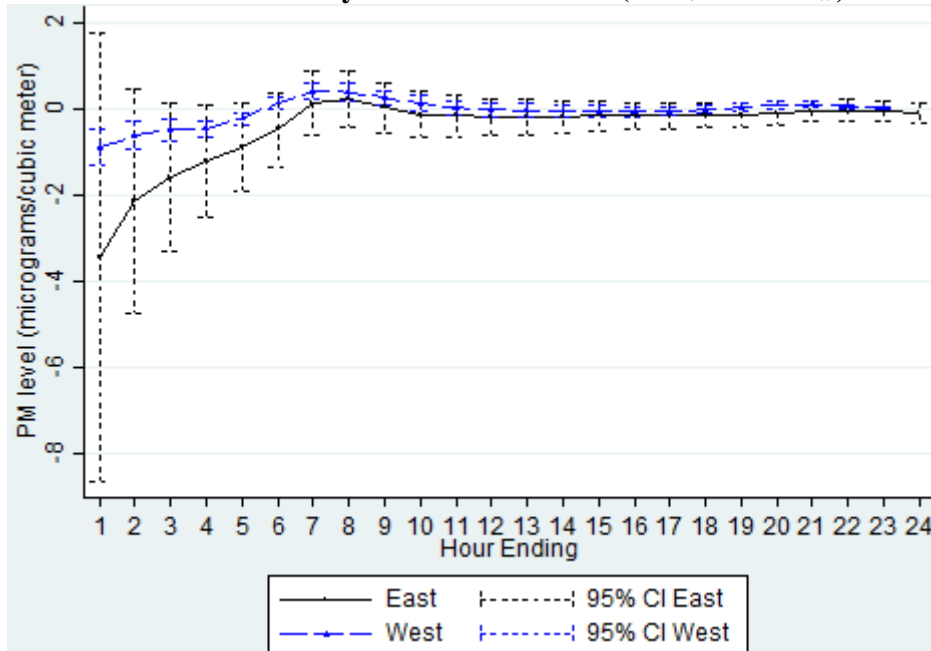
**Figure 7 – Ground Level Ozone by Hour with 95% CI (1980-2017)**



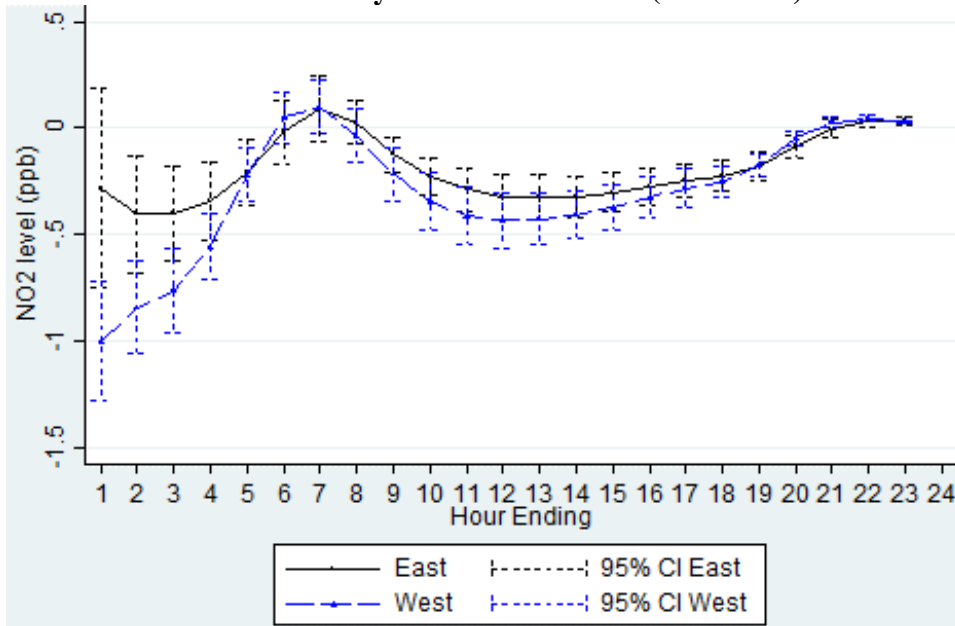
Notes: Results of estimation of [A] Equation (1) and [B] modified Equation (1) using GMT for the period 1980-2017. Includes counties within 50 miles of a U.S. time zone border. Plot is of the  $\beta$ 's for *East* and *West* by hour. Omitted category is hour ending 24 in Panel A and hour ending 5 in Panel B. Standard errors clustered by monitor.

**Figure 8– Particulate Matter and NO<sub>2</sub> by Hour with 95% CI**

**Panel A: Particulate Matter by Hour with 95% CI (PM<sub>10</sub> and PM<sub>2.5</sub>; 1993-2017)**

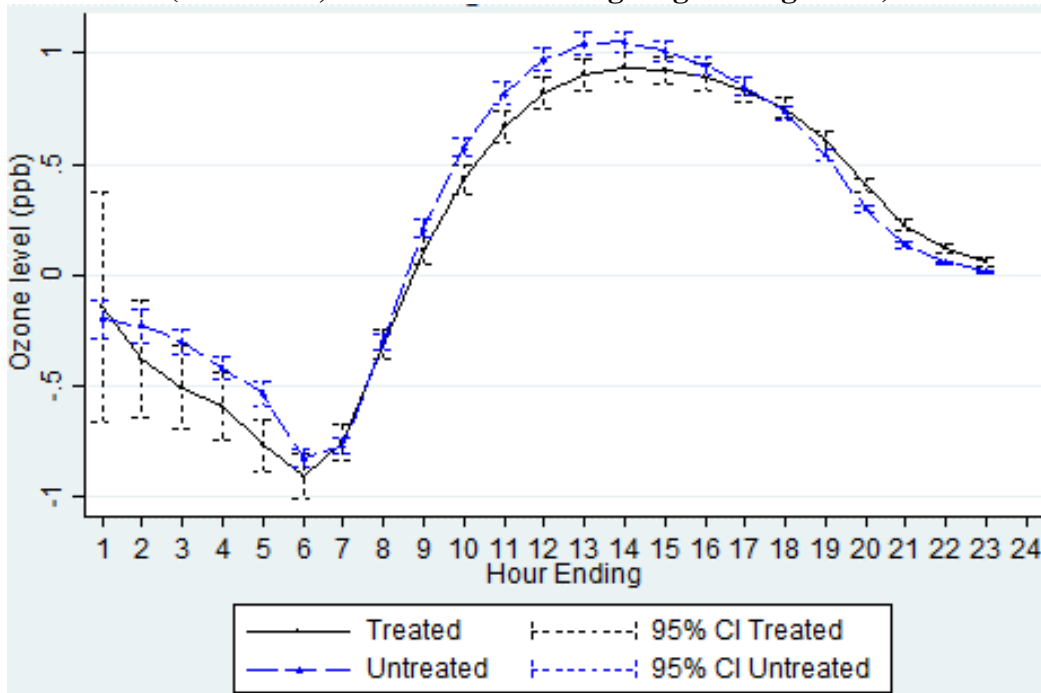


**Panel B: NO<sub>2</sub> by Hour with 95% CI (1980-2017)**



Notes: Plot is of the  $\beta$ '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 PM<sub>10</sub> and PM<sub>2.5</sub> are included, with a dummy variable for PM<sub>2.5</sub>. 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 – Ozone by Hour under the NO<sub>x</sub> Budget Program (1980-2008; NBP states excluding neighboring states)**



Notes: Estimation of Equation (3), our triple difference equation analyzing the NO<sub>x</sub> Budget Program. “Treated” refers to states participating in the NO<sub>x</sub> 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.