Appendix

A. Analyses of Ozone by Hour Across Time Zone Borders

A.1. Meteorological Controls and Solar Radiation

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

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

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

A.1.1. Wind

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

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

where the variables are defined as before. The new terms are seen next to the coefficients for $\gamma_1$through γ_4, and are the interaction between being on the eastern (western) side of a time zone border and wind speed and wind direction, respectively. Results from this estimation on our subsample can be seen in Figure A1. The results are qualitatively similar for HE7 – HE10; we see a persistent gap between ozone levels on the eastern and western sides of the border. However, in this case we actually see this gap persist into the early afternoon hours.

A.1.2. Temperature

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

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

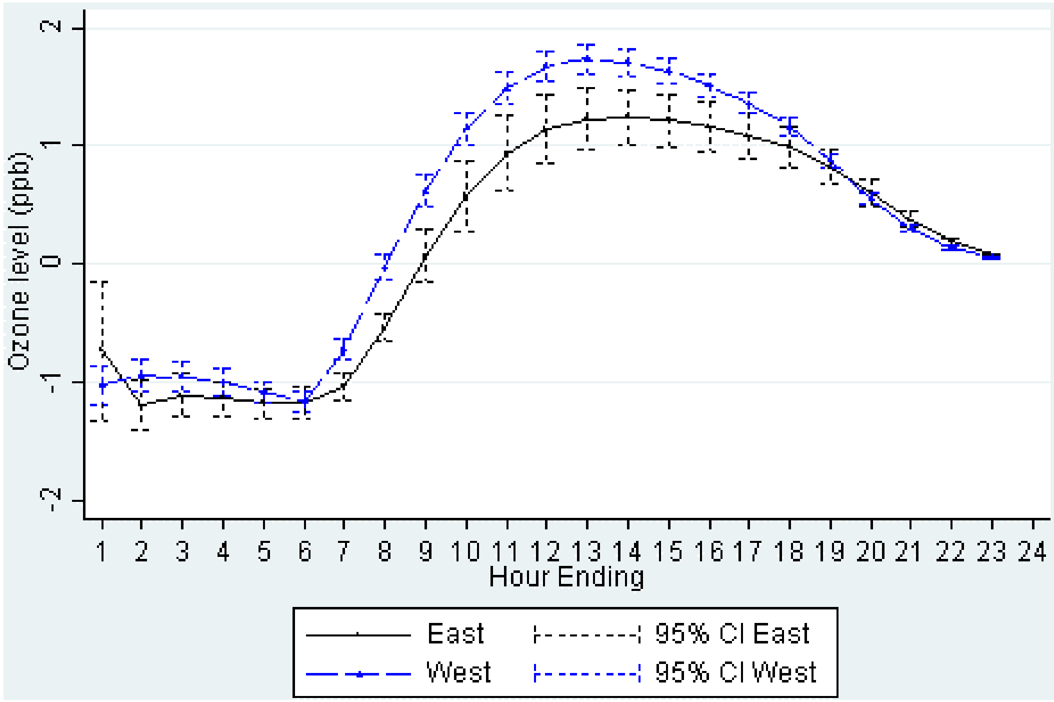
where the variables are defined as before. The new terms, seen next to the coefficients for γ_1 and γ_2, are the interaction between being on the eastern side of a time zone border and contemporaneous hourly temperature.

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

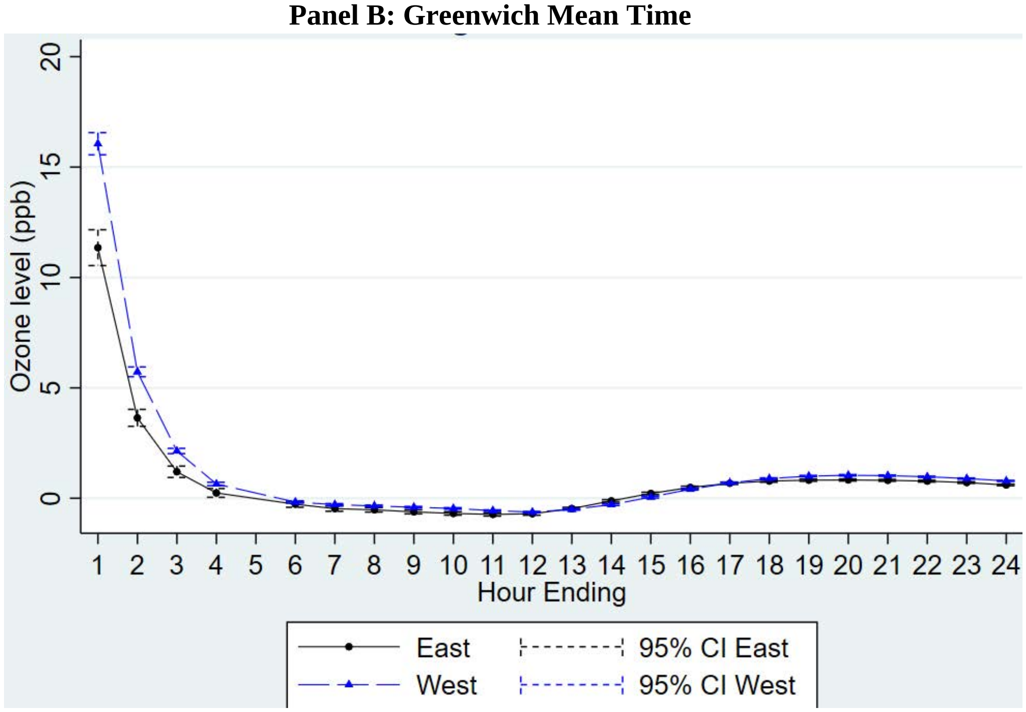
Finally, since the relationship between ozone and temperature may be nonlinear, we include a flexible polynomial form for temperature as in Equation (A3):

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

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



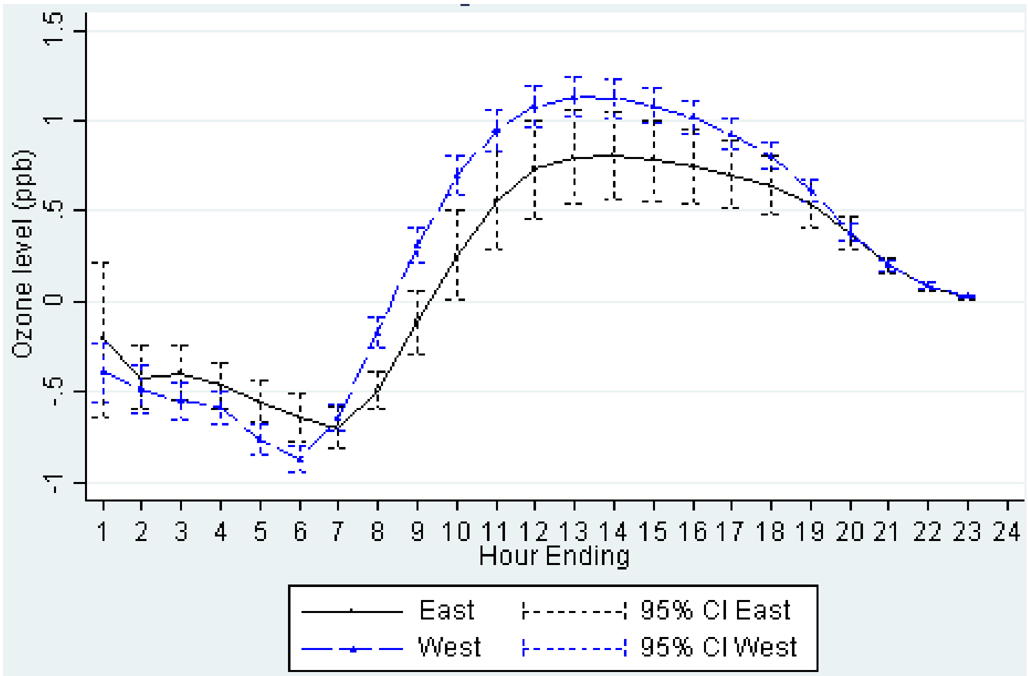
Panel B: Greenwich Mean Time



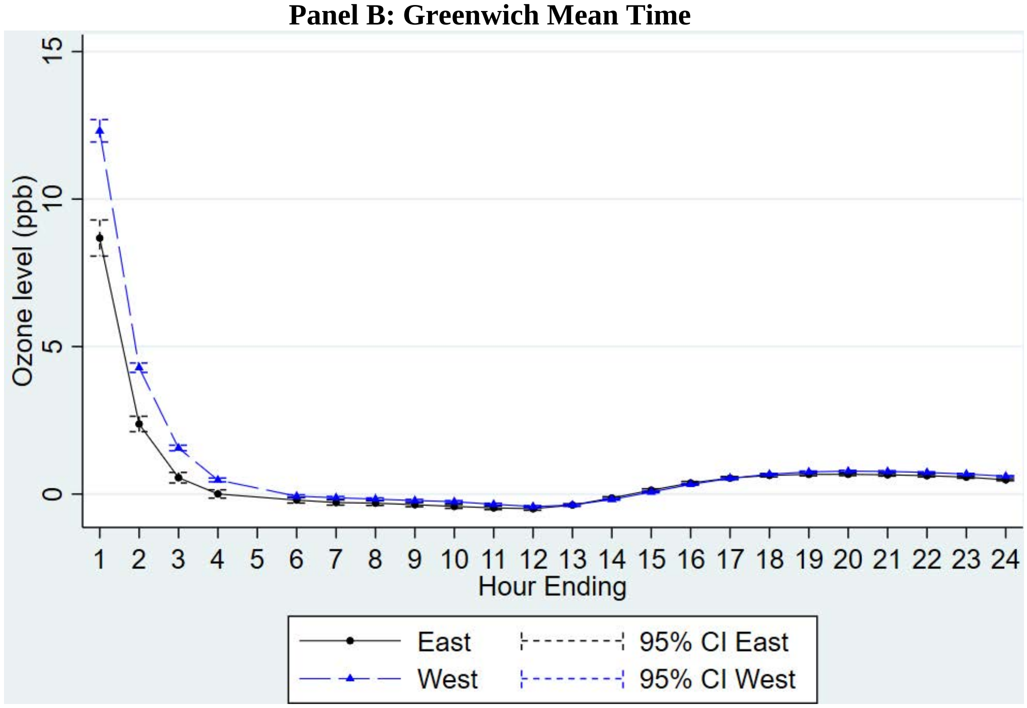
Notes: Results of estimation of Equation (A1) for the period 1980-2017. Includes counties within 50 miles of a U.S. time zone border. Plot is of the β's for *East* and *West* by hour. Omitted category is hour ending 24 local time. Standard errors clustered by monitor.

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

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

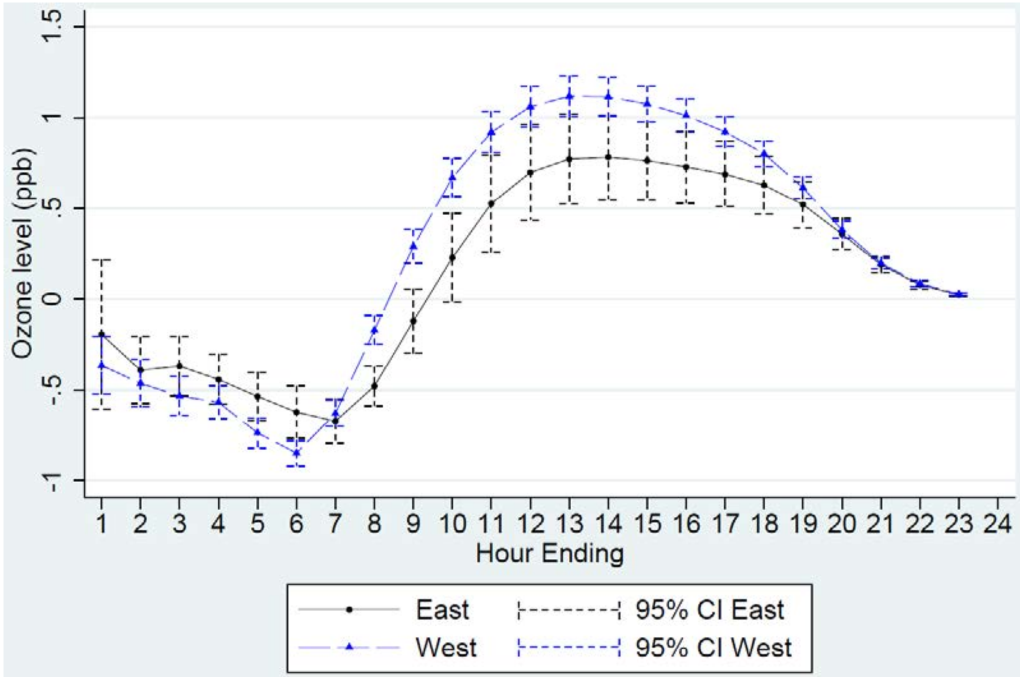


Panel B: Greenwich Mean Time

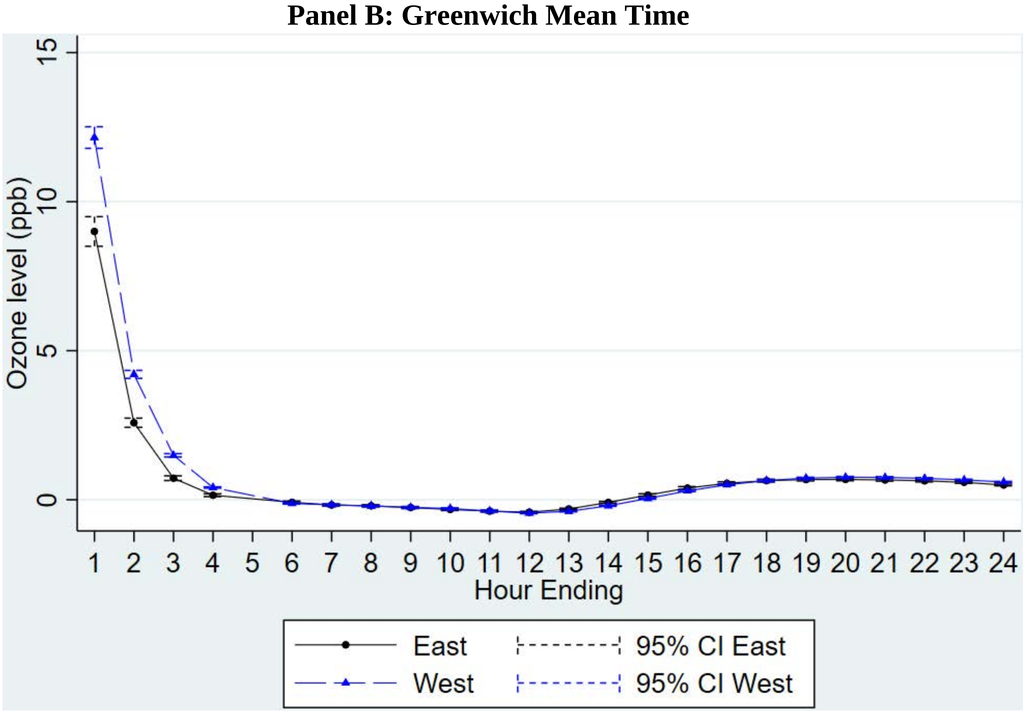


Notes: Results of estimation of Equation (A2) for the period 1980-2017. Includes counties within 50 miles of a U.S. time zone border. Plot is of the β's for *East* and *West* by hour. Omitted category is hour ending 24 local time. Standard errors clustered by monitor.

Figure A3 - Ground Level Ozone by Hour with 95% CI
Including controls for nonlinear temperature (1980-2017)
Panel A: Local Time



Panel B: Greenwich Mean Time



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

A.1.3. Solar Radiation

Another potential concern, similar to the meteorological controls described and presented above, is if there were differences in the levels of solar intensity on either side of the time zone border. The differences we find between east and west in our analyses around time zone borders are due to differences in the timing of emissions and solar intensity for the same *local* hour. Comparing 8AM Eastern to 8AM Central, we would expect higher ozone formation on the west as even if the timing of emissions are the same in GMT (as shown in Section 3.2), the ozone precursors would be in the presence of higher levels of sunlight and solar intensity on the western side of the border. For the same *contemporaneous* hour (e.g., 8AM ET vs. 7AM CT), we would expect the solar radiation to be the same within our narrow window of analysis.

As a robustness check, we processed solar data from the National Solar Radiation Database (NSRDB) for 1991-2005.[39] We map the three closest solar stations to each ozone monitor in our sample and further restrict them to be within 50-miles of the monitor. We then take the average global hourly horizontal irradiance (GHI) among the matched solar stations for each ozone monitor observation in our dataset, similar to the county-level averaging done for the meteorological controls in Section A.1. Figure A4 presents the results of estimating our main Equation (*1*) where we include a control for the hourly solar radiation as measured by GHI. Again, the plot is quite similar to our main results in Figure 7 in the paper.

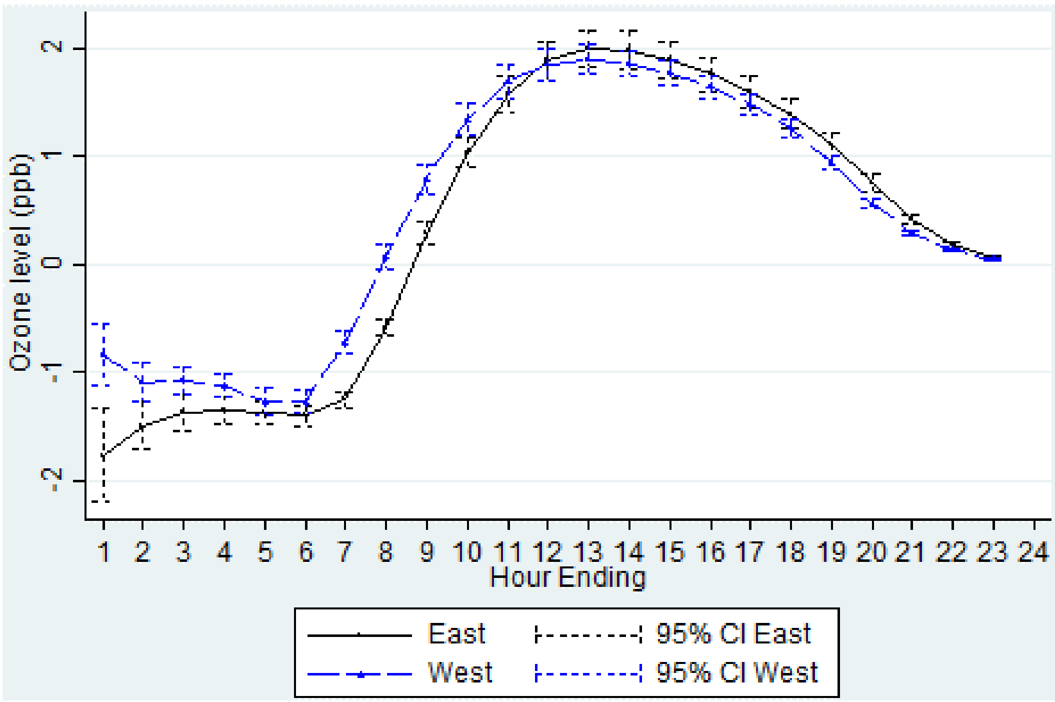
Another purpose for the solar irradiance controls would be to shed light on the *mechanism* behind our main findings. We now interact the hourly coefficients for *East* and *West* with the hourly solar data in the figures below. Basically, in this exercise we force the two sides of the time zone border to have the same solar irradiance in *local* time. Naturally, we do not have estimates in the late evening and early morning hours due to a lack of non-zero solar irradiance in these hours.

For this group of coefficients, displayed in Panel A of Figure A5 with the same scale of our main results (also similar to the scale of Figure A4) and zoomed in for the y-scale in Panel B, the gap between east and west nearly vanishes away. It is on the scale of less than 1/100th of a part per billion (ppb) difference in ozone concentrations, as visible in Panel B of Figure A5. This suggests that differences in the intensity of solar radiation may drive our results. It is important

[39] This data is publicly available at https://www.ncei.noaa.gov/pub/data/nsrdb-solar/solar-only/.

to recognize, however, that the identifying variation in this case is quite different. We are forcing the solar irradiance to be the same at 8am ET in Kingston and 8am CT in Crossville, for instance. That would *not* happen often. It could happen, for example, in times when it is not cloudy at 8am ET but it is cloudy at 8am CT (9am ET).

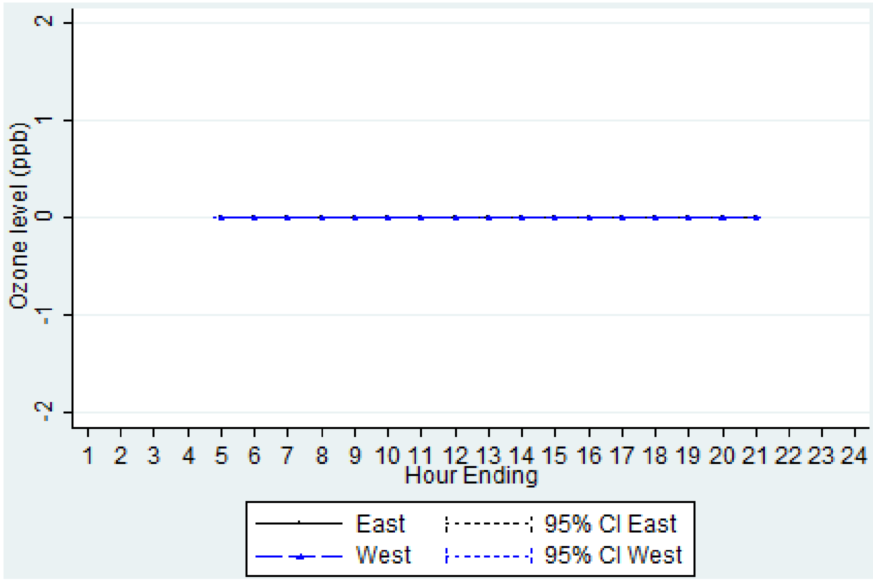
Figure A4 – Ground Level Ozone by Hour with 95% CI
Including controls for solar irradiance (1991-2005)



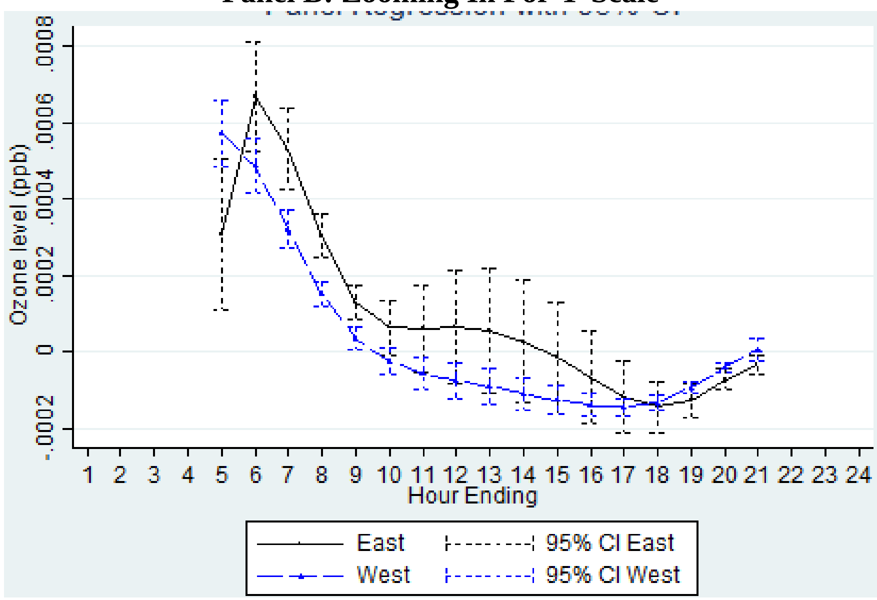
Notes: Results of estimation of alternate Equation (1) for the period 1991-2005. Includes counties within 50 miles of a U.S. time zone border. Plot is of the β's for *East* and *West* by hour. Omitted category is hour ending 24. Standard errors clustered by monitor.

Figure A5 - Ground Level Ozone by Hour with 95% CI
Interacting hourly coefficients with solar irradiance (1991-2005)

Panel A



Panel B: Zooming In For Y-Scale



Notes: Results of estimation of alternate Equation (1) interacting hourly coefficients with GHI for the period 1991-2005. Includes counties within 50 miles of a U.S. time zone border. Plot is of the β's for *East* and *West* by hour. Omitted category is hour ending 24. Standard errors clustered by monitor.

A.2. NO_x/VOC-Limited Status, Alternative Distances to the Border, and Other Results

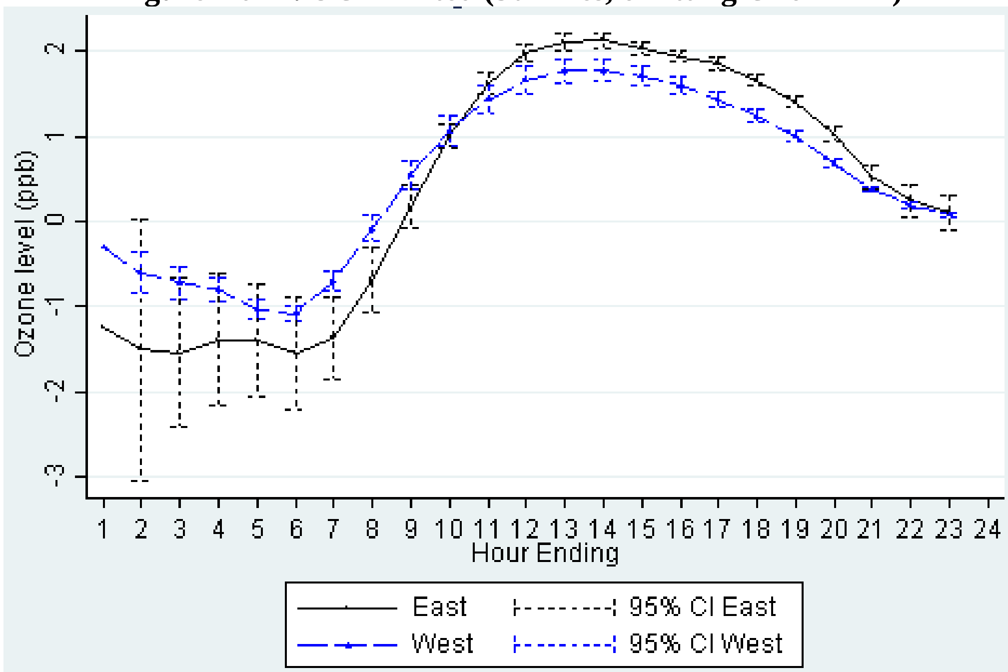
A.2.1. NO_x/VOC-Limited Status

First, we take daily measures of both ambient NO_x and VOC from EPA's AirData database for 1980-2017. For each county-day, we calculate the ratio of VOCs to NO_x and classify a day as either 1) NO_x -Limited, 2) VOC-Limited, or 3) Neutral.[40] Counties are identified as being NO_x - or VOC-limited in a year based on which category has the largest tally of days in a given year. Since these statuses are fairly stable year-to-year, we fill in missing years as NO_x -Limited, VOC-Limited, or Neutral by the total count of days in each category across a 5-year period.

We estimate a modified version of Equation (1) where we interact the hourly coefficients β_t^E and β_t^W with controls for counties that are NO_x - or VOC-limited. Results from this estimation are presented separately for each group and can be seen in Figure A5 – Figure A7. Notwithstanding that these results are only from a matched subset of our full dataset, the results in Figure A5 suggest that the pattern we see in Figure 7 may be driven by VOC-Limited areas. Similar to the main results in the paper; we see a significant gap between ozone levels on the eastern and western sides of the border in the morning hours (HE7-HE8). Moving into the afternoon, the ozone concentration on the west dips below the levels on the east as would be expected. Results for Neutral and NOx-Limited counties in Figure A6 and Figure A7, respectively, display a similar trend as our main results but with no statistically significant differences in ozone concentrations. Taken together, these results could provide evidence that the estimates we find in the main paper may be driven by changes in ozone concentrations near urban areas (which are predominantly VOC-Limited). The observed differences between east and west in the morning hours (HE7 – HE8) and reverse in the afternoon could further indicate that rush hour effects may be driving the differences in ozone concentrations in Figure 7.

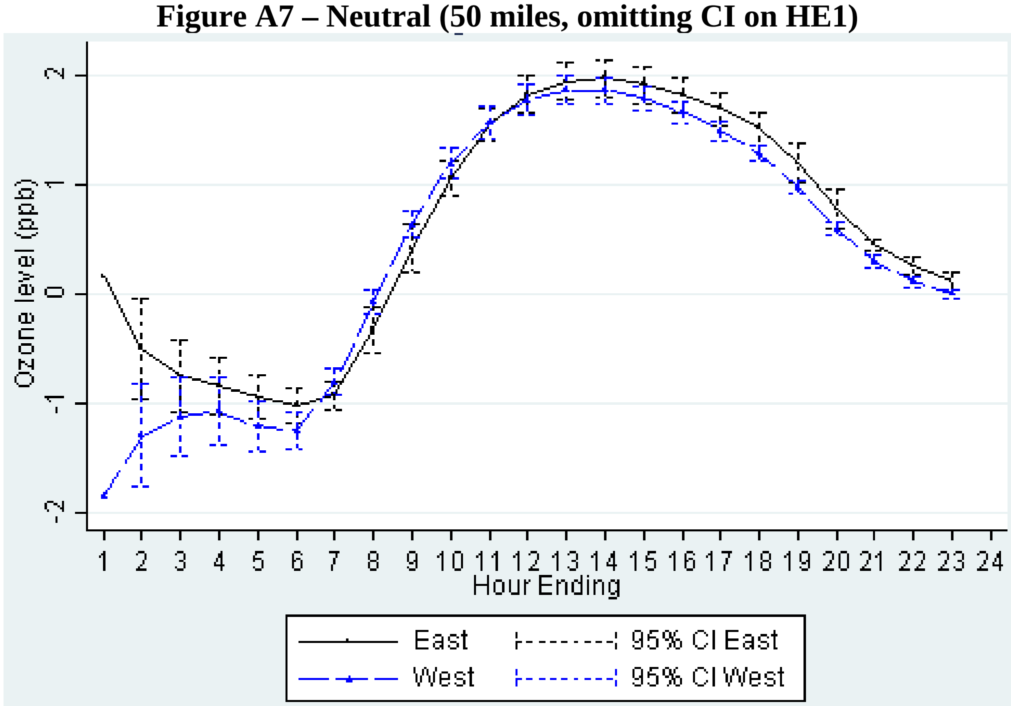
[40] Following NRC (1991), days with a ratio of VOCs to NO_x of 4 or below are identified as VOC-Limited and 15 or above as NO_x -Limited; the remainder are Neutral.

Figure A6 – VOC-Limited (50 miles, omitting CI on HE1)



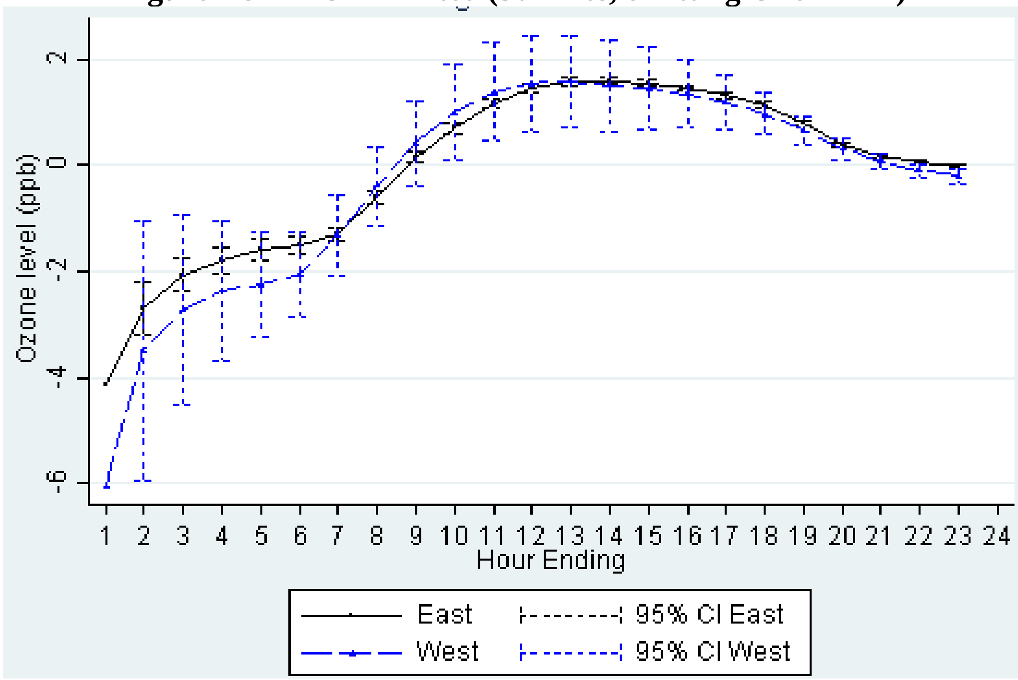
Notes: Results of estimation of modified Equation (A1) for the period 1980-2017. Includes counties within 50 miles of a U.S. time zone border. Plot is of the β's for *East* and *West* by hour. The omitted category is hour ending 24. Large, overlapping confidence intervals not shown for HE1. Standard errors clustered by monitor.

Figure A7 – Neutral (50 miles, omitting CI on HE1)



Notes: Results of estimation of modified Equation (A1) for the period 1980-2017. Includes counties within 50 miles of a U.S. time zone border. Plot is of the β's for *East* and *West* by hour. The omitted category is hour ending 24. Large, overlapping confidence intervals not shown for HE1. Standard errors clustered by monitor.

Figure A8 – NOx-Limited (50 miles, omitting CI on HE1)

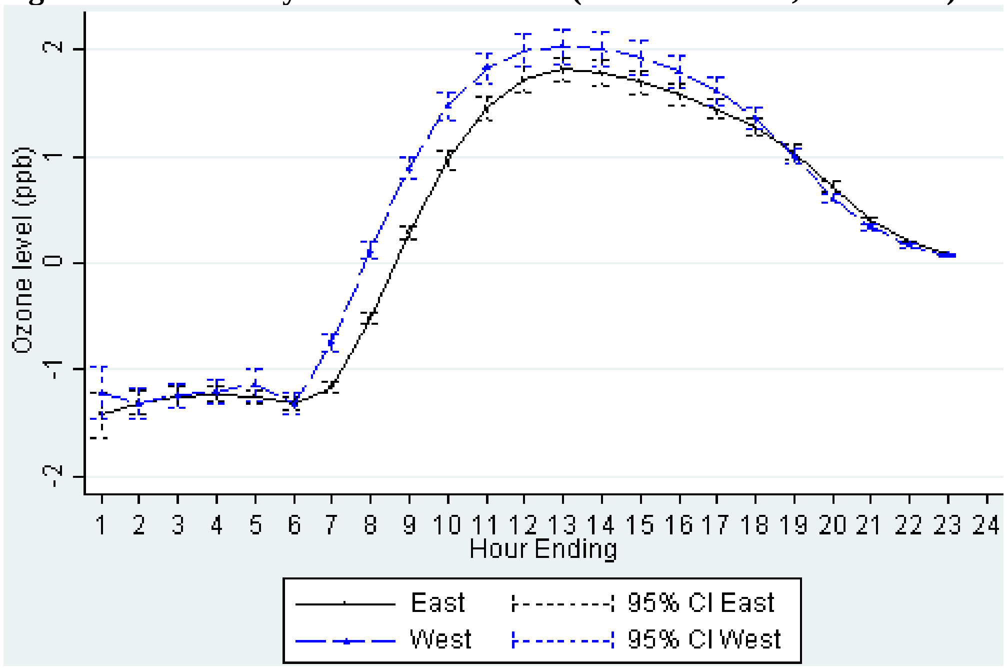


Notes: Results of estimation of modified Equation (A1) for the period 1980-2017. Includes counties within 50 miles of a U.S. time zone border. Plot is of the β's for *East* and *West* by hour. The omitted category is hour ending 24. Large, overlapping confidence intervals not shown for HE1. Standard errors clustered by monitor.

A.2.2. Alternative Distances from the Time Zone Border

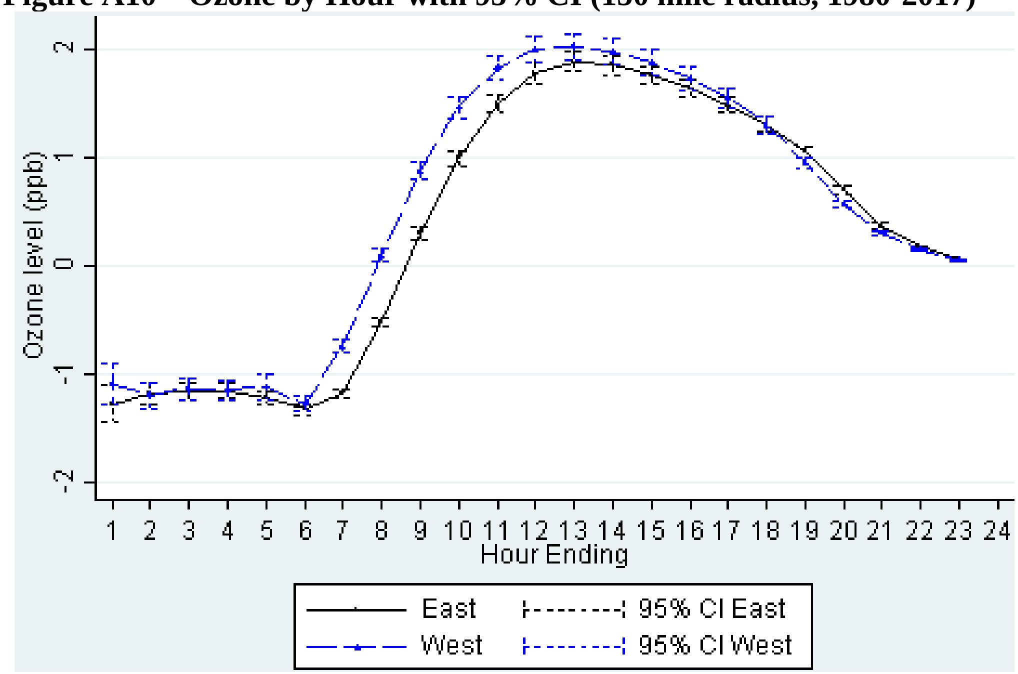
Our main results in the paper focus on a 50 mile radius from the time zone border, which we argue is narrow enough to ensure characteristics are similar on either side of the border yet wide enough to have sufficient data. As a robustness check, we estimate our main Equation (1) with radii of 100, 150, and 200 miles from the time zone border in Figure A8 – Figure A10. The differences by hour are summarized in Table A1. Across each of these distances, our results are qualitatively similar with our main results presented in Figure 7.

Figure A9 – Ozone by Hour with 95% CI (100 mile radius, 1980-2017)



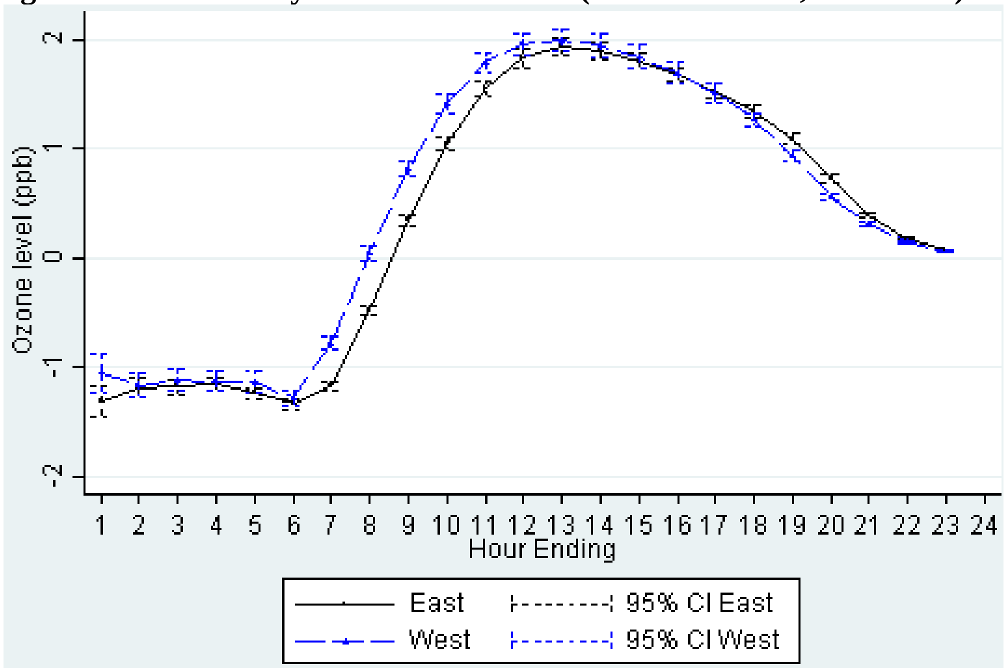
Notes: Results of estimation of Equation (1) for the period 1980-2017. Includes counties within 100 miles of a U.S. time zone border. Plot is of the β's for *East* and *West* by hour. Omitted category is hour ending 24. Standard errors clustered by monitor.

Figure A10 – Ozone by Hour with 95% CI (150 mile radius, 1980-2017)



Notes: Results of estimation of Equation (1) for the period 1980-2017. Includes counties within 150 miles of a U.S. time zone border. Plot is of the β's for *East* and *West* by hour. Omitted category is hour ending 24. Standard errors clustered by monitor.

Figure A11 – Ozone by Hour with 95% CI (200 mile radius, 1980-2017)



Notes: Results of estimation of Equation (1) for the period 1980-2017. Includes counties within 200 miles of a U.S. time zone border. Plot is of the β's for *East* and *West* by hour. Omitted category is hour ending 24. Standard errors clustered by monitor.

A.2.3. Exploring Potential Differences Overnight

Here we investigate potential sources regarding the gap between hour 23 and hour 1 in our main results for local time in Figure 7. First, we run a linear probability model for whether there is a reading in hour 24 (and another model for hour 1) on state, month-of-year, and year fixed effects. The reference (omitted) categories are Arizona, July, and 2000 – regressions include an overall intercept. The idea is to capture reporting differences across states, months of the year, and years.

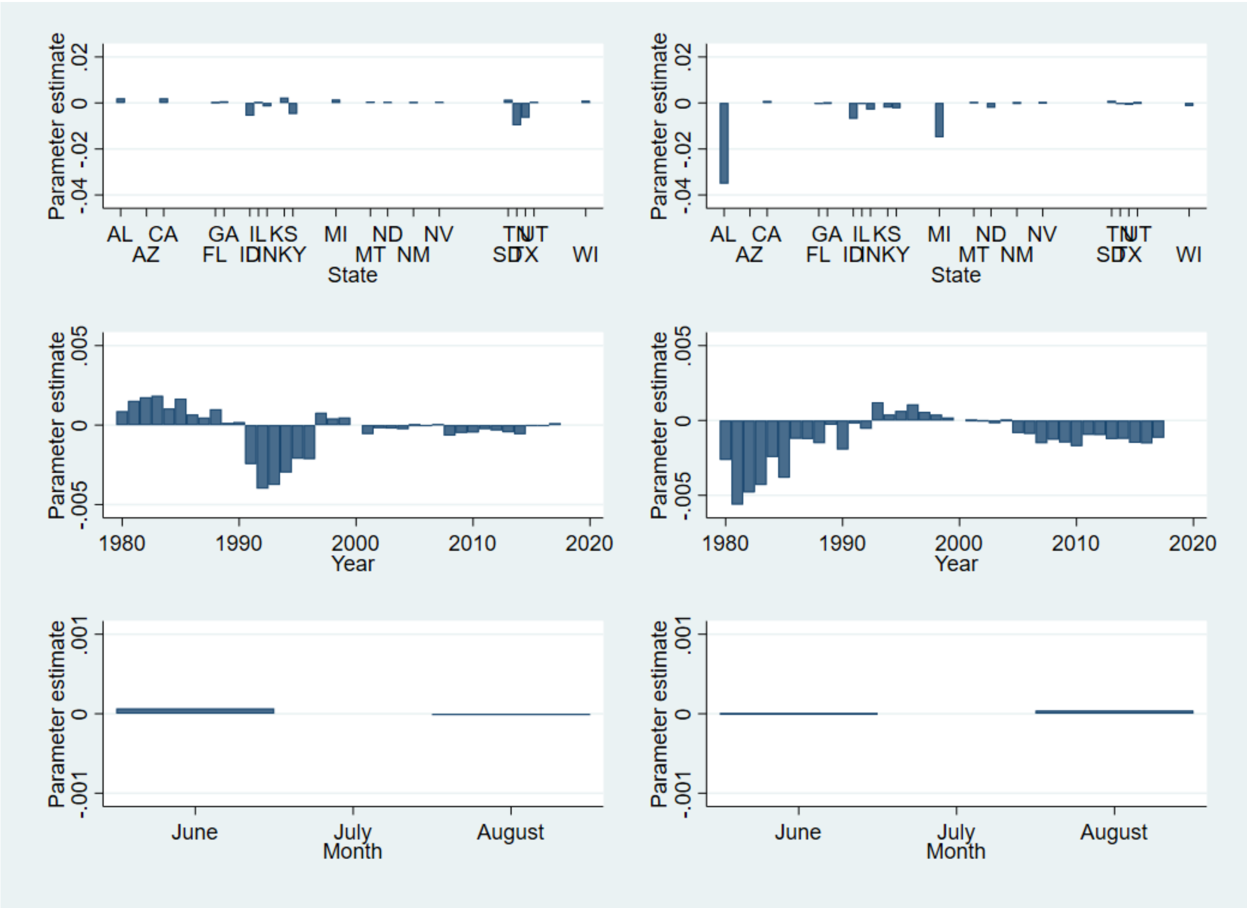
As Figure A13 shows, the most important differences in reporting happen across decades. There are fewer observations in the 1980s and the early 1990s for HE1 relative to HE24. This makes sense because until 1997 the ozone NAAQS were based on the 2nd highest hourly measurement of the year, so there was no incentive to report monitor reading for all hours, especially during the night. With the 1997 change, which went into effect only in 2004 after a long litigation, the ozone standards changed from the 2nd highest of year to the average of the 4th highest 8-hour average over three years. In this case, the incentives to report monitor reading for many more hours of the day increased. For months of year, on the other hand, there does not seem to be any major differences in reporting. For states, there are some outliers comparing

Table A1 – Hourly Differences between West and East (1980-2017, Summer) For Alternative Distances from the Time Zone Border

	Maximum Distance to Time Zone Border			
Hour Ending	50 Miles	100 Miles	150 Miles	200 Miles
1	0.694***	0.203	0.186	0.263*
	(0.191)	(0.165)	(0.131)	(0.115)
2	0.340**	-0.00984	-0.0159	0.025
	(0.109)	(0.0953)	(0.0808)	(0.073)
3	0.272**	0.0118	0.0279	0.066
	(0.0847)	(0.0763)	(0.0659)	(0.06)
4	0.201**	0.0196	0.0151	0.032
	(0.0707)	(0.0663)	(0.0569)	(0.053)
5	0.0980	0.122	0.104	0.106
	(0.0643)	(0.0848)	(0.0659)	(0.059)
6	0.146*	-0.00236	0.0562	0.064
	(0.0602)	(0.0565)	(0.0464)	(0.044)
7	0.534***	0.422***	0.439***	0.394***
	(0.0546)	(0.0505)	(0.0404)	(0.039)
8	0.641***	0.643***	0.617***	0.532***
	(0.0572)	(0.0503)	(0.0398)	(0.038)
9	0.485***	0.605***	0.572***	0.47***
	(0.0715)	(0.0633)	(0.0495)	(0.045)
10	0.315***	0.506***	0.472***	0.365***
	(0.0844)	(0.0799)	(0.0615)	(0.054)
11	0.148	0.371***	0.334***	0.236***
	(0.0914)	(0.0927)	(0.0714)	(0.062)
12	0.0390	0.271**	0.218**	0.134*
	(0.0938)	(0.0994)	(0.0770)	(0.067)
13	-0.0142	0.216*	0.142	0.068
	(0.0923)	(0.102)	(0.0789)	(0.068)
14	-0.0292	0.226*	0.126	0.049
	(0.0882)	(0.104)	(0.0798)	(0.068)
15	-0.0294	0.228*	0.117	0.035
	(0.0826)	(0.101)	(0.0772)	(0.066)
16	-0.0292	0.216*	0.101	0.015
	(0.0767)	(0.0936)	(0.0713)	(0.061)
17	-0.0385	0.172*	0.0645	-0.021
	(0.0704)	(0.0816)	(0.0625)	(0.053)
18	-0.0673	0.0873	-0.00238	-0.079
	(0.0623)	(0.0667)	(0.0515)	(0.044)
19	-0.122*	-0.0345	-0.100*	-0.158***
	(0.0515)	(0.0505)	(0.0392)	(0.033)
20	-0.146***	-0.104**	-0.130***	-0.165***
	(0.0374)	(0.0347)	(0.0265)	(0.023)
21	-0.0955***	-0.0634**	-0.0656***	-0.084***
	(0.0215)	(0.0211)	(0.0163)	(0.014)
22	-0.0473***	-0.0241*	-0.0222*	-0.032***
	(0.0111)	(0.0120)	(0.00959)	(0.008)
23	-0.0159*	-0.00472	-0.00253	-0.007
	(0.00625)	(0.00721)	(0.00541)	(0.005)

Notes: Difference in estimated hourly coefficients for *East* and *West* from Equation (1) for different radii from the time zone border.

Figure A12 - Heterogeneity in Ozone Monitor Reporting in HE24 (Left) and HE1 (Right) Across States, Years, and Months of the Year

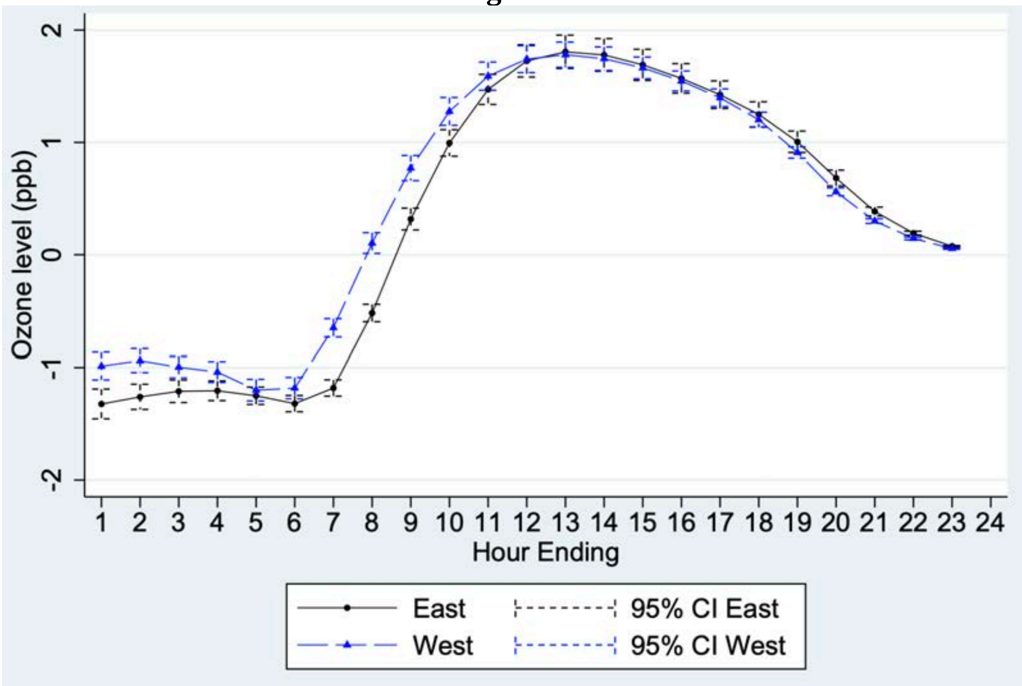


Notes: This figure displays the coefficients of state, year, and month-of-year fixed effects from linear probability models for whether an ozone monitor reported readings at HE24 (left column) and HE1 (right column). As usual, HE stands for hour ending. All coefficients reported in the same column of panels come from the same regression. The reference (omitted) categories are Arizona, July, and 2000, as regressions include an overall intercept.

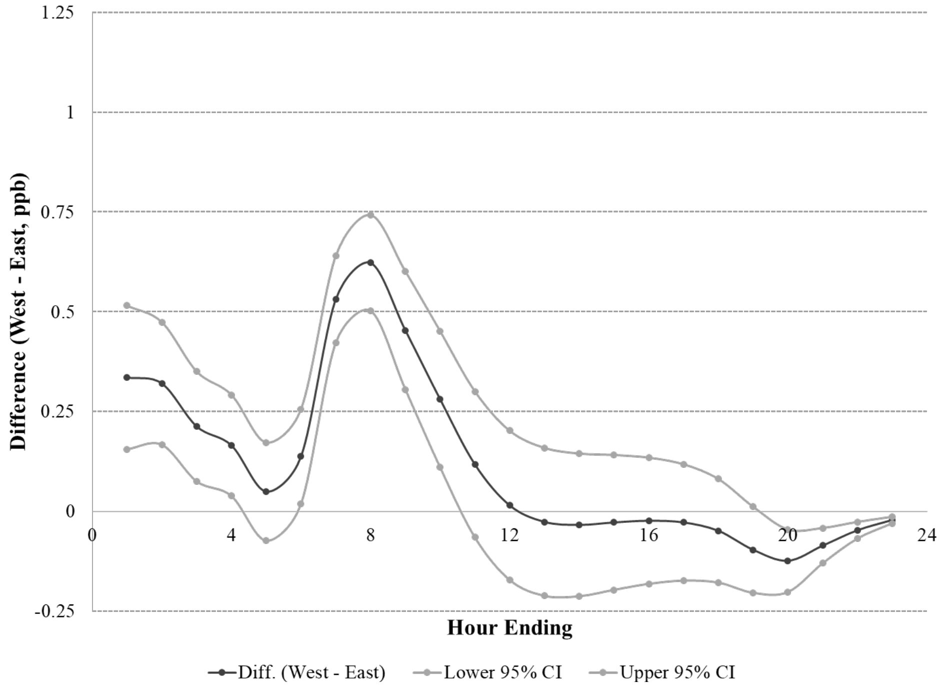
HE24 to HE1. For example, Texas and Tennessee are relatively underreported as a share of observations in HE24 as compared to HE1, while Alabama and Michigan are relatively over reported in HE24 as compared to HE1.

Given these potential differences in reporting, we then re-run the analysis with only observations from monitor-date pairs such that the monitor reported ozone concentrations for all 24 hours of that day. Although a monitor must report observations for all 24 hours in a day for that date-monitor pair to be included in this subsample, it is not required to report 24 hours for every day in the sample. For example, if a monitor reported 24 hours on June 1st and only 18 hours on June 2nd, we would include the data from June 1st but not June 2nd for that monitor. For

Figure A13 - Ground Level Ozone by Hour with 95% CI (1980-2017)
Sample Restricted to 24-Hour Monitor-Date Pairs
Panel A: Regression Results



Panel B: Hourly Differences



Notes: Results of estimation of Equation (1) for the period 1980-2017. Includes counties within 50 miles of a U.S. time zone border. A monitor must report observations for all 24 hours in a day for that date-monitor pair to be included in this subsample. Plot is of the β's for East and West by hour. Omitted category is hour ending 24. Standard errors clustered by monitor.

reference, there are over 9.5 million observations and 1,045 monitors in our main sample. When we limit to monitors reporting 24 hours per day, these drop to about 7.2 million observations and 979 monitors. Figure A14 shows that when restricting to monitors that report 24 hours in a given day, the gap between the western and eastern coefficients in HE1 is not eliminated, but it is reduced considerably without any noticeable change in the estimated effect we observe in the morning hours (6am–11am).

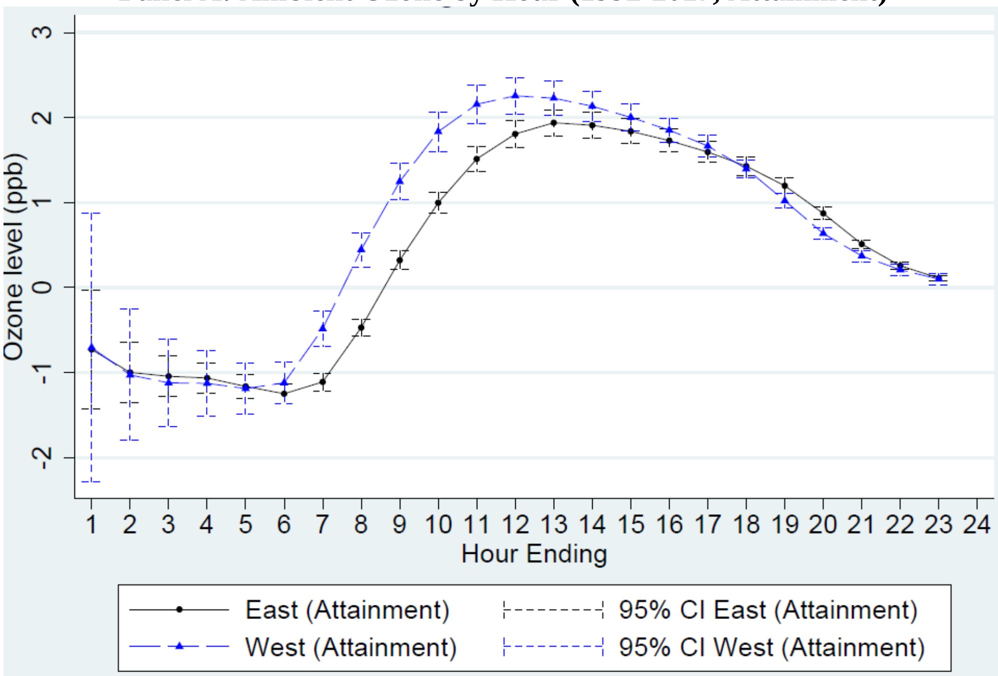
A.2.4. Additional Alternative Estimations

The alternative estimations presented for county attainment status and action days in Figure A14 and Figure A15 below are discussed in Sections 3.3.1 and 3.3.2, respectively.

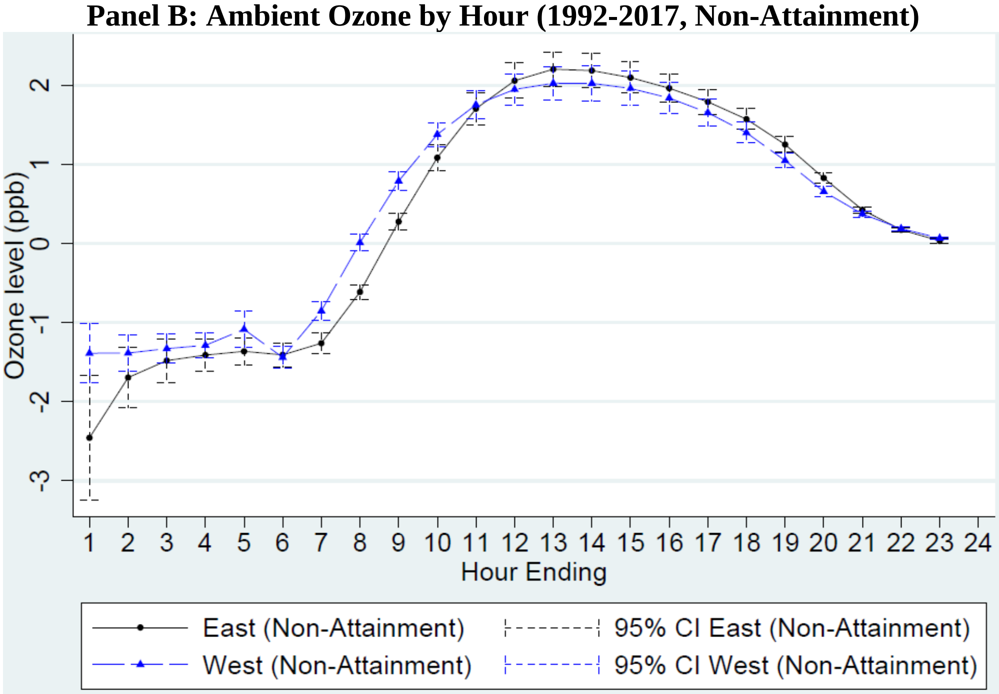
A.2.4.1. Non-Attainment Status

Figure A14 - Ambient Ozone by Hour and Attainment Status

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



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



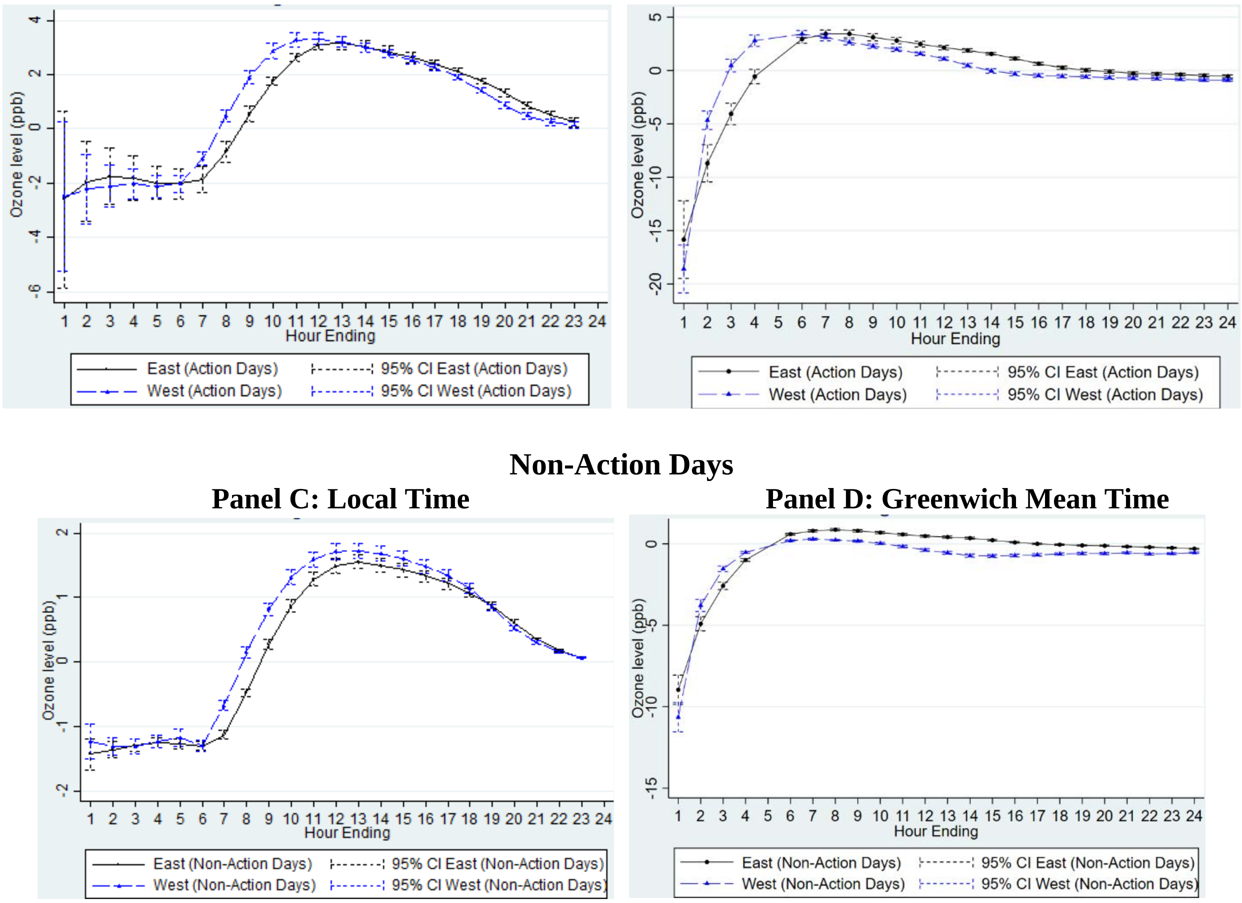
Notes: Results of estimation of Equation (2) for the period 1980-2017. Includes counties (A) in or (B) out of attainment within 100 miles of a U.S. time zone border. Plot is of the β's for *East* and *West* by hour. The omitted category is hour ending 24. Standard errors clustered by monitor.

A.2.4.2. Action Days

Figure A15 – Ambient Ozone by Hour (2004-2017, Action Days)

Action Days

Panel A: Local Time **Panel B: Greenwich Mean Time**

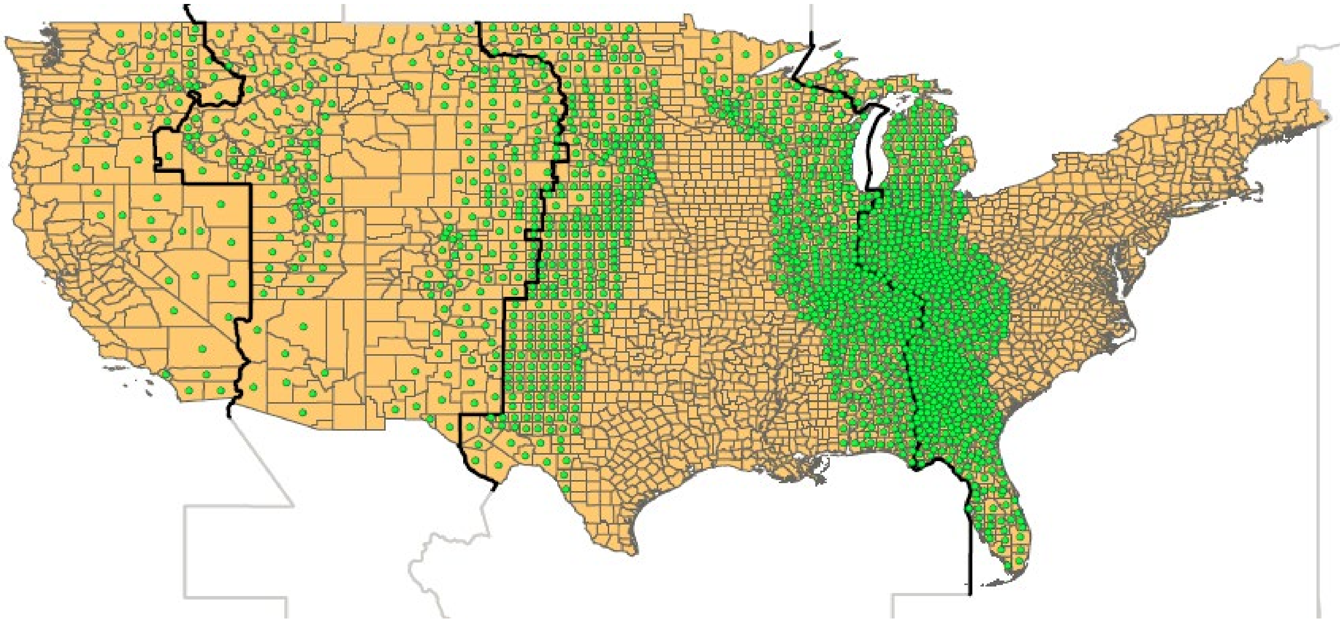


Notes: Results of estimation of a modified version of Equation (2) as described in Section 3.3.2 for the period 2004-2017. Includes counties within 100 miles of a U.S. time zone border that called an action day alert, limited to reporting areas confirmed as participating on EPA's AirNow website. Plot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

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

Figure A16 – Counties and Monitors within 200 Miles of a U.S. Time Zone Border

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



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

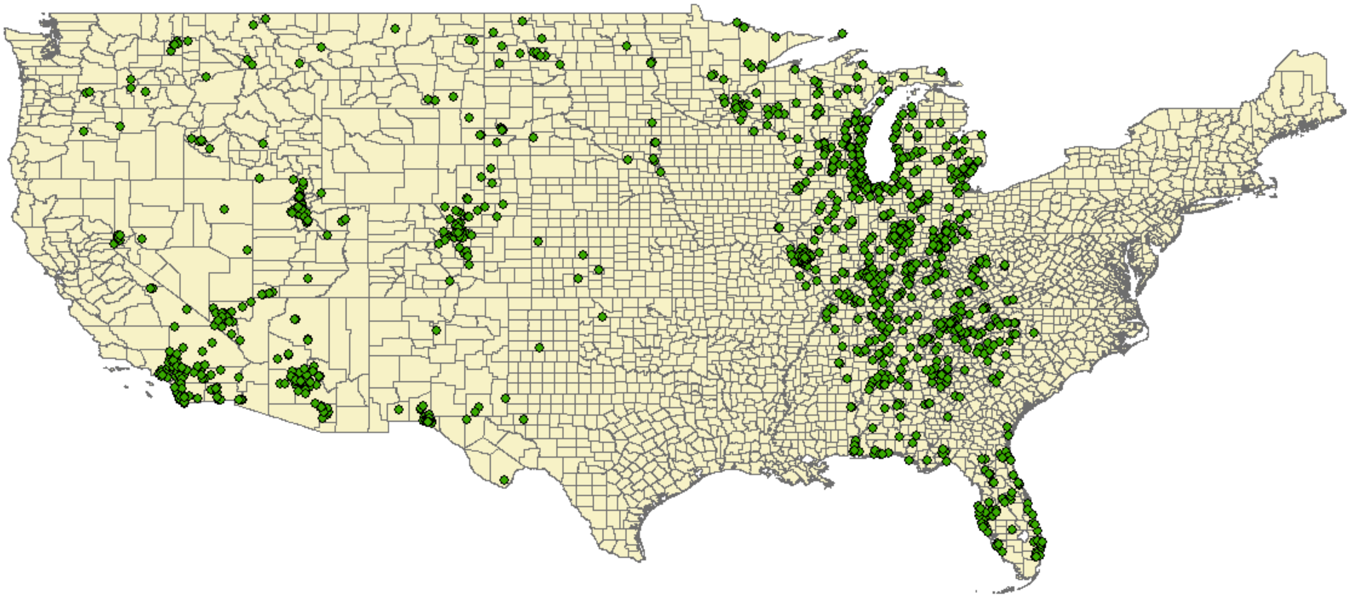
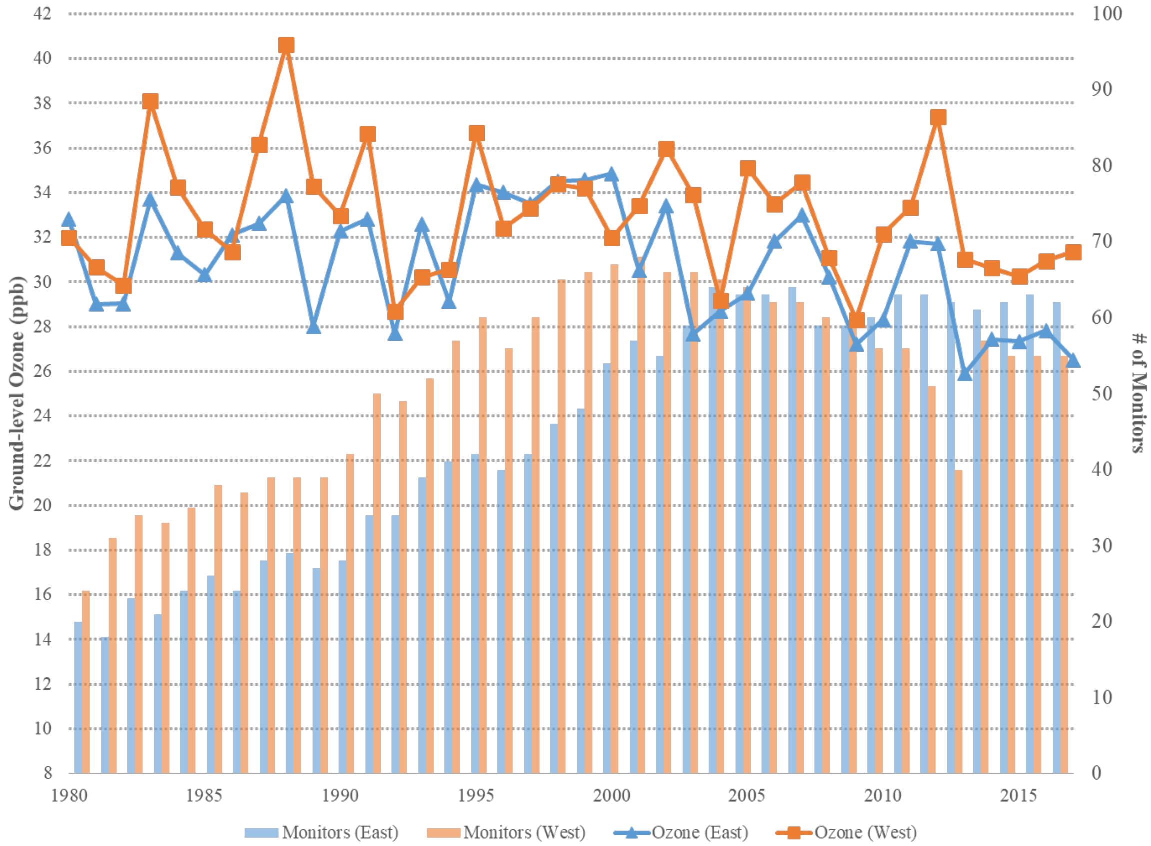
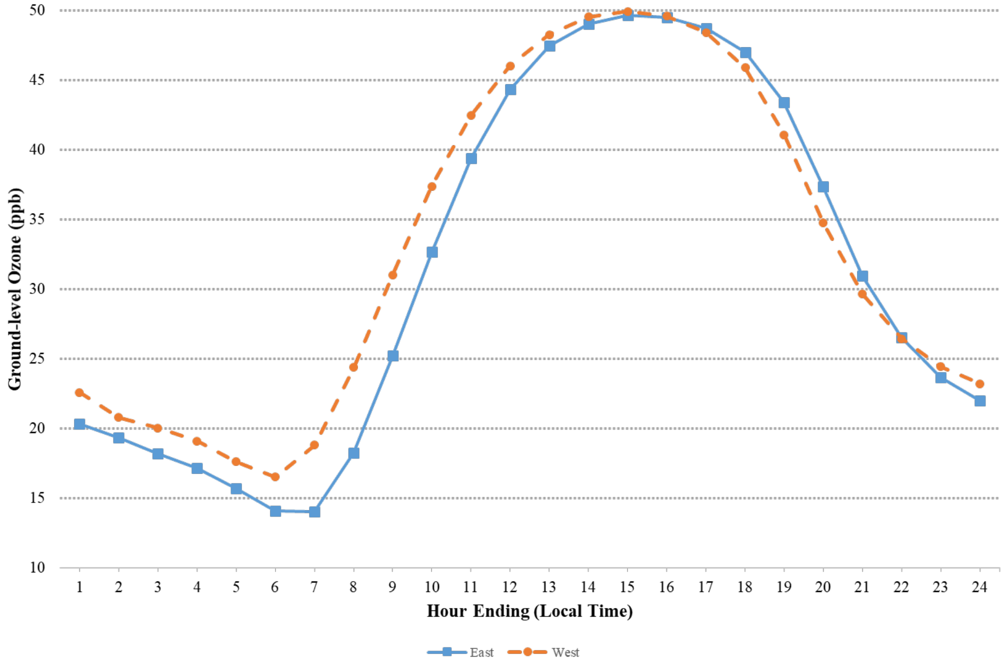


Figure A17 – Ozone Summary Statistics (Central Time zone, 1980-2017)



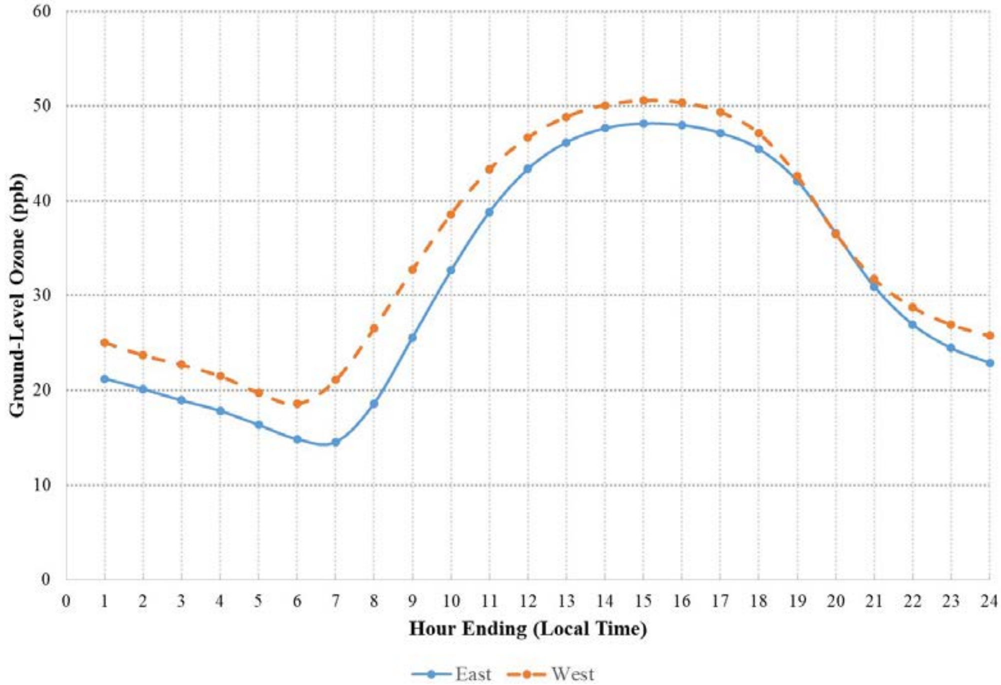
Notes: Average hourly ozone and monitor count across all counties within 50 miles of the Central time zone border. Data from EPA's AirData database, restricted to valid ozone monitor-years. Valid monitor-years are defined as having: 1) at least 9 hours reported between 9AM and 9PM and 2) at least 75%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

Figure A18 - Average Ozone by Hour (Central Time Zone, 200 miles, 1980-2017)



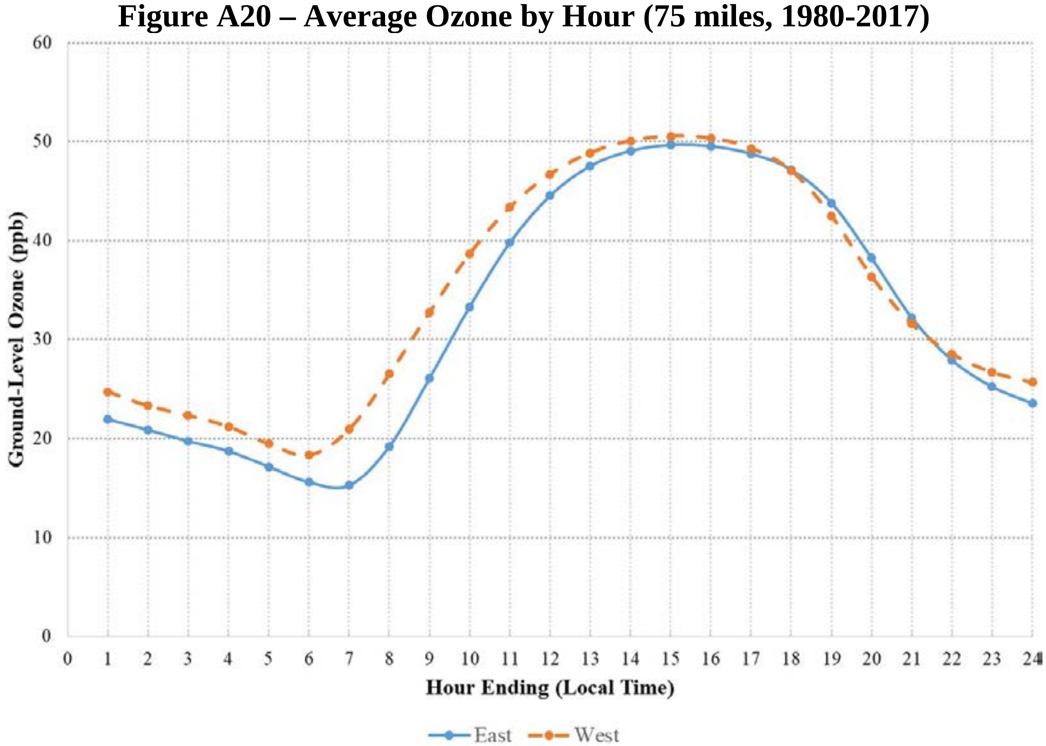
Notes: Average hourly ozone across all counties within 200 miles of the Central time zone border. Data from EPA's AirData database, restricted to valid monitor-years. Valid monitor-years are defined as having: 1) at least 9 hours reported between 9AM and 9PM and 2) at least 75% of hours June 1 - August 31 report an observation.

Figure A19 – Average Ozone by Hour (50 miles, 1980-2017)



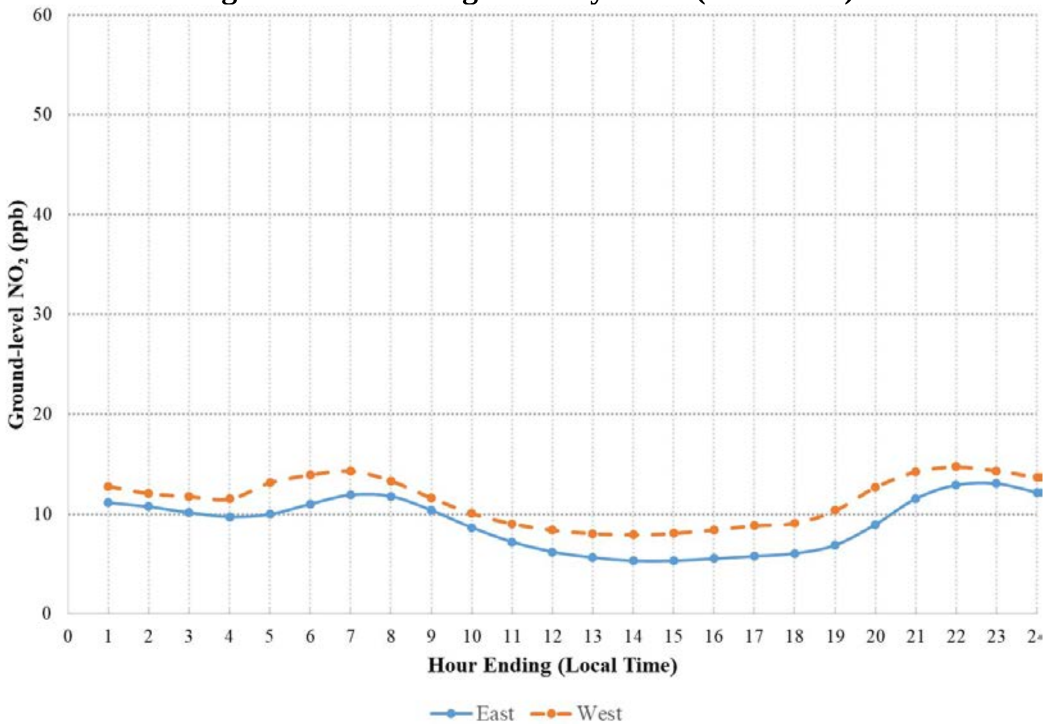
Notes: Average hourly ozone across all counties within 50 miles of a U.S. time zone border. Data from EPA's AirData database, restricted to valid monitor-years. Valid monitor-years are defined as having: 1) at least 9 hours reported between 9AM and 9PM and 2) at least 75% of hours June 1 - August 31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

Figure A20 – Average Ozone by Hour (75 miles, 1980-2017)



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

Figure A21 – Average NO2 by Hour (1980-2017)



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

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

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

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

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

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

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

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

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

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

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

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

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

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

A.5. History of NAAQS

Table A6 – Historical Ambient Ozone NAAQS

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

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

Table A7 – Historical Particulate Matter NAAQS

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

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

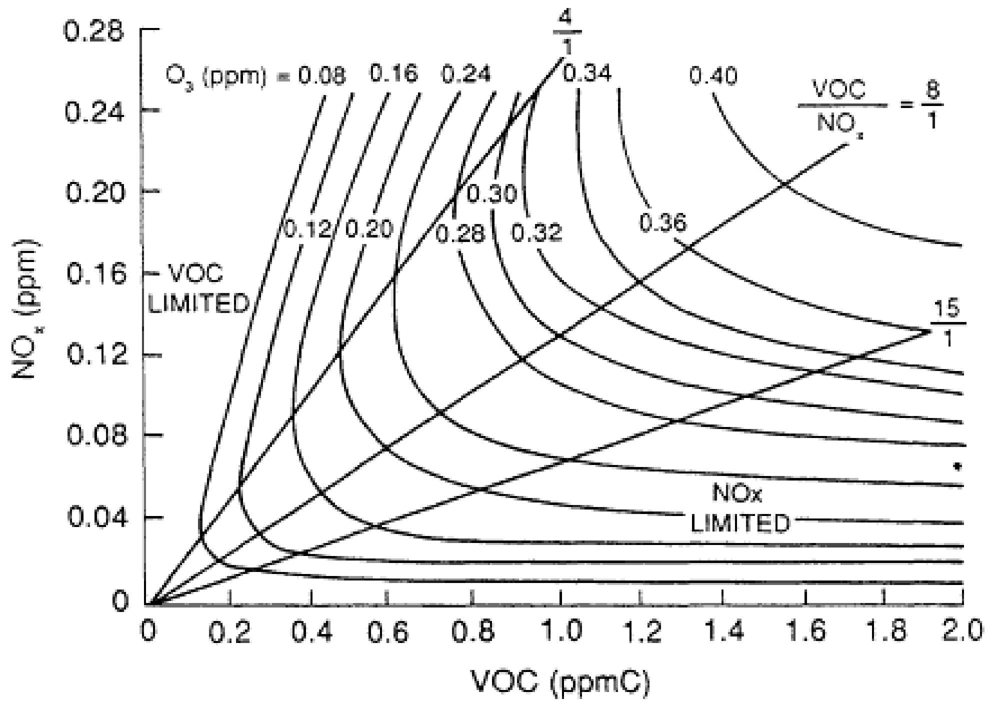
Table A8 – Historical Nitrogen Dioxide NAAQS

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

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

A.6. Ozone Precursors and Ozone Formation

Figure A22 – Relationship Between NOx and VOCs in Ozone Formation



Source: National Research Council. 1991. *Rethinking the Ozone Problem in Urban and Regional Air Pollution*. Washington, DC: The National Academies Press.

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

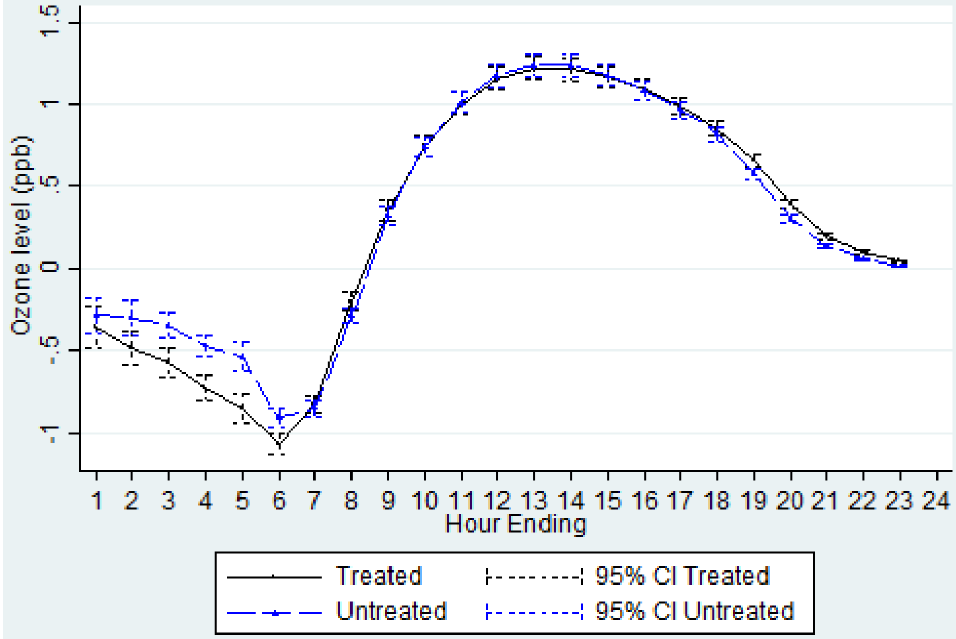
B.1. Non-Participants

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

As a robustness check, we can thus re-estimate Equation (3) by limiting our sample to only states that did not participate in the NO_x Budget Program, where now *treat* is defined as equal to 1 if the NO_x Budget Program was in effect (May 2003 – May 2008), and zero otherwise.[41] The results are presented in Figure B1, and show the hourly shape we would expect without any significant differences between April and May for non-participating states. This suggests that non-participating states operated the same (in terms of productions and/or their use of emission control technology) across both months.

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

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

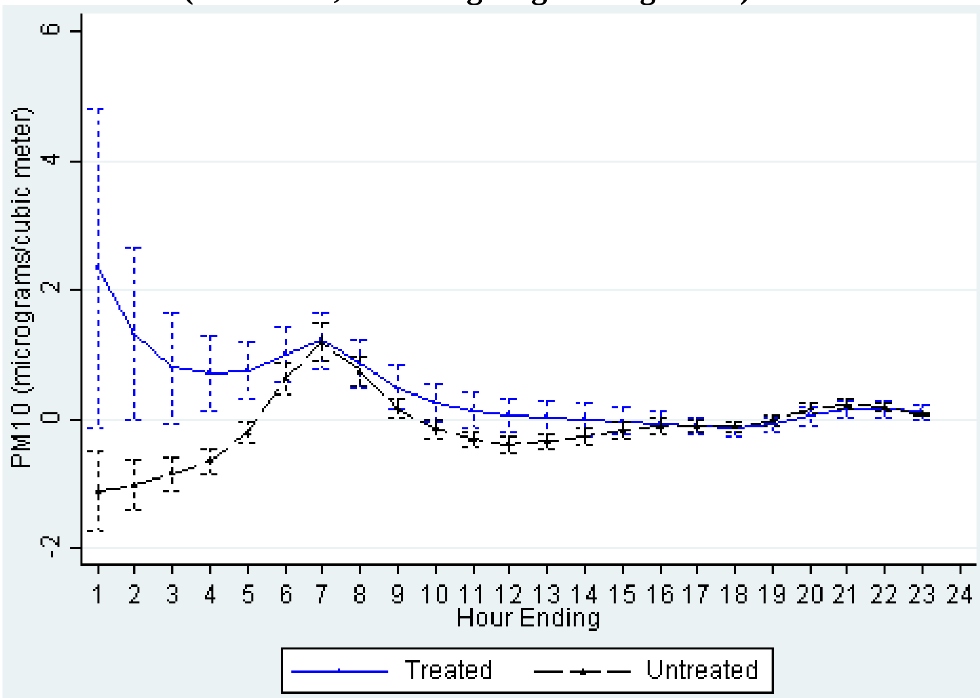


Notes: Results of estimation of Equation (3) for the period 1980-2008, limited to states that did not participate in the NOx Budget Program and were not neighboring participating states (following Deschenes, Greenstone, and Shapiro, 2017). Plot is of the β's for *Treat* and *Untreat* by hour. Omitted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

B.2. Other Pollutants

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

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



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

B.3. NO_x/VOC-Limited

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

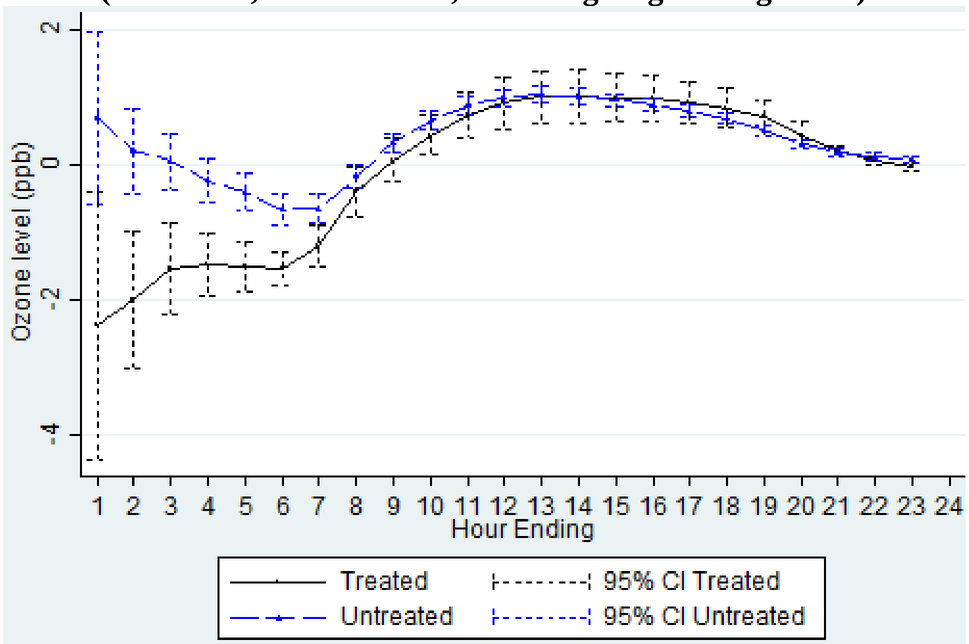
$$P_{ichdmy} = \beta_0 + \beta_1^{\tau} Treat_{icdmy} * \tau * Limited + \beta_2^{\tau} Control_{icdmy} * \tau * Limited + \beta_3\, NBPyear_{iy} * NBPstate_{ic} + \beta_4 NBPmonth_{im} * NBPstate_{ic} + \gamma_1 temp_{hcdmy} + \eta_i + \delta_{dmy} + \epsilon_{ichdmy} \quad \text{(B1)}$$

where the variables are defined as in Equation (3), with the new term *Limited* representing a series of dummy variables for a county being 1) NO_x-Limited, 2) VOC-Limited, and 3) Neutral.[42]

Results are presented separately for each group – NO_x-Limited, VOC-Limited, and Neutral in Figure B3, Figure B4, and Figure B5, respectively. We observe some heterogeneity in the differences between treated and untreated hours across the three figures. Namely, we see no significant difference due to the Program in NO_x-Limited counties, while the small differences we observe in Figure 9 in the main paper appear to be driven by Neutral or VOC-Limited counties. NO_x-Limited counties are the counties with the highest marginal cost of NO_x emissions in terms of ozone formation, and thus NO_x emissions abatement in these counties provides the largest marginal benefit. Yet it is these counties here where we find no significant difference in the change in hourly ambient ozone concentrations caused by the Program. In the areas where it mattered most, the NO_x Budget Program did not incentivize firms to shift their production away from the harmful peak ozone hours.

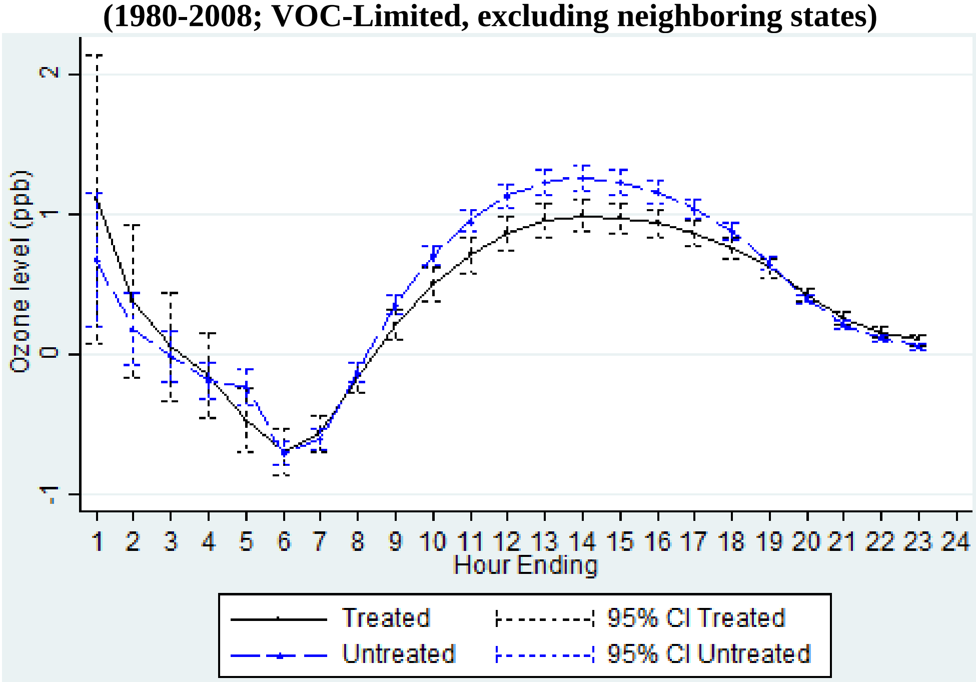
[42] See Appendix Section A.2.1 for more detail on how these variables were constructed.

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



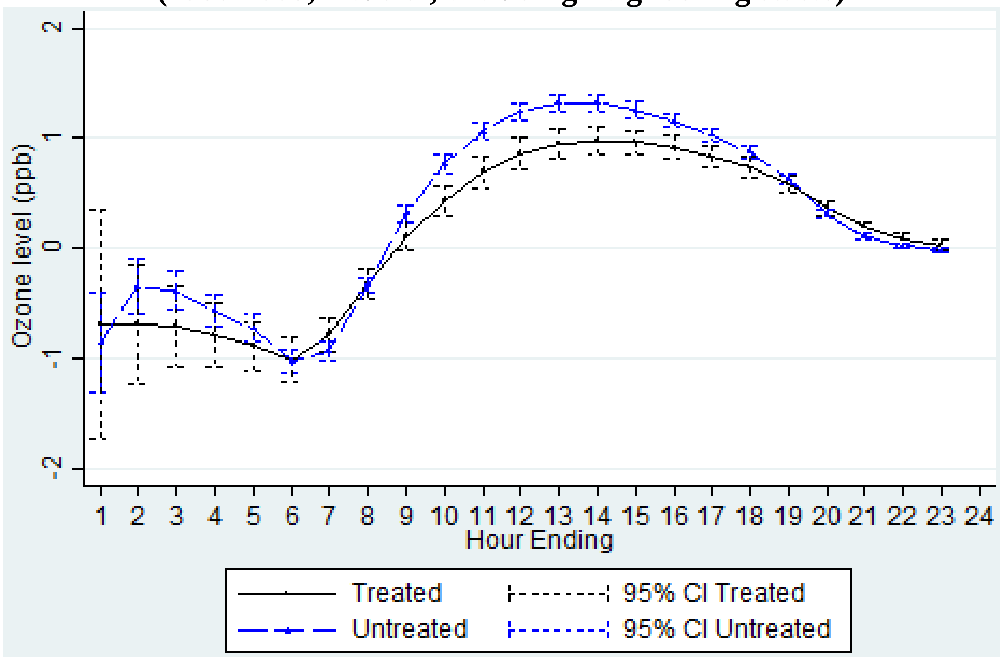
Notes: Estimation of Equation (B1). "Treated" refers to states participating in the NO_x Budget Program during the period when the program was active (May 2003 – May 2008); "Untreated" refers to all other observations. Following Deschenes, Greenstone, and Shapiro (2017), neighboring states to those states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

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



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

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

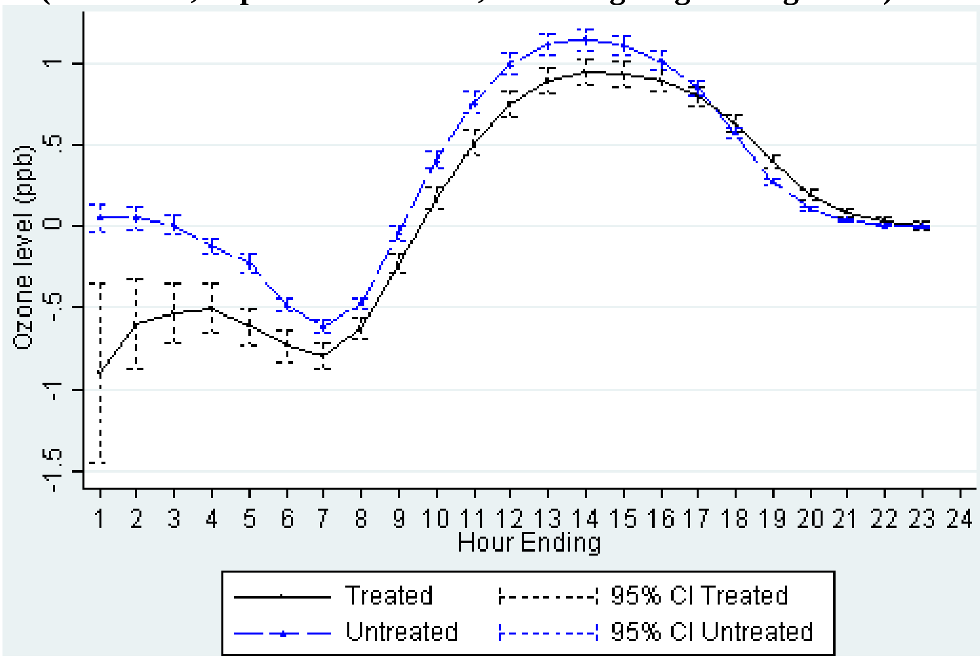


Notes: Estimation of Equation (B1). "Treated" refers to states participating in the NO_x Budget Program during the period when the program was active (May 2003 – May 2008); "Untreated" refers to all other observations. Following Deschenes, Greenstone, and Shapiro (2017), neighboring states to those states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

B.4. Timing Sensitivity: September/October

We estimate Equation (3) where we shift the period of analysis from the 1st month before and after the NBP was in effect (April, May) to the last month the NBP was in effect and the 1st month after (September, October). It is worth noting that our sample size is smaller in October relative to April/May since the typical ozone season runs from April 1 – September 30th and ozone monitoring is therefore unavailable in some locations. Nonetheless, the results in Figure B6 are qualitatively similar to our main estimation in Figure 9.

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



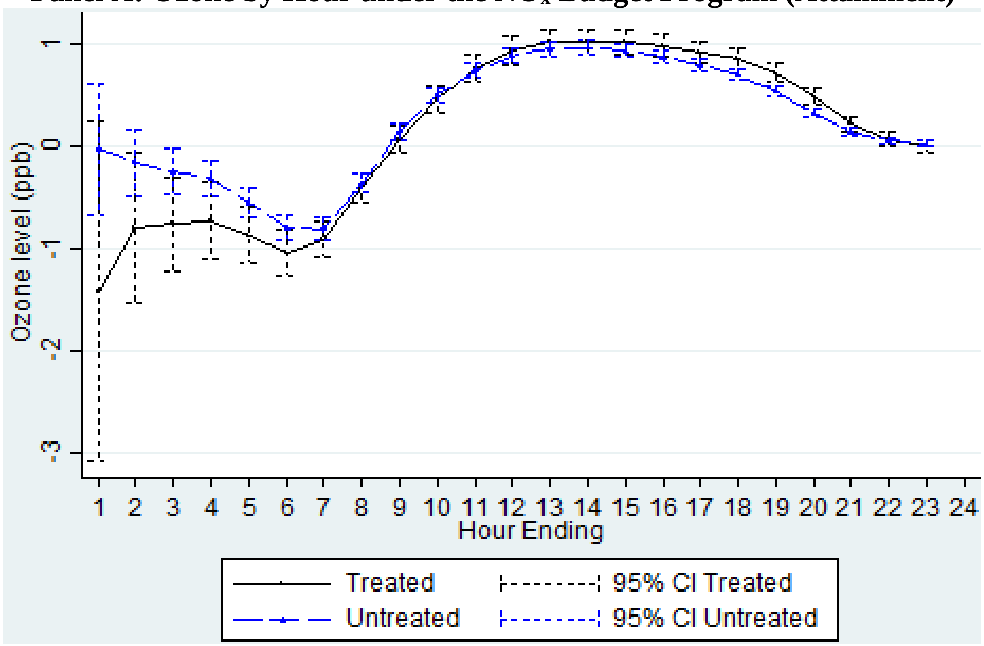
Notes: Estimation of Equation (3), our triple difference equation analyzing the NO_x Budget Program for the months of September and October. "Treated" refers to states participating in the NO_x Budget Program during the period when the program was active (Sept. 2003 – Sept. 2008); "Untreated" refers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

B.5. Non-Attainment Status

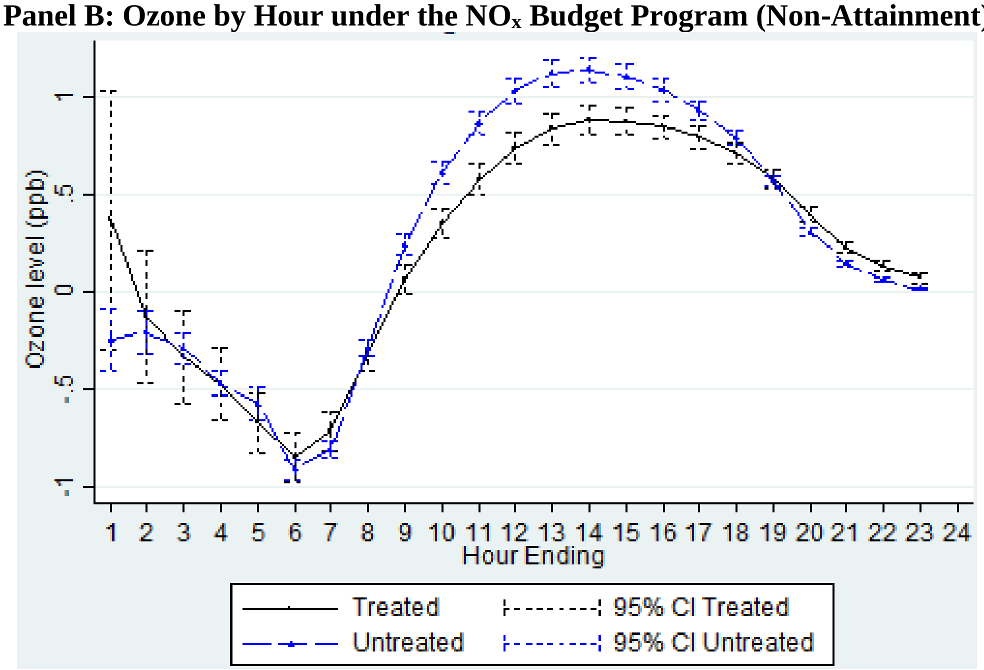
One could imagine that the effect we measure may vary by a county's attainment status; perhaps the Program focused predominately on non-attainment counties and caused firms in these counties to shift economic activity. Under this alternative, the results we find from estimating Equation (3) could be 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 β's are interacted with the county's attainment status. Results from this alternative estimation are presented in Figure B7 and are discussed in Section 5.3.1 of the main paper.

Figure B7 – Ozone by Hour and Attainment Status under the NOx Budget Program
(1980-2008; excluding neighboring states)

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



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



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

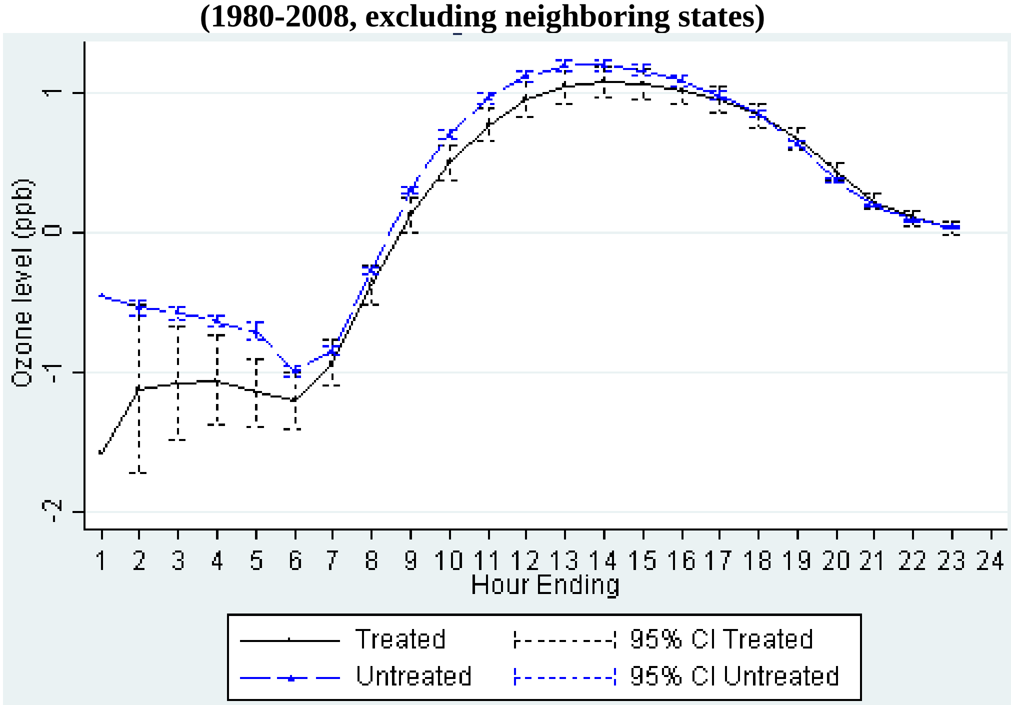
B.6. Two-Way Fixed Effects Estimation following Deschenes, Greenstone, and Shapiro (2017)

As a robustness check, we estimate a version of the two-way fixed effect estimation from Deschenes, Greenstone, and Shapiro (2017). The estimating equation is:

$$Y_{cst} = \beta_0 + \beta_1^{\tau} Treat_{idmy} * \tau + \beta_2^{\tau} Control_{idmy} * \tau + \gamma_1 temp_{hdmy} + \mu_{ct} + \eta_{st} + \nu_{cs} + \epsilon_{cst} \quad \text{(B2)}$$

Standard errors are clustered at the state-year level. The results from this alternative estimation are presented in Figure B8. Even without the monitor fixed effects and day-by-month-by-year time trend in our main specification, the results from this alternative specification are qualitatively similar to our main results in Figure 9.

Figure B8 - Ozone by Hour under the NOx Budget Program (1980-2008, excluding neighboring states)



Notes: Estimation of Equation (B2), the triple difference equation analyzing the NO_x Budget Program for the months of April and May based on Deschenes, Greenstone, and Shapiro (2017). "Treated" refers to states participating in the NO_x Budget Program during the period when the program was active (Sept. 2003 – Sept. 2008); "Untreated" refers to all other observations. Following Deschenes, Greenstone, and Shapiro (2017), neighboring states to those states participating in the Program are excluded. Large, overlapping confidence intervals not shown for HE1.Standard errors clustered by state-year.

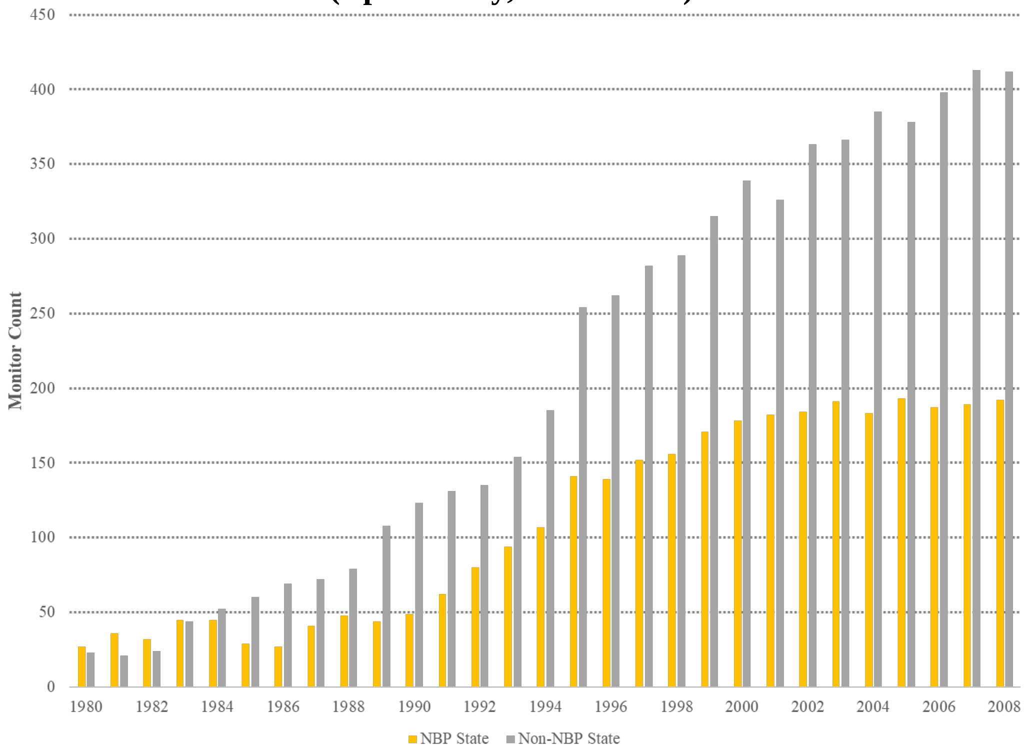
B.7. Additional Tables and Figures

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

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

Notes: Differences in estimated hourly coefficients for Treat and Control from estimation of Equation (3) as shown in Figure 9.

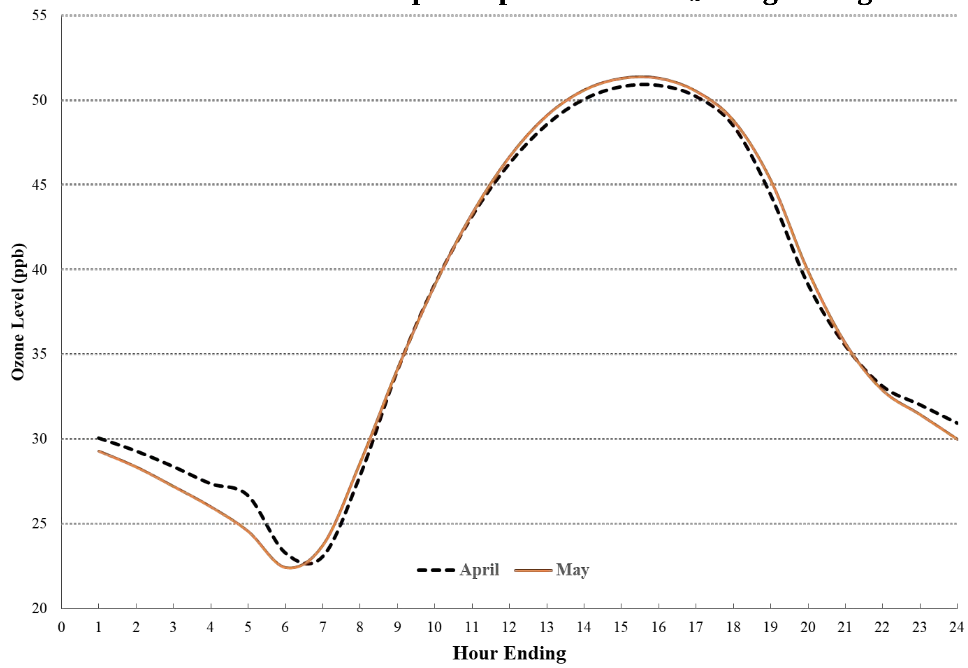
Figure B9 – Count of Ozone Monitors by Year
(April – May, 1980 – 2008)



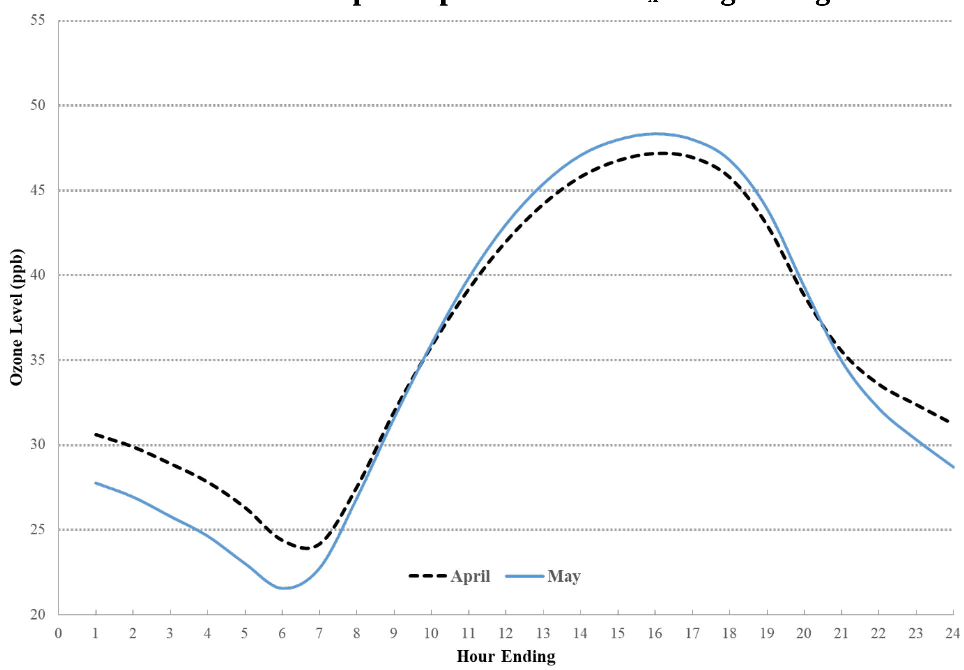
Notes: Count of monitor-year observations for April-May of each calendar year from our dataset of hourly ozone levels matched with contemporaneous hourly temperature. Counts are separated by whether a state did or did not participate in the NO_x Budget Program. Data from EPA's AirData database.

Figure B10 – Average Hourly Ozone (April 2003 – May 2008)

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

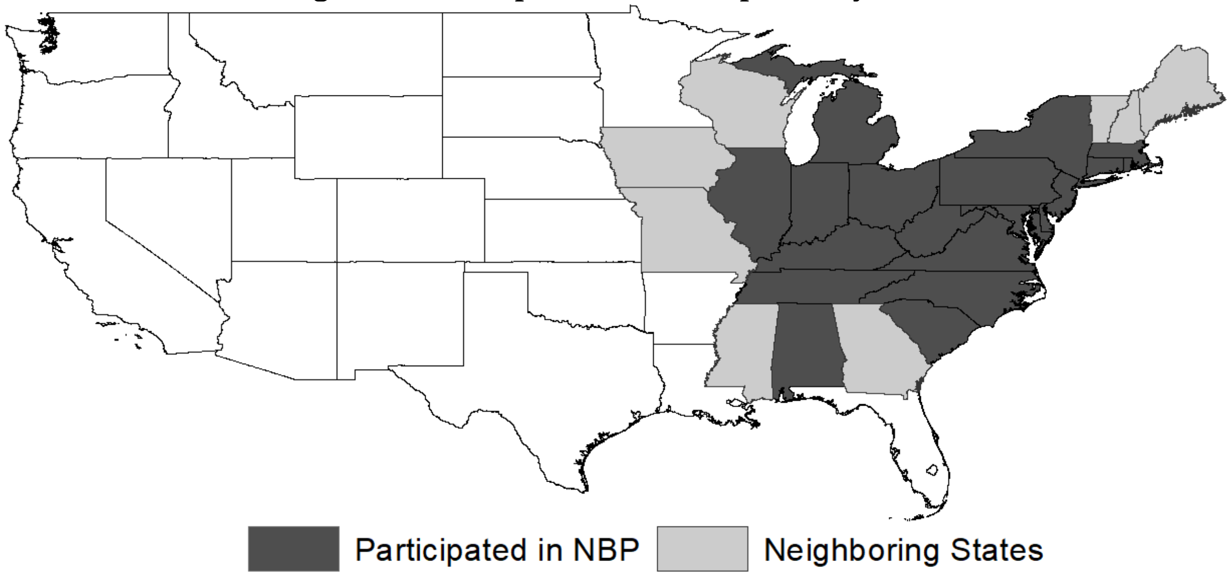


Panel B: States that participated in the NO_x Budget Program



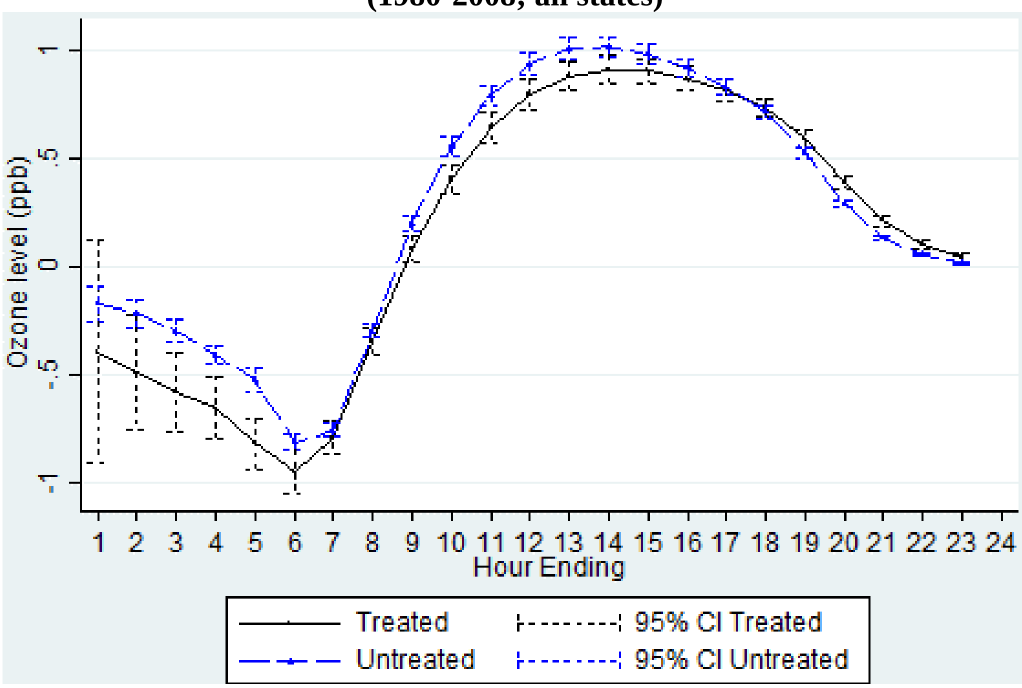
Notes: Average hourly ozone from EPA's AirData database. Hourly ozone levels averaged across all states that did not participate (Panel A) or participated (Panel B) in the NO_x Budget Program, based on our sample of counties with ozone monitor data matched to contemporaneous hourly temperature.

Figure B11 – Map of NBP Participation by State



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

Figure B12 – Ozone by Hour under the NO_x Budget Program (1980-2008; all states)



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

C. Stylized Model

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

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

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

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

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

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

The firm's problem is given by:

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

The Lagrangian for this problem is:

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

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

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

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

The regulator's problem is:

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

where E is the emissions cap.

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

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

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

and aggregate are then:

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

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

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

C.2. Firms with Temporal Differentiation

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

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

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

The Lagrangian for the firm's problem is:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

The Lagrangian for the regulator's problem is:

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

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

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

FOCs:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Aggregate emissions in each period are then:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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