DOES ETHANOL IN GASOLINE AFFECT AIR QUALITY? EVIDENCE FROM NASCAR

A Thesis

Presented to the Faculty of the Graduate School

of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Master of Science in Applied Economics and Management

by

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May 2021

ABSTRACT

Whether ethanol gasoline is more environmental-friendly than pure gasoline in air pollutants' emissions has been an important but controversial topic for over a decade. To investigate the question, we use quasi-experiment methods to analyze the changes in types of air pollutants' concentrations near the race tracks taken by the NASCAR fuel-switching policy, which shifted from pure gasoline to an E15 blend implemented in 2011. We find that switching fuel to have 1 million racing miles in one race day can reduce up to 12.4% of ambient NO_2 concentrations within areas 50 miles around the race tracks. Our research also suggests that before 2011 in the areas around the race tracks, especially in the Northeast states of the U.S., there might exist a relative deficiency of volatile organic compounds (VOC), which impeded and even reduced the accumulation of ground ozone, when more man-made NO_x was produced during racing days.

BIOGRAPHICAL SKETCH

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ACKNOWLEDGMENTS

I would like to express my gratitude to my advisor Professor Ivan Rudik for his generous help with my course choice, master's thesis and Ph.D. application. His devotion to research and patience deeply affect me. I also appreciate the precious suggestions on my thesis and Ph.D. application provided by Professor Shanjun Li.

In addition, the support from my classmates and friends is also crucial for me to keep going.

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Chapter 1. Introduction

1.1 Overview

Motor vehicles have been one of the major sources of air pollutants for decades. The contributions of motor vehicle emissions to ambient pollution levels in developed countries were 90% in carbon monoxide, 25-30% in $PM_{2.5}$, 40% in NO_x, and 21% in air toxics (Greenbaum, 2013). Therefore, reducing vehicle emissions has long been a major focus by the Environmental Protection Agency (EPA) since the enactment of the Clean Air Act of 1970.

Setting fuel standards has been an important method to reduce air pollution. The action at the federal level can be traced back to 1973, when the EPA issued regulations to reduce lead in gasoline for the first time (EPA, n.d.). In 1990, in order to reduce carbon monoxide emissions, the agency mandated gasoline producers to add oxygenates (EPA, n.d.). As one of the effective options to meet the requirement, ethanol experienced a fast expansion in its production in the U.S. from the 1990s. Also because ethanol was then treated as a substitute for gasoline to protect national energy security, its production increased further after the passage of the Energy Independence and Security Act of 2007 (EISA) and was regulated by EPA's Renewable Fuel Standards (RFS).

Despite the fast growth of production promoted by various statutes and regulations in the past few decades, the future of ethanol fuel remains somewhat unknown. The EISA will not mandate ethanol fuel use after 2022 and there has been no subsequent statute mandating the amount of ethanol fuel use (Congressional Research Service, 2020). Therefore, how to deal with the RFS program afterward and regulate the amount of ethanol production will soon become a question. To be qualified as renewable fuel defined by EPA, ethanol fuel has at least 20% less life-cycle greenhouse emission (EPA, n.d.) than regular gasoline. However, the types of air pollutants triggered by gasoline combustion in transportation engines are far beyond greenhouse gases. If the blends with more portions of ethanol (such as E15) could generate fewer such products than pure gasoline and even currently used E10, the future development of ethanol-gasoline would be more promising in reducing damages from motor vehicle emissions.

In this paper, we empirically analyze the changes of concentrations in types of air pollutants brought by NASCAR's most recent fuel-switching policy in 2011. In 2011, NASCAR adopted Sunoco Green E15, an unleaded racing fuel that contains 15 percent ethanol, as the fuel for all of its national series races. The types of air pollutants we study are: nitrogen dioxide (NO_2), ground-level ozone (O_3), carbon monoxide (CO), coarse and fine particulate matters (PM_{10} and $PM_{2.5}$). We find that the new ethanol blend has statistically significantly reduced ambient NO_2, compared to the previous gasoline without oxygenates. Switching from pure gasoline to E15 fuel to have 1 million racing miles in one race day can reduce up to 12.4% of ambient NO_2

concentrations within areas 50 miles around the race tracks. There have been negative changes to the concentrations of ozone (-2.18%), CO (-4.96%), PM_{10} (-9.44%) and $PM_{2.5}$ (-3.88%) in the same condition, but these results are not statistically significant. On the other hand, our research shows that O_3 concentrations decrease on race days, even before switching to E15.

In general, these results are robust to filtering out the races whose policies could confound the regression outcomes, or reducing the radius to 10 miles, except that of ozone which has complicated atmospheric chemistry. The pollution effects of car racing, whether prior to or after the adoption of E15, have not shown observable daily lagging effects providing additional evidence the changes in ambient pollution are being caused by the races and not other factors. The reductions of ozone concentrations before the fuel change could be attributed to the differences in the ambient VOC and NO_2 levels among the states in which the race tracks are located. Our findings suggest that in the areas around the race tracks, especially in the Northeast states of the U.S., there might exist a relative deficiency of volatile organic compounds (VOC), which impedes and even reduces the accumulation of ground ozone, when more man-made NO_x is produced during the race days. Moreover, we observe that within a 25-mile radius around the race tracks, the magnitudes for the changes of NO_2 and ozone concentrations might increase when monitors are downwind relative to the race tracks, but the results are statistically insignificant.

1.2 Background

1) Health, environmental and economic effects resulting from types of air pollutants:

Health impacts correlated with short-term exposures to ambient PM comprise premature mortality, adverse lower-respiratory symptoms, lung malfunctions and changes in heart rate rhythm (Walsh, 2011). Increasing $PM_{2.5}$ concentration by 1 $\mu g/m^3$ could raise 0.3–0.6% number of traffic accidents relating to vehicles in one day, through weakening drivers' cognitive ability, raising anxiety, and leading to more offensive behaviors (Sager, 2019). Short-term exposure to a highly-concentrated CO could lead to deficient oxygen transported to the heart and chest pain, known as angina (EPA, n.d.). People are especially susceptible to the pollutant when exercising or under stress. A high concentration of NO_2 can stimulate the human respiratory system. Short-run exposures can intensify respiratory diseases and result in respiratory symptoms, such as wheezing or dyspnea (EPA, n.d.). Elevated ozone concentration can cause coughing, throat irritation, and airway inflammation. It can also weaken lung function and make people breathe more rapidly and shallower than normal, thereby containing a person's activity. People with a deficient intake of certain nutrients, such as vitamins C and E, are more likely to be negatively impacted by ozone exposure (EPA, n.d.).

2) Previous research on the types of pollutants' emissions comparisons between ethanol blend and pure gasoline:

2-1 Particulate Matter

Costagliola et al. (2013) reported a 30-95% reduction in the number of particulates emitted from E10-E85 gasoline and a 10%-98% reduction of PM_1. The ultra-fine particles (with diameters lower than 20nm) accounted for a much smaller proportion for the ethanol blends. The empirical study by Salvo et al. (2017) on São Paulo's changes in air pollutions (when the city switched to less percentage volume of ethanol and then reversed back), partially agreed with the observations above. The article held that there was no significant change in the daily concentration of $PM_{2.5}$ during the whole period, while those of ultrafine particles (with 7-100 nm in diameter) increased by one-third in the mornings when people substituted ethanol with gasoline.

2-2 NO_x

NO_x itself is not a single chemical substance. Instead, it denotes several chemical compounds. EPA treats nitrogen dioxide (NO_2) as the only surrogate for this family, because NO_2 is the most common structure of NO_x in the air produced by human activities (Office of Air Quality, 1999). Therefore, we do not further distinguish NO_2 and NO_x in the following parts of the research. Maricq et al. (2012) noted that engine-out NOx emissions were cut down by 10-20%, when ethanol took up more than 10 or 17 percent volume of the fuel blends, depending on different calibration settings. Najafi et al. (2009) held a different point, however, and reported that NO_x emission rose when the ethanol took up more percentage volume in the fuel. Specifically, the NO_x concentrations from the tested car's exhaust at 3000 rpm using E5, E10, E15 and E20 were 12.57%, 33.94%, 33.6% and 45.55% higher than that of gasoline.

2-3 Ozone

Much pertinent research on the change of ozone production taken by ethanol blends has been derived through VOC emission analysis, since ozone is not a direct output by gasoline-powered motor vehicles and VOC is an important type of contributor to the pollutant. Tibaquirá et al. (2018) estimated a 17% decrease in the ozone formation when sedan-type vehicles used E20 to substitute pure gasoline, with the emissions of several types VOC, such as toluene, benzene and 1,3-butadiene, showing over 30% decreases brought by the blend. The empirical analysis on ozone concentrations in Sao Paulo from 2010 to 2013 by Salvo and Wang (2017), however, yielded an opposite conclusion. Using multi-way fixed effects regression, the paper implied that ozone concentrations increased by 7-9%, when E25 was substituted for E20.

2-4 carbon monoxide

Costagliola et al. (2013) found that CO emissions decreased linearly with increasing alcohol content in the blends, given that extra oxygen enhanced combustion efficiency which drew down CO discharge. Najafi et al. (2009) observed the CO concentrations from the tested car's exhaust at 3000 rpm using E5, E10, E15 and E20 were 13.7%, 24.31%, 27.93% and 45.42% lower than that of gasoline.

3) NASCAR-related information:

Given race cars are defined as nonroad vehicles and solely used for competition, they usually have been exempted from the regulations of automobiles and fuels established by EPA. As a result, NASCAR had been criticized for its negative image of environmental protection. Until now some of the games under the association may have not given up leaded fuel, which was banned by the Clean Air Act over two decades ago for passenger vehicles. Many NASCAR series are still using carburetors, a kind of fuel-mixture device out of the market for many years because of its incompatibility with the catalytic converters.

Nevertheless, NASCAR has been making some efforts to be environmental-friendly. From 2007, the NASCAR top national series adopted Sunoco 260 GTX, a type of unleaded racing gasoline containing no oxygenates or metallic additives (Criticism of NASCAR, n.d.). Since the beginning of the 2011 season, NASCAR has comprehensively adopted Sunoco Green E15, an unleaded racing fuel that contains 15 volume percent ethanol, as the race fuel for all of its top national series games. Inspired by the analyses on the ambient lead concentrations brought about by the NASCAR's fuel-switching policy in 2007 by Hollingsworth and Rudik (2020), we here investigate the changes of air pollutants' concentrations caused by the next and newest fuel-shifting policy in 2011.

1.3 Research Contributions

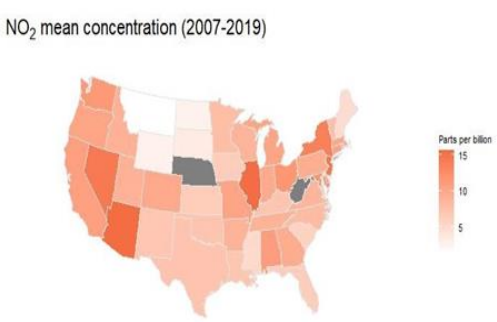
Most of the air pollutants analyses on ethanol blends investigated above are based on lab experiments, using one or two engines popular on market, controlling some key parameters and following a standardized drive cycle (such as US06). Our research provides an alternative method to figure out the air pollutants' emissions by referring to empirical approaches, allowing for more heterogeneity in engine characteristics, driving patterns and the outside environment.

Our research also has other advantages. The fuel shifting policy took place simultaneously (from the beginning of 2011) for all pertinent NASCAR games across the U.S., so there would be fewer heterogeneous issues from the time aspect, facilitating our regression analysis. The types of fuel used before and after the policy implementation were uniform, removing concerns about the uncertainties of the results brought about by different properties of oils used for racing. The race tracks and the race dates for the NASCAR national series games over years have been relatively stable, so the fixed-effects regressions below would suffer less from truncated samples. The states having such races cover a broad area of the U.S, including the East Coast, Midwest, South and Southwest, and thus the research results can provide more comprehensive insights into environmental effects resulting from switching to ethanol fuel. Because of the above characteristics, there has not been simultaneous causality between local pollution levels and fuel types used by the relevant racing cars.

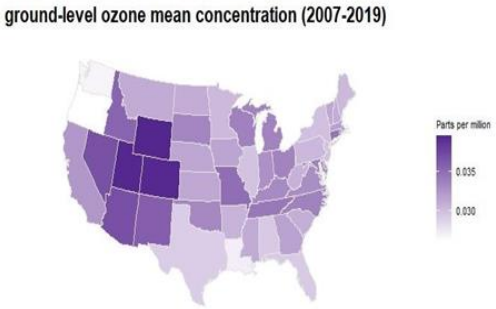
Chapter 2. Data Description

2.1 Air pollution data

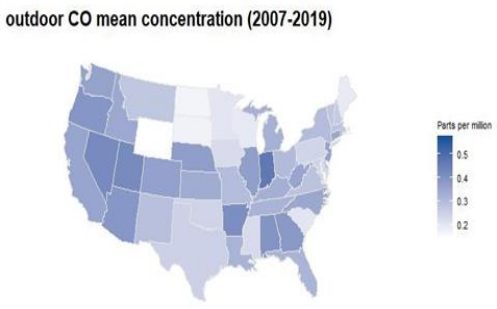
The air pollution data are publicly available from EPA's Air Quality System (AQS). Here we focus on the datasets containing daily mean concentrations of NO_2 (parts per billion), ozone (parts per million), CO (parts per million), PM_{10} (micrograms per cubic meter at 25℃), $PM_{2.5}$ (micrograms per cubic meter at local temperature) and VOC (parts per billion). The data describe the dates of measurement, the pollutants' concentrations, units of measurements, longitudes, latitudes, and the states' and counties' information for all monitors. The time interval we analyze spans from 2007 to 2019. The concentrations of the air pollutants are shown in Figure 2.1 series below.



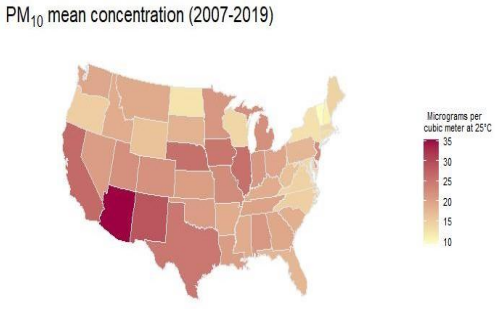
(a) NO_2



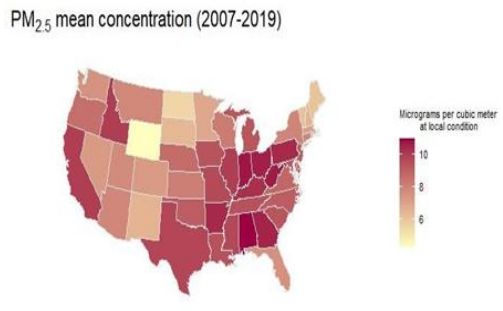
(b) ozone



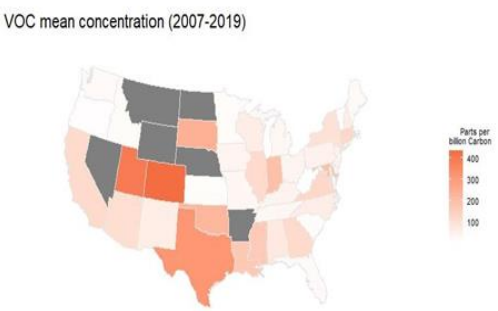
(c) CO



(d) PM_{10}



(e) $PM_{2.5}$



(f) VOC

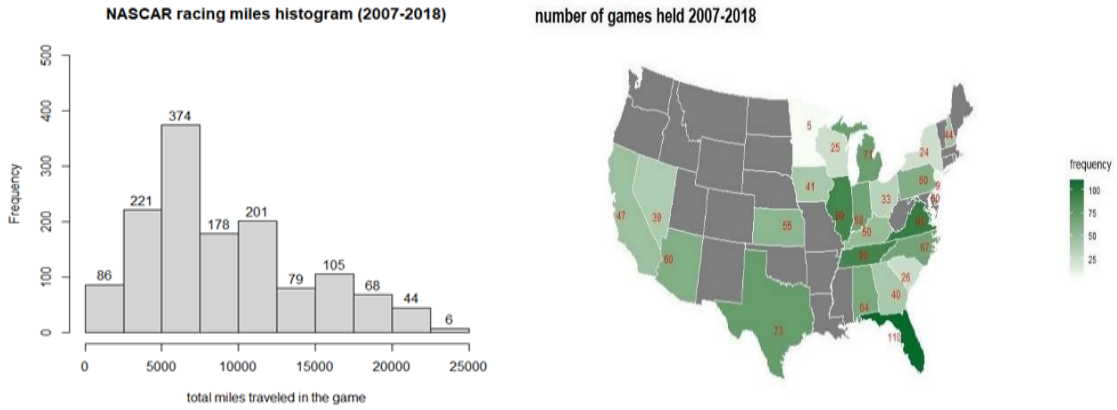
Figure 2.1: Air pollutants concentration by state (2007-2018)

Note that some monitor sites might have multiple methods to measure an air pollutant's daily concentrations. Therefore, we calculate the arithmetic mean of these daily outcomes, according to the longitude and latitude of the monitor site. To avoid outliers with extremely high values stem from some disasters, such as natural disasters and production accidents, we logarithmize these pollutants' concentrations for regression analysis.

2.2 Racing Data

We collect the race data from Racing Reference (https://www.racing-reference.info/), a website storing historical race data for the NASCAR national series, including Cup Series, Xfinity Series, Camping World Truck Series (CWTS) and ARCA Series. The data file we use here starts from June 1949 and ends in November 2018, with 5009 records in total. The data comprise the racing date, racing series name, total miles traveled by race cars in a game, number of drivers, and the number of spectators. Given the time interval of the research, we only use the data ranging from 2007 to 2018, with 1362 games during the time. Note that the numbers of spectators have been

mostly unavailable since 2013. Total racing miles of the games in the period are distributed as Figure 2.2 (a), mainly concentrating around 5,000 to 20,000 miles. East areas have most of the races, manifested in Figure 2.2 (b).



(a) (b)

Figure 2.2: NASCAR racing miles distribution (a) and racing number distribution (b) (2007-2018)

2.3 Weather Data

Weather data we use here belong to publicly available NCEP_Reanalysis 2 data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their website at https://psl.noaa.gov/. We select the datasets containing global daily mean temperature (°K) at 2-meter level (with 1.875° latitude and 1.904129° longitude for each grid), daily precipitable water content (kg/m^2) calculated by treating the entire atmosphere as a single layer (with 2.5° latitude and 2.5° longitude for each grid), and daily mean u-wind speeds and v-wind speeds (m/s) at 10-meter level (with 1.875° latitude and 1.904129° longitude for each grid). The u-wind denotes the wind velocity

from west to east, and the v-wind denotes the wind velocity from south to north. To know about the daily weather conditions at each monitor site, we need to find which grid the pollution monitor is in. Then we can join the weather information into the monitors' data.

Moreover, to calculate the wind direction, we adopt the formula:

$$\text{Angle} = \text{mod}\left(\arctan\left(\frac{\text{u\_wind velocity}}{\text{v\_wind velocity}}\right), 360\right)$$

By this formula, we treat the arrow pointing northward as angle zero and increase the angle when rotating the arrow clockwise until the arrowhead reaches its starting point (e.g. from $359°$ to $0°$). Therefore, the range of angle $\in [0, 360]$.

Chapter 3. Empirical Strategy

To understand the pollution change resulting from the switch to the E15 gasoline, we apply multiple models to help answer: 1) whether NASCAR racings can lead to statistically significant changes of pollutants' concentrations, compared to the days without races, and more importantly, 2) whether switching to the E15 gasoline since 2011 can cause statistically significant changes of pollutants' concentrations, compared to the hypothetical situation before 2011 (use the old fuel to run the same mileage).

The simplest method to figure out the effects is an OLS model:

$$\ln(Pollution_{zit}) = Constant_z + \omega_{z1} * Miles_{it} + \omega_{z2} * D_{y\geq 2011} * Miles_{it} + \varepsilon_{zit}$$

z represents the type of pollutant, *t* represents the date, *i* represents the specific monitor site. Here, *Miles* represents the total mileage in millions of miles traveled by the race cars within a specified radius around the monitors, and here we set two radii: 50 miles and 10 miles. To check if the fuel-switching policy effective in 2011 has had impacts on the pollution levels compared to the previous cases, we set $D_{y\geq 2011}$ as a dummy variable, which takes value 1 from the beginning of 2011 and 0 otherwise (2007-2010). This model has very strict settings: It assumes that the residual does not contain any factor possibly correlated with the total miles driven by the game players. Else, there would be omitted variable bias.

Since some features around monitor sites differ from each other, which can affect pollution levels captured by monitors. Meanwhile, these latent factors are hard to be quantified and directly added to the model. We can capture these unique characteristics using the interactive effects between monitor sites and day of week, month of year and year. So we select a multi-way fixed-effects model to achieve these goals.

Moreover, we notice that daily weather conditions may also have impacts on pollutants' concentrations. For example, increased temperature facilitates ozone formation (Allen, 2004), a day with precipitation tends to have a lower NO_2 and PM_{10} concentration (Kim et al., 2014), and the concentration of air pollutants has a negative correlation with wind speed (Liu et al., 2020). Therefore, we include temperature, precipitation and wind speed as control variables into the regression and take a 3rd order polynomial for each.

We should also be aware that the cars driving on the road near the race tracks are also important contributors to ambient air pollution, which can be captured by monitors. Typically many spectators of the races drive cars to the race tracks on the game days, so the more people watching on-site, the more their impacts on the pertinent monitors' readings. Therefore, we set the multi-level fixed effects model as follow:

$$\ln(Pollution_{zit}) = \omega_{z1} * Miles_{it} + \omega_{z2} * D_{y\geq 2011} * Miles_{it} + \beta_z * Spectator_{it} + \sum_{\substack{C\in\{temperature,precipitation,wind\ speed\} \\ p\in\{1,2,3\}}} \alpha_{zcp} * C_{it}^{p}$$

$$+ \theta_{ziw} + \phi_{zim} + \tau_{ziy} + \varepsilon_{zit}$$

Here *z* represents the type of pollutant, *t* represents the date, *i* represents the specific monitor site. *Miles* represents the total mileage (divided by 1 million) traveled by the race cars within a specified radius around the monitors, and here we set two radii: 50 miles and 10 miles. *W* represents the day of the week, *m* represents the month of the year, *y* represents the year. C represents the control variables (temperature, precipitation, and wind speed), p represents power (from 1 to 3). *Spectator* represents the number of attendances whose contribution to air pollution could be captured by the monitors on the racing days.

θ captures the weekly cycle of pollution of a single monitor site, which can be used to show the characteristics of the local commute pattern. ϕ captures the seasonal effect of a single monitor site, which can help to show the characteristics of the local geographical and environmental features (such as mountain vs plain, North vs South, and Mediterranean climate vs Continental climate). τ captures the annual situation of a single monitor site, which facilitates manifesting the changes in local economic conditions and environmental regulations.

We assume that the residuals of the same monitor site are correlated with each other across time, and thus we select clustered standard errors for each monitor site. Besides, to make our conclusions more conservative, we also have results setting cluster levels by county, which cover large scope (more conservative) than those by a single monitor site.

Chapter 4. Major Results

4.1 NO_2 (z) (50 miles range)

	Cluster by monitor site (OLS)	Cluster by monitor site (FE)			Cluster by county (FE)
	(1)	(2)	(3)	(4)	(5)
			+ weather	+ weather & spectator	+ weather & spectator
ω_{z1} (by 1/million)	17.866***	3.782***	2.961***	6.016**	6.016*
	(4.472)	(1.163)	(1.073)	(2.602)	(3.427)
ω_{z2} (by 1/million)	-3.181	-5.488***	-5.047***	-12.446***	-12.446***
	(4.119)	(1.329)	(1.371)	(2.907)	(4.509)
Num. Obs.	1786893	1786893	1786893	806784	806784
FE: i & m		X	X	X	X
FE: i & w		X	X	X	X
FE: i & y		X	X	X	X

* p < 0.1, ** p < 0.05,

*** p < 0.01

Table 4.1

The OLS regression shows that NASCAR racing can increase ambient NO_2 levels. The fixed-effects models (last four columns) all agree with this result, but their slopes are much smaller than that of the OLS (6.016 vs 17.866). The reason could be that NASCAR races are usually held in more populated places, where the average NO_2 are higher. Therefore, the multi-level fixed-effects models are more appropriate in this case.

In the fixed-effects models, even with different controls and clusters, there would be less concentrated NO_2 after switching to E15 than before, and the results are statistically significant. Comparing (2) and column (3), we find that the weather conditions around the racing tracks may contribute a higher level of NO_2. Believing that we should include the numbers of spectators into the regressions (who are an

important source of air pollutants), we prefer (4) to (3). But the differences in (3) and (4) may be partially attributed to the truncated data (from 2013 there have been hardly numbers of spectators recorded in the dataset) and the strong correlation between attendances and miles driven. When using a larger cluster level ((5) vs (4)), the fuel-changing policy still yields a statistically significant reduction of NO_2 concentrations. Therefore, we observe that within a 50 miles range around a race track on a race day, there would be about 12.4% fewer NO_2 concentration, if substituting pure gasoline with E15 to achieve 1 million race mileage.

4.2 Ozone (z) (50 miles range)

	Cluster by monitor site (OLS)	Cluster by monitor site (FE)			Cluster by county (FE)
	(1)	(2)	(3)	(4)	(5)
			+ weather	+ weather & spectator	+ weather & spectator
ω_{z1} (by 1/million)	3.921***	0.433	0.002	-6.576***	-6.576***
	(0.974)	(0.632)	(0.572)	(1.224)	(2.097)
ω_{z2} (by 1/million)	-3.823***	-1.904***	-1.171*	-2.182***	-2.182*
	(1.061)	(0.676)	(0.622)	(0.77)	(1.118)
Num. Obs.	4793067	4793067	4793067	2234167	2234167
FE: i & m		x	x	x	x
FE: i & w		x	x	x	x
FE: i & y		x	x	x	x

* p < 0.1, ** p < 0.05,

*** p < 0.01

Table 4.2

The OLS regression shows that NASCAR racing can increase ambient ozone levels. However, the fixed-effects models (especially the last two columns) all disagree with this result. The reason could be that NASCAR races are usually held in more populated places, where the average ozone levels are much higher than the average

level in the U.S. Therefore, the multi-way fixed-effects models are more appropriate in this case.

Comparing column (2) and column (3), we find that the weather conditions around the racing tracks may contribute to lower levels of ozone after 2011, but the effect is not large. Believing that we should include the numbers of spectators into the regressions (who are an important source of air pollutants), we prefer (4) to (3). The differences in (3) and (4) suggest that spectators of NASCAR racing significantly increase the ambient ozone levels near the race tracks on racing days. On the other hand, these differences may be partially attributed to the truncated data (from 2013 there have been hardly numbers of spectators recorded in the dataset) and the strong correlation between attendances and miles driven. From (4) we observe that within a 50 miles range around a race track on a race day, there would be about 2.182% fewer ozone concentrations, if substituting pure gasoline with E15 to achieve 1 million race mileage, and the result is statistically significant. However, when using a larger cluster level ((5) by county vs (4) by monitor site), this statistical significance no longer holds, by 95% CI. We can infer that the correlations of residuals for the ozone regression across monitor sites within the same county truly exist, are positive in general, and impactful to change our conclusion.

4.3 CO (z) (50 miles range)

Cluster by monitor site (OLS)	Cluster by monitor site (FE)			Cluster by county (FE)
(1)	(2)	(3)	(4)	(5)
		+ weather	+ weather & spectator	+ weather & spectator

ω_{z1} (by 1/million)	3.387	-1.295	-1.162	3.232	3.232
	(3.475)	(1.206)	(1.183)	(2.565)	(3.179)
ω_{z2} (by 1/million)	3.357	-0.449	-0.607	-4.961	-4.961
	(3.893)	(1.897)	(1.913)	(3.631)	(4.714)
Num. Obs.	1391236	1391236	1391236	691360	691360
FE: i & m		X	X	X	X
FE: i & w		X	X	X	X
FE: i & y		X	X	X	X

* p < 0.1, ** p < 0.05,

*** p < 0.01

Table 4.3

We hardly observe any statistically significant coefficient in all four columns on the right side, thus failing to reject the null hypothesis that the fuel change has not led to any variation in the concentration of CO with 50 miles around a race track on a game day. The reason behind this could be that motor vehicles contribute most of the carbon monoxide in the air, so the daily traffic flow (not just from the spectators) near the race tracks can also contribute much to ambient CO levels. Compared to the total traffic flow variations, the amount of CO generated by racing might be too small to be captured.

4.4 PM_{10} (z) (50 miles range)

	Cluster by monitor site (OLS)	Cluster by monitor site (FE)			Cluster by county (FE)
	(1)	(2)	(3)	(4)	(5)
			+ weather	+ weather & spectator	+ weather & spectator
ω_{z1} (by 1/million)	9.916**	-2.011*	-1.961*	-4.258	-4.258
	(4.457)	(1.045)	(1.106)	(3.056)	(5.579)
ω_{z2} (by 1/million)	2.726	-2.700*	-2.369	-9.439**	-9.439
	(3.307)	(1.606)	(1.583)	(3.692)	(8.435)
Num. Obs.	1937004	1937004	1937004	836524	836524

FE: i & m	x	x	x	x
FE: i & w	x	x	x	x
FE: i & y	x	x	x	x

* p < 0.1, ** p < 0.05,

*** p < 0.01

Table 4.4

The OLS regression shows that NASCAR racing can increase ambient PM_{10} levels, and this result is statistically significant. However, the fixed-effects models all disagree with this result. The reason could be that NASCAR races are usually held in places, where the average PM_{10} levels are much higher than the average level in the U.S. Using the fixed-effects models is preferred.

The differences in (3) and (4) suggest that spectators of NASCAR may contribute to ambient PM_{10} levels near the race tracks on racing days. But the differences in (3) and (4) may be partially attributed to the truncated data (from 2013 there have been hardly numbers of spectators recorded in the dataset) and the strong correlation between attendances and miles driven. From (4) we observe that within a 50 miles range around a race track on a race day, there would be about 9.439% fewer PM_{10} concentrations, if substituting pure gasoline with E15 to achieve 1 million race mileage, and the result is statistically significant. However, when using a larger cluster level ((5) by county vs (4) by monitor site), this statistical significance no longer holds, by 95% CI. We can infer that the correlations of residuals for the PM_{10} regression across monitor sites within the same county truly exist, are positive in general, and impactful to change our conclusion.

4.5 $PM_{2.5}$ (z) (50 miles range)

	Cluster by monitor site (OLS)	Cluster by monitor site (FE)			Cluster by county (FE)
	(1)	(2)	(3)	(4)	(5)
			+ weather	+ weather & spectator	+ weather & spectator
ω_{z1} (by 1/million)	5.987***	-2.408*	-1.483	-8.016***	-8.016*
	(1.758)	(1.33)	(1.232)	(3.077)	(4.172)
ω_{z2} (by 1/million)	1.318	1.714	-0.513	-3.884*	-3.884
	(2.16)	(1.544)	(1.532)	(2.118)	(3.011)
Num. Obs.	2325517	2325517	2325517	900631	900631
FE: i & m		X	X	X	X
FE: i & w		X	X	X	X
FE: i & y		X	X	X	X

* p < 0.1, ** p < 0.05, *** p < 0.01

Table 4.5

The OLS regression shows that NASCAR racing can increase ambient $PM_{2.5}$ levels, and this result is statistically significant. However, the fixed-effects models all disagree with this result. The reason could be that NASCAR races are usually held in places, where the average $PM_{2.5}$ levels are much higher than the average level in the U.S. Using the fixed-effects models is preferred.

Comparing column (2) and column (3), we find that the weather conditions around the racing tracks may contribute to lower levels of $PM_{2.5}$ on racing days. The differences in (4) and (3) suggest that spectators of NASCAR racing significantly increase the ambient $PM_{2.5}$ levels near the race tracks on racing days. But these differences may be partially attributed to the truncated data (from 2013 there have been hardly numbers of spectators recorded in the dataset) and the strong correlation between attendances and miles driven. From (4) we observe that within a 50 miles range around a race track on

a race day, there would be about 3.884% fewer $PM_{2.5}$ concentrations, if substituting pure gasoline with E15 to achieve 1 million race mileage, but the result is not statistically significant by 95% CI. Column (5) further confirms this finding.

4.6 Summary

Here we make a brief conclusion. We find that the average air pollutants' concentrations are higher than the nation's average values. As a result, multi-way fixed-effects models are more proper options. We also find that weather conditions and spectators of NASCAR, though affect outcomes with different extents and sometimes different directions by types of pollutant, are also important factors in the regression. The significantly larger estimated standard errors in columns (5) than columns (4) for all pollutants' regressions imply that the correlations of types of pollutants' concentrations across monitor sites within the same county are positive in general. This finding makes setting clusters at county level a more preferred option. Thus we choose conclusions in the (5) columns to report. We find that within a 50 miles range around a race track on a race day, there would be about 12.4% fewer NO_2 concentration, if substituting pure gasoline with E15 to run 1 million racing mileage. For the other types of pollutants, we do not observe any statistically significant changes to their concentrations brought about by the fuel-shifting policy in 2011.

In addition, the plots of lagging effects are shown in the Appendix part. We do not observe any evident daily lagging effects for all types of air pollutants.

Chapter 5. Robustness Test, Discussion and Further Investigations

5.1 Confounding Factors Affecting the Outcomes

Here we test the robustness of the results to several factors. We notice that in 2012 NASCAR Cup Series adopted an Electronic Fuel Injection (EFI) system to replace carburetors (Stenquist, 2012), which have continued to be used by Xfinity and CWTS series. In general, an EFI system can control the air/fuel ratio more accurately than a carburetor does, making engines more efficient and fewer emissions (Jerew, 2020; Dunst, 2016). Given that the regressions listed above contain the year 2012, the estimated changed pollutants' concentrations since 2011 might be partially brought about by the switching to the EFI system for the Cup Series. Therefore, we exclude the Cup Series games in the robustness check.

In addition, many ARCA Series racing cars were acquired from Cup Series (Thornsburg, 2021) and kept on duty for an extended period, which could help save the budget. Although racing vehicle's engine does not need to be rebuilt after each race (Prince, 2014; Joneson, 2017) (a single NASCAR race typically does not exceed 500 miles), as most NASCAR Cup Series teams used to do before 2018 (Happer, 2019), the most durable engine parts may not work well when going over 10,000 miles (Prince, 2014). In this case, the maintenance condition of the ARCA series' racing cars would be a concern, which could also affect their air pollutants' emissions. In 2020, there was an engine failure case for the series due to no engine rebuilding since 2015 (Smith, 2020). The 5-year interval between the two correlated issues suggested

that the factor maintenance should not be negligible, since other game participants might also have similar backgrounds without engine failure during the games. To avoid this risk, we also delete the ARCA Series games in the robustness check.

Therefore, the racing data that remained for robustness check contain only races under the Xfinity series and the CWTS series, and we follow the same regressions as the (5) columns in the last part for comparisons.

robustness check (50 miles range, FE cluster by county)		
	NO_2 (z)	
	original (spectator 07-12)	robust (spectator 07-12)
ω_{z1} (by 1/million)	6.016*	13.612***
	(3.427)	(4.765)
ω_{z2} (by 1/million)	-12.446***	-13.449**
	(4.509)	(6.353)
	Ozone (z)	
	original (spectator 07-12)	robust (spectator 07-12)
ω_{z1} (by 1/million)	-6.576***	-0.085
	(2.097)	(1.74)
ω_{z2} (by 1/million)	-2.182*	0.156
	(1.118)	(2.382)
	CO (z)	
	original (spectator 07-12)	robust (spectator 07-12)
ω_{z1} (by 1/million)	3.232	7.215
	(3.179)	(7)
ω_{z2} (by 1/million)	-4.961	-3.282
	(4.714)	(8.696)
	PM_{10} (z)	
	original (spectator 07-12)	robust (spectator 07-12)

ω_{z1} (by 1/million)	-4.258	-8.901
	(5.579)	(9.033)
ω_{z2} (by 1/million)	-9.439	2.684
	(8.435)	(5.327)

	$PM_{2.5}$ (z)	
	original (spectator)	robust (spectator)
ω_{z1} (by 1/million)	-8.016*	2.75
	(4.172)	(6.442)
ω_{z2} (by 1/million)	-3.884	3.818
	(3.011)	(7.835)
FE: i & m	X	X
FE: i & w	X	X
FE: i & y	X	X

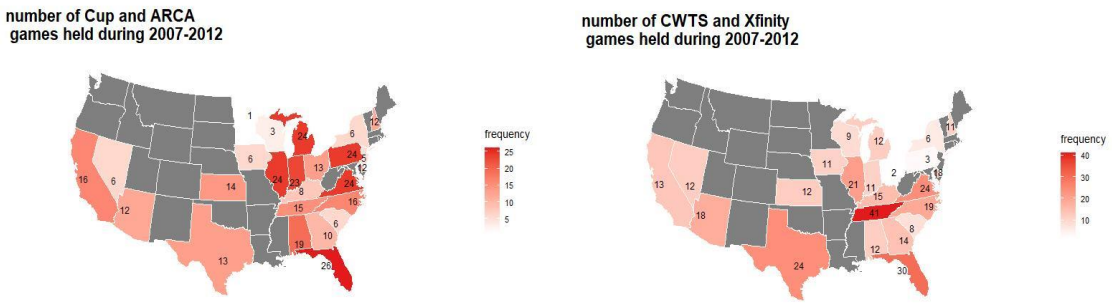
* p < 0.1, ** p < 0.05, *** p < 0.01

Table 5.1

From Table 5.1 shown above, we see that in general, the robustness check yields very similar results after switching to ethanol blend in 2011, compared to the previous part. Therefore, we further confirm that shifting to E15 fuel can reduce ambient NO_2 concentrations within areas 50 miles around the race tracks on a game day, compared to using pure gasoline. On the other hand, we still find this fuel-shifting policy implemented in 2011 may not have effects on the concentrations of other types of air pollutants in the research, same as before. Therefore, the results we derived in the last part are robust.

We should notice that when using the original racing data, we observe the NASCAR games held before 2011 could reduce the ambient ozone concentration, and the result is statistically significant. However, this situation does not hold when using the

truncated racing data for robustness check. One possible explanation is that the spatial distributions of the NASCAR series (especially between Cup & ARCA and CWTS & Xfinity) differ markedly, as shown in Figure 5.1 (a) and (b) below. In contrast with CWTS and Xfinity series, Cup series and ARCA series races usually focus on the Northeast part of the U.S. and Florida, the places having fewer VOC concentrations than South and Southwest (see Figure 2.1(f)), manifested in the above figure. We notice that negative mileage coefficients on ozone regressions may be related to the VOC-limited scenario mentioned by Salvo and Wang (2017). In the next section, we will investigate the intersectional effects among car mileage, VOC and NO_2.



(a) (b)

Figure 5.1: Cup & ARCA vs CWTS & Xfinity races distribution in the U.S. 48 states

5.2 Interactive Effects on Ozone Concentration

We should be aware that although car driving can help produce ozone, the behavior does not directly generate ozone. Instead, ozone is a "synthetic product" of VOC and NO_X under the sunlight (EPA, n.d.). The relation between VOC and NO_X on forming ozone is somewhat complex, which could be briefly denoted by Figure 5.2.

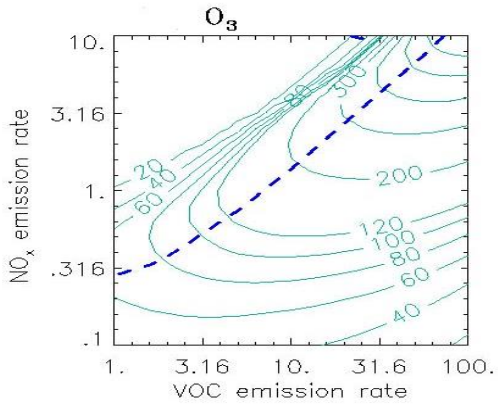


Figure 5.2

(Credit to Dr. Sanford Sillman)

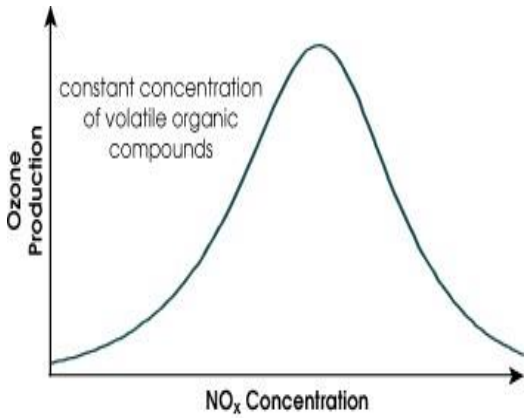


Figure 5.3

(Credit to NOAA Aeronomy Laboratory)

Given a constant VOC level, when NO_X reaches a certain point, its additional concentration may decrease ambient ozone level, as shown in Figure 5.3 (VOC-limited). Our findings (reduced ozone level on the game days) in the previous part may be pertinent to this situation. Therefore, we run the regressions taking the interactive effects between NO_2 and mileage and VOC and mileage on the game days into account to see the results. Different from the above model, here we set the dummy variables for both the time before 2011 and that after 2011.

$$\ln\left(Pollution_{ozone_{it}}\right) = \omega_{z1} * D_{y<2011} * Miles_{it} + \omega_{z2} * D_{y\geq 2011} * Miles_{it} +$$

$$+ \sigma_{ozone\_1} * D_{y<2011} * Miles_{it} * \ln\left(Mean\_Pollution_{NO2_{iy}}\right)$$

$$+ \sigma_{ozone\_2} * D_{y<2011} * Miles_{it} * \ln\left(Mean\_Pollution_{VOC_{iy}}\right)$$

$$+ \sigma_{ozone\_3} * D_{y\geq 2011} * Miles_{it} * \ln\left(Mean\_Pollution_{NO2_{iy}}\right)$$

$$+ \sigma_{ozone\_4} * D_{y\geq 2011} * Miles_{it} * \ln\left(Mean\_Pollution_{VOC_{iy}}\right)$$

$$+ \beta_z * Spectator_{it}$$

$$+ \sum_{\substack{C\in\{temperature,precipitation,wind\ speed\} \\ p\in\{1,2,3\}}} \alpha_{zcp} * C_{it}^{p}$$

$$+ \theta_{ziw} + \phi_{zim} + \tau_{ziy} + \varepsilon_{zit}$$

From Table 5.2 below, we observe that the first two entries in the second column are not statistically significant (by 90% CI), manifesting that the NASCAR racing itself has not directly produce ozone, similar to daily driving. Therefore, we choose results from the first column. The outcomes before 2011 show obvious VOC-limited phenomena: the concentrations of ozone go up with racing mileage when the local areas have a higher concentrated VOC, while going to the opposite direction with more mileage and the increased level of local NO_2.

Ozone 07-12 VOC & NO_2 (year-level)		
	NO_2 & VOC	NO_2 & VOC (reference)
ω_{z1}		1.134
		(8.006)
ω_{z2}		-11.74
		(10.434)
σ_{ozone_1}	-6.371***	-6.765*
	(2.217)	(3.712)
σ_{ozone_3}	-2.599	0.479
	(3.191)	(4.927)
σ_{ozone_2}	1.855*	1.781*
	(1.088)	(0.92)
σ_{ozone_4}	-0.889	-0.028
	(1.44)	(1.177)
Num. Obs.	1213667	1213667
FE: i & m	X	X
FE: i & w	X	X
FE: i & y	X	X

* p < 0.1, ** p < 0.05, *** p < 0.01

Table 5.2

On the other hand, after 2011 the VOC-limited situation was not statistically significant anymore. Even switching to a new fuel, we should expect that more NO_2 was generated than days without race; on a racing day, the ozone decreasing situation near a race track should continue after 2011. It could be that in 2011 and 2012, in the areas near the race tracks there was neither NO_X-limited case nor VOC-limited one, and then ozone was somewhat insensitive to minor variations in NO_X and VOC.

5.3 Wind Direction Effects

Besides the effects of pollutants' concentrations brought by the ambient wind speed, the wind direction above the race tracks relative to the monitors around may also have impacts on the monitors' readings. When a monitor is positioned in the downwind direction of a race track on a game day, it could have a larger reading regarding some air pollutant than the upwind one does. To check whether this consideration can truly affect the pollution outcomes, we take wind direction into account and incorporate the pertinent parts into the previous model in Part V:

$$\ln(Pollution_{zit}) = \omega_{z1} * Miles_{it} + \omega_{z1\_cos} * Cos_{it} * Miles_{it}$$

$$+ \omega_{z2} * D_{y\geq 2011} * Miles_{it} + \omega_{z2\_cos} * D_{y\geq 2011} * Cos_{it} * Miles_{it}$$

$$+ \beta_z * Spectator_{it}$$

$$+ \sum_{\substack{C\in\{temperature,precipitation,wind\ speed\} \\ p\in\{1,2,3\}}} \alpha_{zcp} * C_{it}^{p}$$

$$+ \theta_{ziw} + \phi_{zim} + \tau_{ziy} + \varepsilon_{zit}$$

Cos_{it} represents the bearing angle between the arrowhead from a race track to its corresponding monitor *i* and the wind direction above the race track on that day (calculated in Part IV). If the cosine value equals 1 (bearing angle is 0), the wind right above the race track is blowing directly to monitor *i*. If the cosine value equals -1 (bearing angle is -1), the wind right above the race track is blowing opposite to monitor *i*.

NO_2:

coefficient	10 miles	25 miles	50 miles
ω_{z1}	11.398**	12.481***	5.859*
	(4.841)	(3.31)	(3.236)
ω_{z2}	5.625	0.299	0.296
	(4.536)	(2.981)	(2.185)
ω_{z1_cos}	-20.070**	-11.854**	-12.183***
	(9.719)	(4.777)	(4.654)
ω_{z2_cos}	-15.679	-6.913	2.503
	(15.878)	(8.575)	(6.433)
Num. Obs.	806784	806784	806784
FE: i & m	X	X	X
FE: i & w	X	X	X
FE: i & y	X	X	X

* p < 0.1, ** p < 0.05,
*** p < 0.01

Table 5.3

Ozone:

coefficient	10 miles	25 miles	50 miles
ω_{z1}	-9.641**	-5.697**	-6.588***
	(4.222)	(2.361)	(2.043)
ω_{z2}	-3.365*	-0.816	-1.254
	(1.813)	(1.069)	(0.858)
ω_{z1_cos}	2.208	-0.853	-2.182*
	(3.414)	(1.589)	(1.12)
ω_{z2_cos}	2.791	1.312	0.948
	(4.556)	(2.138)	(1.617)
Num. Obs.	2234167	2234167	2234167
FE: i & m	X	X	X
FE: i & w	X	X	X
FE: i & y	X	X	X

* p < 0.1, ** p < 0.05,
*** p < 0.01

Table 5.4

From Table 5.3 and Table 5.4, we observe that within a 25-mile radius around the race tracks, the magnitudes for the changes of NO_2 and ozone concentrations might increase when monitors are downwind relative to the race tracks, but the results are statistically insignificant.

Chapter 6. Conclusions

We show that within a 50 miles range around a race track on a race day, there would be about 12.4% fewer NO_2 concentration, if substituting pure gasoline with E15 to achieve 1 million race mileage. The result is robust when reducing the radius (shown in the appendix) or deleting some spurious racing data. Therefore, we may hold that ethanol blend can produce less NO_2 than pure gasoline does, when driving the cars for the same mileage and holding the other factors not changed.

There might be less amount of ozone (-2.18%), CO (-4.96%), PM_{10} (-9.44%) and $PM_{2.5}$ (-3.88%) brought by the ethanol blend in the same condition, but these results are not statistically significant. The outcomes do not vary much in the robustness check part. Therefore, we consider that the ethanol blend may not have an advantage over pure gasoline in these air pollutants.

From 2007 to 2010, the U.S. had obvious VOC-limited phenomena in its ozone concentration patterns: the concentrations of ozone increased racing mileage when the local areas had elevated VOC levels, while falling with more mileage and the increased level of local NO_2. However, this situation might be no longer held in 2011 and 2012.

APPENDIX

When shrinking the radius from 50 miles around race tracks to 10 miles, except for $PM_{2.5}$, the results (shown in Appendix) do not qualitatively much differ from those in the last part. Because setting a 10-mile range excludes over 3/4 races (there were no monitors around), we prefer a 50-miles radius here.

NO2 regression (10 miles range)					
	Cluster by monitor site (OLS)	Cluster by monitor site (FE)			Cluster by county (FE)
	(1)	(2)	(3)	(4)	(5)
			+ weather	+ weather & spectator	+ weather & spectator
ω_{z1} (by 1/million)	40.606***	3.792**	3.324	10.669**	10.669**
	(5.433)	(1.92)	(2.06)	(5.219)	-5.067
ω_{z2} (by 1/million)	4.643	-6.986	-6.356	-18.840*	-18.840*
	(7.658)	(4.633)	(4.684)	(9.931)	-10.33
Num. Obs.	1786893	1786893	1786893	806784	806784
FE: i & m		X	X	X	X
FE: i & w		X	X	X	X
FE: i & y		X	X	X	X

* p < 0.1, ** p < 0.05, *** p < 0.01

Table A.1

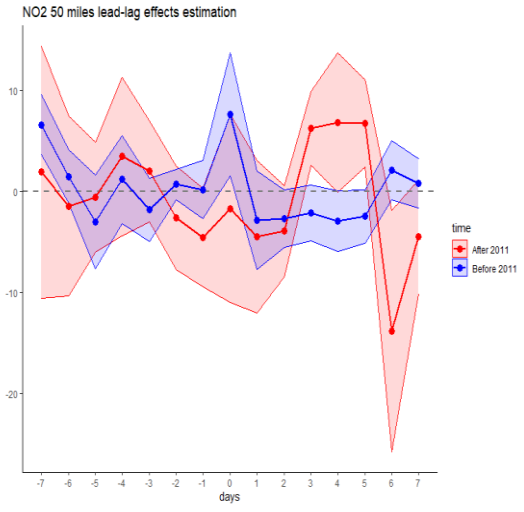


Figure A.1

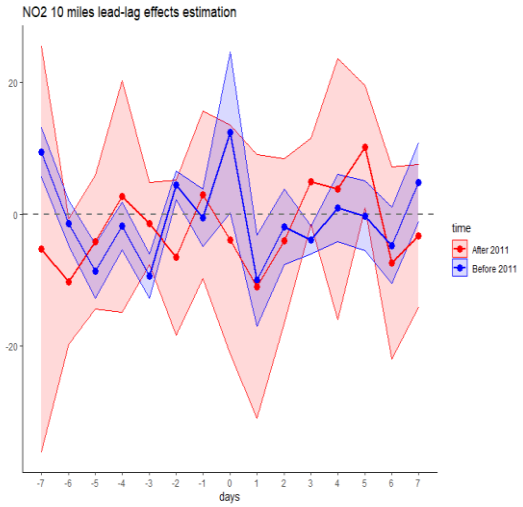


Figure A.2

Ozone regression (10 miles range)					
	Cluster by monitor site (OLS)	Cluster by monitor site (FE)			Cluster by county (FE)
	(1)	(2)	(3)	(4)	(5)
			+ weather	+ weather & spectator	+ weather & spectator
ω_{z1} (by 1/million)	-4.307	-3.637	-4.230*	-9.531***	-9.531**
	(2.865)	(2.521)	(2.269)	(3.341)	(4.722)
ω_{z2} (by 1/million)	3.536	0.565	1.96	2.473	2.473
	(4.108)	(2.554)	(2.435)	(2.668)	(3.257)
Num. Obs.	4793067	4793067	4793067	2234167	2234167
FE: i & m		X	X	X	X
FE: i & w		X	X	X	X
FE: i & y		X	X	X	X

* p < 0.1, ** p < 0.05, *** p < 0.01

Table A.2

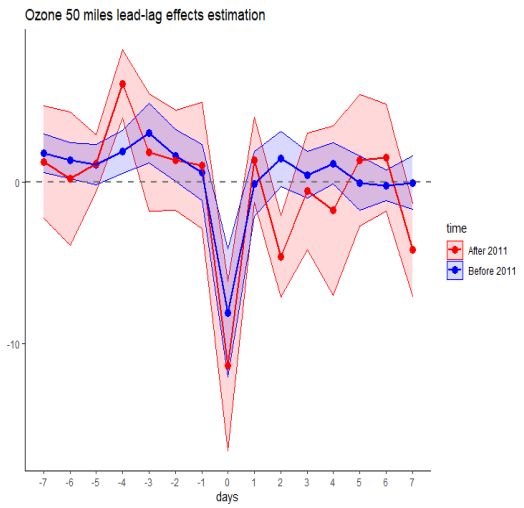


Figure A.3

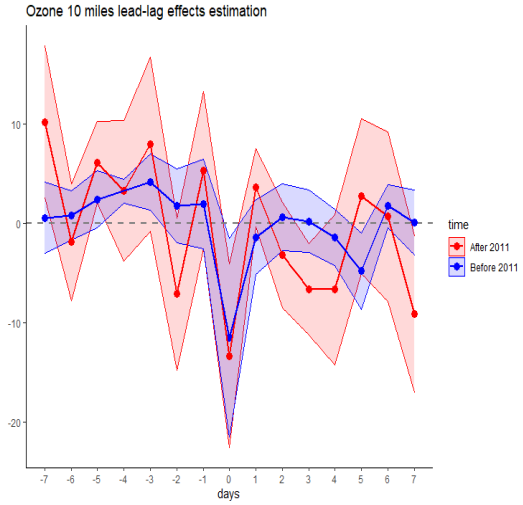


Figure A.4

CO regression (10 miles range)					
	Cluster by monitor site (OLS)	Cluster by monitor site (FE)			Cluster by county (FE)
	(1)	(2)	(3)	(4)	(5)
			+ weather	+ weather & spectator	+ weather & spectator
ω_{z1} (by 1/million)	12.300*	0.84	-0.207	1.787	1.787
	(7.091)	(2.884)	(2.819)	(5.118)	(4.423)
ω_{z2} (by 1/million)	3.287	2.434	4.127	-0.686	-0.686
	(7.036)	(3.185)	(3.289)	(6.315)	(7.895)
Num. Obs.	1391236	1391236	1391236	691360	691360
FE: i & m		X	X	X	X
FE: i & w		X	X	X	X
FE: i & y		X	X	X	X

* p < 0.1, ** p < 0.05, *** p < 0.01

Table A.3

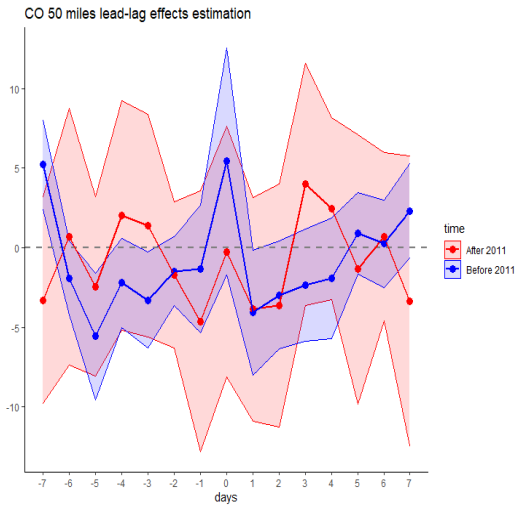


Figure A.5

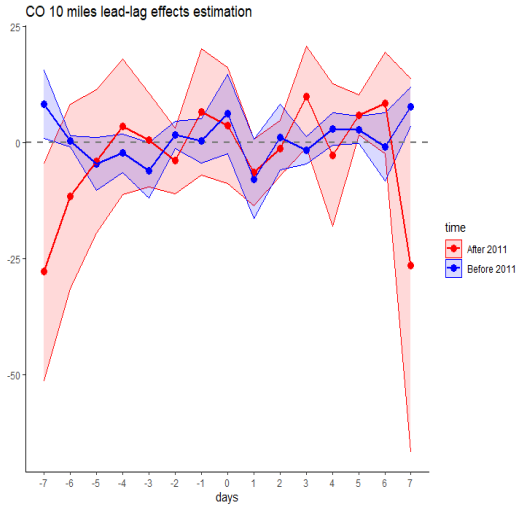


Figure A.6

PM10 regression (10 miles range)					
	Cluster by monitor site (OLS)	Cluster by monitor site (FE)			Cluster by county (FE)
	1	2	3	4	5
			+ weather	+ weather & spectator	+ weather & spectator
ω_{z1} (by 1/million)	6.914	(2.683)	-3.492	-4.867	-4.867
	(6.63)	(2.257)	-2.421	(4.68)	(6.279)
ω_{z2} (by 1/million)	2.137	-1.479	0.869	-14.691	-14.691
	(8.705)	(5.702)	(5.083)	(13.393)	(16.971)
Num. Obs.	1937004	1937004	1937004	836524	836524
FE: i & m		X	X	X	X
FE: i & w		X	X	X	X
FE: i & y		X	X	X	X

* p < 0.1, ** p < 0.05, *** p < 0.01

Table A.4

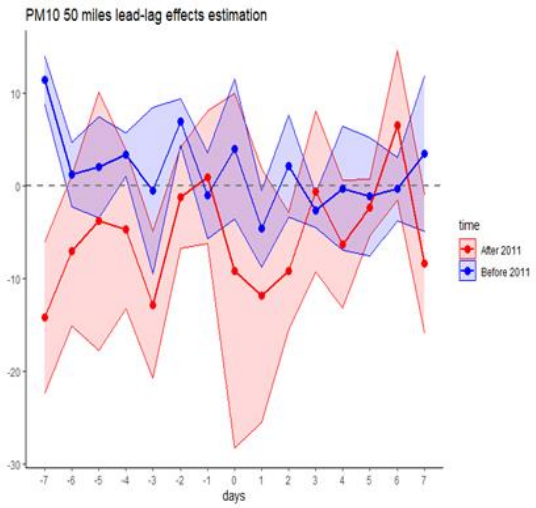


Figure A.7

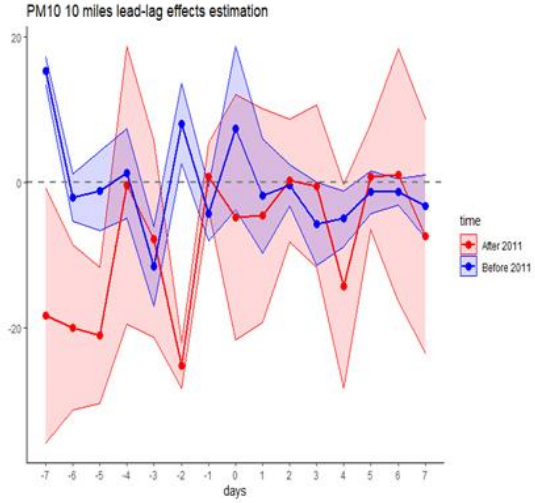


Figure A.8

PM2.5 regression (10 miles range)					
	Cluster by monitor site (OLS)	Cluster by monitor site (FE)			Cluster by county (FE)
	(1)	(2)	(3)	(4)	(5)
			+ weather	+ weather & spectator	+ weather & spectator
ω_{z1} (by 1/million)	17.745***	-0.877	-2.096	-0.706	-0.706
	(5.917)	(2.543)	(2.484)	(5.574)	(7.721)
ω_{z2} (by 1/million)	5.946	5.164	6.58	-20.376***	-20.376***
	(5.33)	(4.058)	(4.253)	(5.752)	(6.182)
Num. Obs.	2325517	2325517	2325517	900631	900631
FE: i & m		X	X	X	X
FE: i & w		X	X	X	X
FE: i & y		X	X	X	X

* p < 0.1, ** p < 0.05, *** p < 0.01

Table A.5

Figure A.9

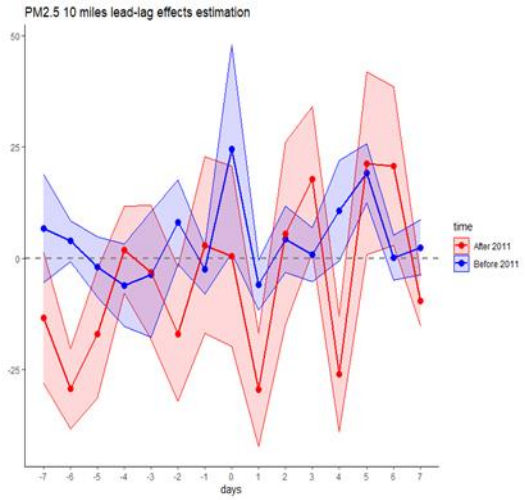


Figure A.10

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