Reformulated Gasoline and Tropospheric Ozone on Colorado's Front Range

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Abstract

After classifying Denver as a “severe” nonattainment area, the Environmental Protection Agency (EPA) required Reformulated Gasoline (RFG) to be sold in the Denver Metro/North Front Range area beginning in June 2024 to reduce ozone formation. This paper evaluates the effect of RFG on ground-level ozone using both difference-in-differences and triple difference estimators. Using 8-hour maximum ozone levels from EPA monitors from 2019 to 2024, I compare counties in the nonattainment (treated) area to two control groups: other counties in Colorado and counties in similar cities in the West. Difference-in-differences models estimate that ozone increased somewhat significantly by 2.62-4.65% during the RFG implementation period. However, triple difference specifications estimate a non-significant decrease of 1.52–2.49% in ground-level ozone in the nonattainment area during the same period. This suggests that the effect of RFG was not strong enough to negate increasing ozone trends in the Denver Metro/North Front Range nonattainment area.

Introduction

The Denver area has struggled to manage its smog problem for over a century. The “brown cloud”, familiar to Denverites in the summer months, is attributed, in part, to high levels of tropospheric ozone created from a mixture of high temperatures, sunshine, and vehicle emissions. Research has linked ground-level ozone pollution to asthma, higher rates of respiratory ailments, and lower crop yields (EPA, 2015). Despite more than half a century of emissions regulation, many areas of the US continue to experience ambient air concentrations of ozone that exceed standards set by the EPA. Located at the foothills of the Rockies, with 300 days of sunshine, hot summers, and a growing number of car commuters, the Denver area provides a perfect breeding ground for ozone formation. After being classified as a “severe” nonattainment area of ozone pollution in 2022, the EPA required RFG, an alternative fuel mixture designed to reduce ambient ozone concentrations, to be sold in the Denver area beginning on June 1, 2024. Therefore, this paper estimates the effect of the RFG program on ambient ozone concentrations throughout the Front Range.

In order to avoid high gasoline prices associated with RFG, the state of Colorado made alternate attempts to reduce ambient ozone levels. After these efforts proved unsuccessful, the EPA required RFG to be sold throughout the Denver nonattainment area beginning June 1, 2024. According to AAA, gas prices increased by an average of 15 cents per gallon due to the policy (Phillips, 2024). This paper helps us to understand whether the resources spent on targeting inputs to gasoline are appropriately allocated.

In my analysis, I use daily air pollution data from the EPA Air database, collected from monitors across Colorado and other Western states, to evaluate the effect of RFG on ground-level ozone concentrations. From this, I build an 8-hour ozone variable, which represents the highest average value of eight consecutive hours of ozone at a given monitor on a given day, consistent with EPA standards. I estimate effects by observing changes in ozone levels before and after RFG requirements were implemented in Denver compared to changes in ozone levels in counties without RFG requirements using both a difference-in-differences (DiD) and a differences-in-differences-in-differences (DDD) approach.[1]

I employ two different control groups to strengthen my results: a Rest-of-Colorado control, as well as Other Western Cities (cities similar to Denver, including Cheyenne, WY, Albuquerque, NM, Las Vegas, NV, and Phoenix, AZ). The Rest-of-Colorado control provides an understanding of how ozone levels in the Denver area change relative to the rest of the state, which experiences similar weather patterns and rates of population growth to the Denver area. The Other Western Cities control allows me to compare Denver to other cities that are possible breeding grounds for ozone formation, with higher population densities and city highway systems that the Rest-of-Colorado does not necessarily possess. These cities are confined to the Western United States and experience a dry heat summer similar to Denver, assuming that this provides a similar ozone-forming climate. Additionally, this second control group eliminates concerns about spillovers from RFG in the Front Range. It is reasonable to assume that a person may fill their gas tank in Denver and drive to neighboring counties untreated with RFG, which may alter results. However, this concern is less prevalent in these farther-away cities.

Using DiD and DDD specifications, I find that the effect of RFG was not strong enough to negate increasing ozone trends in the Denver Metro/North Front Range nonattainment area.

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[1] A third approach, regression discontinuity in time, is also proposed for future research.

Difference-in-differences results show that ozone increased somewhat significantly by 2.62-4.65% during the RFG implementation period. However, triple difference specifications estimate a non-significant decrease of 1.52–2.49% in ground-level ozone in the nonattainment area during the same period.

Literature Review

This paper contributes to the greater stream of literature that examines the effectiveness of environmental policies in reducing pollutant concentrations. In the past, policymakers have attempted to reduce ozone levels by increasing public transit use. However, research suggests that increases in public transit infrastructure have little effect on ozone levels (Webster, 2024; Chen & Whalley, 2012). Instead of targeting transportation mode choice, RFG targets inputs to gasoline, and compared to public transit take-up, the impact of RFG should be seen on a larger scale in Denver since residents are more likely to use personal vehicles than public transit (Burdick, 2018).

Existing research indicates that strict standards on gasoline composition can translate to a significant decrease in tailpipe emissions. Lim & Won (2019) found that CO2 reductions from the California Air Resources Board (CARB) gasoline standards are comparable to the effect of increasing gasoline prices by 145.43% or replacing 26% of petroleum used in transportation with cleaner alternative clean fuels (natural gas or electricity). The RFG program, which limits the amount of volatile organic compounds (VOCs), a main ingredient in ozone formation, in gasoline sold at the pumps, is expected to decrease ground-level ozone levels. This, like CARB's program, allows consumers to maintain their normal routines while reducing negative externalities (ozone formation). My research contributes to a more robust understanding of how ozone-targeting policies in gasoline impact pollution.

In the eastern US, efforts have been made to reduce ozone precursors, such as nitrogen oxides (NOx), to decrease smog in the region. The NOx Budget Trading Program, which operated from 2003 to 2008, effectively reduced ozone concentrations with a cap-and-trade system for NOx emissions (Deschenes et al., 2017). This suggests that reducing other precursors to ozone formation, including VOCs, which this paper examines, should also help reduce ground-level ozone concentrations.

More extreme measures to reduce pollution have seen success at a steep cost. Viard & Fu (2015) found that driving restrictions in Beijing improved air quality, and Dang & Trinh (2021) found that global NO2 and PM2.5 concentrations decreased by 5 percent and 4 percent, respectively, following COVID-19 lockdowns. Both papers present findings in which pollution levels significantly decrease due to harsh restrictions on consumer behavior (targeting mobility), demonstrating that pollution reduction *is* possible. However, neither of these scenarios presents reasonable long-term solutions for emissions reductions in the US due to high costs and lack of feasibility.

Other existing research focuses on the effects of RFG in the 1990s and early 2000s, finding that RFG had an insignificant effect on ozone concentrations (Auffhammer & Kellogg, 2011). Marcus (2017) confirms this finding and adds that RFG had an insignificant impact on asthma rates, an expected outcome of increased ozone, from 1995 to 2000. These findings indicate that it can be difficult to create gasoline standards that effectively reduce ozone, even when targeting VOCs.

My paper uses a similar difference-in-differences methodology to that in “Clearing the Air” by Auffhammer & Kellog (2011) to evaluate the impacts of RFG in the Denver Front Range during ozone season (June-August). However, I augment this evaluation with a triple difference specification, which provides a better idea of how ozone in the Denver nonattainment area changes from winter to summer over the years of the sample. Additionally, there has been little to no research on RFG programs since 2011, despite changes in program regulations in 2020 (EPA, 2020). Instead of looking at RFG across the entire United States, this paper focuses on the effect of the policy solely in the Denver Metro Area of Colorado. Seeing as the RFG program is new to the Front Range as of 2024, studying the effects of this program in a new location after some tweaks to regulations contributes to the understanding of how RFG’s effectiveness has changed over the last 30 years and what effect it may have going forward.

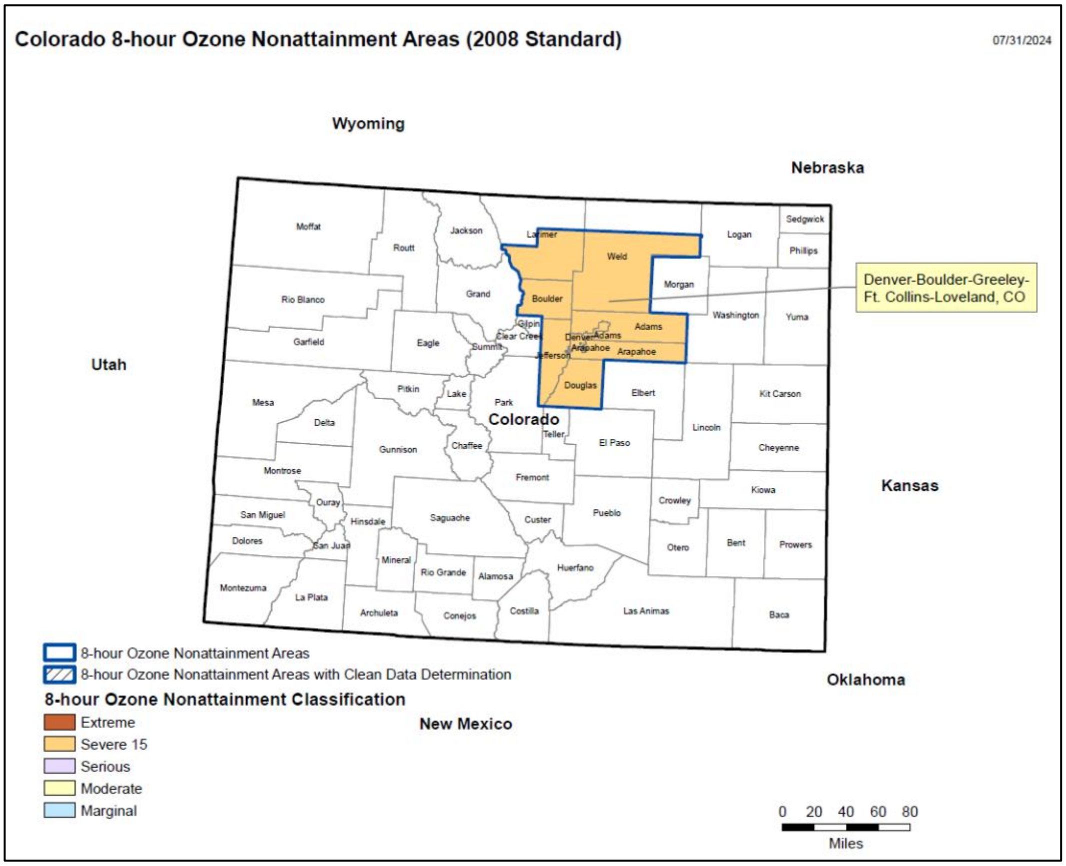
Policy Background

The Clean Air Act Amendments of 1990 mandated the implementation of RFG in 1995 for areas with severe ozone nonattainment. It is intended to reduce ground-level ozone by targeting emissions of its precursors: VOCs and NOx. Ozone forms in warm temperatures and sunlight, making summer regulations particularly important. Thus, EPA requires RFG to be sold in nonattainment areas from June 1 to October 15.

The reactivity of VOCs varies greatly, meaning some compounds contribute far more to ozone formation than others. The effectiveness of gasoline regulations depends on how well they target the most reactive VOCs or the appropriate precursor for a given area. Auffhammer and Kellogg (2011) explain that refiners primarily meet RFG standards by reducing butane, a cost-effective way to meet VOC limits. However, butane is not highly reactive in forming ozone, so while RFG reduces VOC emissions, it may not lead to significantly lower ambient ozone concentrations.

In 2020, the EPA released a final rulemaking streamlining EPA's fuel quality regulations, which simplified compliance requirements for refiners of RFG. Previously, RFG compliance was assessed using the Complex Model, a computer model used to calculate the impact of VOCs in fuel. The new compliance requirement is based on Reid Vapor Pressure (RVP), a measure of how quickly gasoline evaporates. EPA claims that this change in regulation maintains the same stringency and VOC emissions reduction requirements as before while reducing the burden associated with demonstrating compliance and costs to consumers.

Figure 1. Map of EPA Denver Metro/North Front Range Nonattainment Area



The 2022 reclassification of the Denver Metro/North Front Range ozone nonattainment area as severe prompted the EPA to require RFG throughout the area. However, the state of Colorado, wary of increased gasoline prices due to a change in inputs, made alternative attempts to reduce ozone levels. Namely, the Region Transportation District (RTD) “Zero Fare for Better Air” initiative, which eliminated all fares within the RTD system during August 2023 to incentivize alternatives to driving personal vehicles, was ultimately unsuccessful in reducing ozone pollution (Webster, 2024). After unsuccessful attempts at the state level to reduce ozone, the EPA required RFG to be sold throughout the Denver Metro/North Front Range nonattainment area beginning June 1, 2024.

Methodology

My data on ambient air concentration of ozone comes from the EPA Air Database for 2019-2024. This dataset reports hourly readings of ozone concentrations throughout the United States. The RFG program was designed to limit ground-level ozone; therefore, this is my subject of interest. I use the data to construct an eight-hour maximum measure of ozone concentrations at the monitor-day level by calculating the average ozone concentration within all eight-hour periods of each day and then taking the maximum of those averages. I chose this standard because the EPA’s ozone standards have been built around it. I follow EPA data standards by dropping all monitor-days for which observations are not recorded for at least nine hours between 9 AM and 9 PM from the dataset, as well as monitor-years for which 25% of days are missing observations.

I use the log of the eight-hour ozone maximum as my dependent variable and an RFG dummy variable for the treatment status of a given county as my independent variable.

I control for weather in my analysis because ozone concentrations increase with temperature and sunshine. To account for this, daily weather data is acquired from the National Oceanic and Atmospheric Administration (NOAA). This dataset encompasses a range of weather variables, including daily average and maximum temperatures, precipitation, humidity levels, wind conditions, and visibility. The data is collected from over 200 weather stations across the western US. Since these stations are not typically situated directly next to air pollution monitors, I pair each pollution monitor with the closest weather station.

Additionally, I use a control variable for gasoline prices, which may affect the amount of RFG purchased. This data is provided at the weekly level and is obtained from the Energy Information Administration website.

Figure 2.

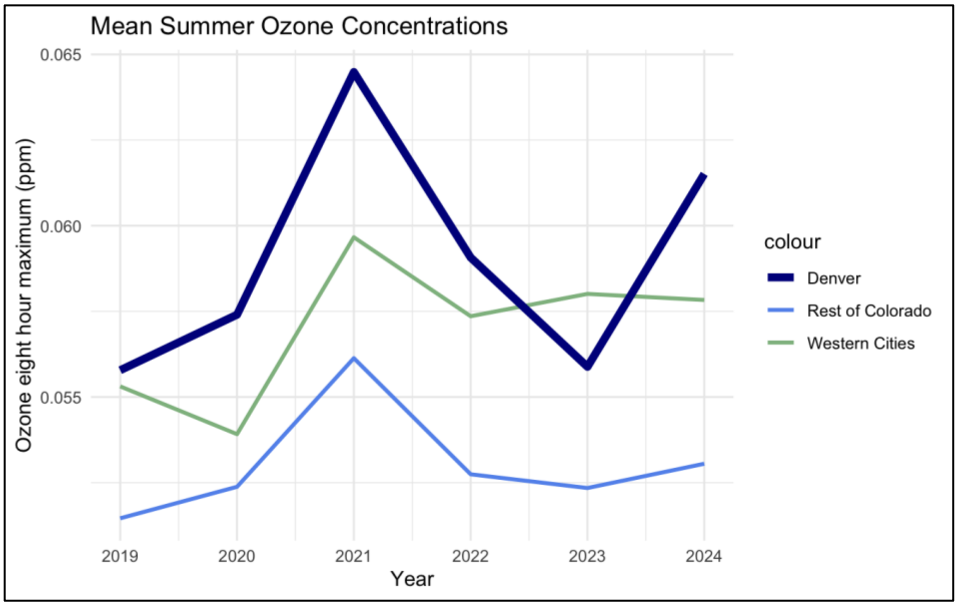
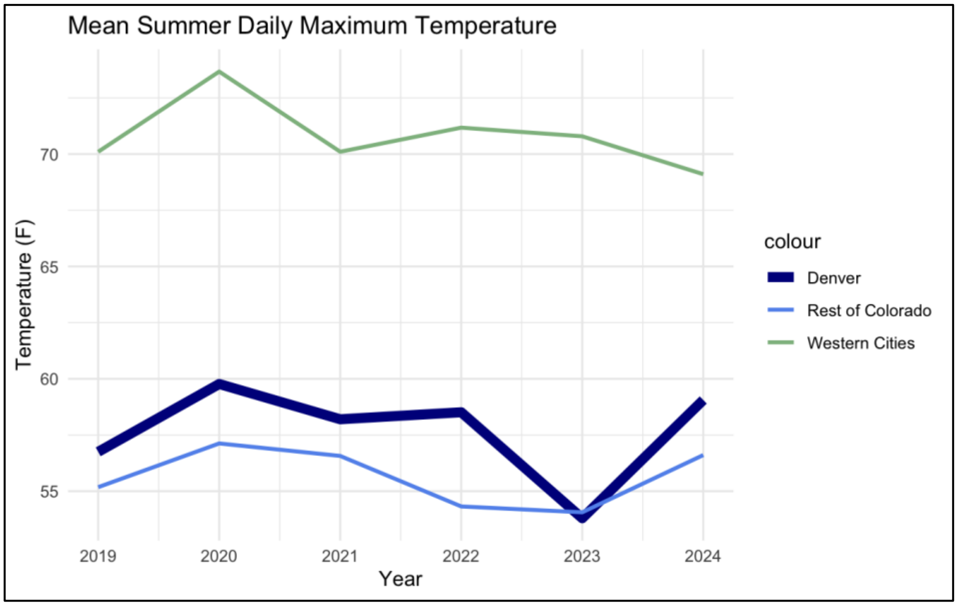


Figure 3.



For the treatment area, I have 7,718 observations of daily maximum eight-hour ozone for 15 monitors. For the Colorado control area, I have 7,973 observations for 16 monitors. And for similar Western cities, I have 16,782 observations for 37 monitors.

My goal is to identify to what extent the RFG program affects ambient ozone concentrations on the Front Range. To accomplish this, I take multiple approaches: a difference-in-differences regression and a triple differences regression, as well as a regression discontinuity in time proposed for future research.

Difference in differences

First, I perform a difference-in-differences (DiD) regression, in which I compare the change in ambient ozone concentrations in treated counties over time to the change in ambient ozone concentrations in untreated counties over time, focusing on ozone season. I compare pollution in the Denver Metro/North Front Range nonattainment area to both control areas: the rest of

Colorado and comparable Western cities. The sample for this regression is restricted to identified counties for treated and untreated groups in the summer months of June through August, during peak ozone season when the effectiveness of RFG is most crucial.

I begin with a simple DiD equation:

$$log(Y_{ity}) \ = \beta_1(treat_c \times 2024_y) \ + \beta_2 treat_c + \beta_3 2024_y + \varepsilon_{cy}$$

The "i" subscript represents monitor, "t" represents day, "c" represents county, and "y" represents year. Each county contains a few monitors. $log(Y_{ity})$ represents the outcome of interest, log ozone. β_1 is my coefficient of interest, which captures the effect of RFG on ozone levels (in percentage terms) in the Front Range through the interaction term $(treat_c \times 2024_y)$ where $treat_c$ is a county-level dummy for the treatment area (synonymous to the ozone nonattainment area in the Denver metro), and 2024_y is a dummy variable equal to 1 in the year 2024 because it is the only year RFG has been required in the Denver area thus far. If RFG successfully reduced ambient ozone concentrations, β_1 should be negative, reflecting a decrease compared to pre-policy years.

Next, I add in additional controls and fixed effects:

$$log(Y_{ity}) \ = \beta_1(treat_c \times 2024_y) \ + W_{ity}\mu_1 + X_{cty}\mu_2 + \gamma_c$$

$$+ \psi_{d(ty)} + \rho_y + \varepsilon_{city}$$

County fixed effects γ_c, day of week fixed effects $\psi_{d(ty)}$, and year fixed effects ρ_y are included. Controls for weather are included in W_{ity}, and gas prices are included in X_{cty}.

The assumption here is that ozone levels at a pollution monitor, when controlling for weather, day of week, and other factors, would only differ on the same day in different years due to the adoption of RFG in 2024. It is assumed that no other policies would impact ozone pollution in the summer of 2024 when RFG is required. This assumption would be violated if, for example, there were commuting behavior changes over the time period (ie. Work-from-home adoption) or wildfires that disproportionately impacted one group's ozone levels, even after weather controls. Another important example would be cross-border fuel purchasing, in which residents of the Denver area buy non-RFG gasoline in untreated counties, which would dilute treatment effects. If this assumption is violated, we have to accept that this regression specification may not give us an accurate estimate of the effects of RFG.

Triple difference

I compare the DiD estimate from the summer months to the DiD estimate from the non-summer months. This comparison allows me to account for other reasons that the ozone concentrations might change differently in Front Range and non-Front Range counties over the same period. The sample for this regression is restricted to the same counties as the DiD model but includes all dates of the year instead of just the summer months.

$$log(ozone_{ity}) = \beta_1(treat_c \times 2024_y \times summer_{s(t)}) + \psi_{d(ty)} + \rho_{cy} + \rho_{s(t)y} + \rho_{cs(t)} + W_{ity}\mu_1 + X_{cty}\mu_2 + \varepsilon_{city}$$

Here, the coefficient of interest is on $(treat_c \times 2024_y \times summer_{s(t)})$, which represents the effect of the RFG program on ozone in percentage terms. $summer_{s(t)}$ is a dummy variable for summertime, which is equal to one for dates between June 1st and August 31st of each year. I have also included two-way fixed effects. Year-by-county fixed effects, ρ_{cy}, account for factors common to a county within a year (e.g., local economic activity). Season-by-year fixed effects, $\rho_{s(t)y}$, control for all factors common to a season and year: for example, they would adjust for a decrease in overall ozone pollution in the summer of 2020 when people were driving less. Finally, county-by-season fixed effects, $\rho_{cs(t)}$, allow for permanent differences in outcomes across county-by-seasons.

This regression exploits three sources of variation. First, I compare the years before the RFG program was implemented on the Front Range to the year 2024. Second, I compare counties treated by RFG to untreated counties. Third, since the RFG program only applies during the summer, I compare summer to the rest of the year.

Regression Discontinuity

Here, I propose a regression discontinuity in time design to compare ambient ozone concentrations in the treated area immediately before and after the RFG program was enacted on the Front Range.[2] I use observations from April 2 – July 31, 2024 (60 days before and after the start of the program) to estimate the effects of RFG. The brief time frame in this approach is justified for two main reasons. First, the implementation of a gasoline standard affects all vehicles at once. This implies an almost instantaneous change in emissions as the standard is implemented. Second, ozone decomposes overnight, meaning daily peak ozone levels quickly reflect any changes in emissions. These factors combined enable the regression to capture the short-term effects of RFG on ozone levels without requiring an extended observation period.

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[2] Due to time constraints, this paper does not report regression discontinuity in time results. However, I suggest this regression as a possible next step in analyzing the effectiveness of the policy.

$$log(Y_{it}) \;=\; \beta_1 RFG_{cty} + W_{ity}\mu_1 + X_{cty}\mu_3 + f(date)_t + \gamma_c + \varepsilon_{city}$$

Here, I introduce a linear phase-in for the effect of RFG to account for the time that it may take consumers to refill their gas tanks with RFG instead of conventional gasoline. On June 1, 2024, the first day the program is implemented on the Front Range, RFG_{cty} is equal to $\frac{1}{30}$, equal to $\frac{2}{30}$ on June 2, and so on, until June 30, when RFG_{cty} is equal to $\frac{30}{30}$ and is equal to 1 through July 31.

I incorporate a flexible time function, $f(date)_t$, to model unobserved variation in pollution levels throughout the year. This helps isolate the policy's effect by eliminating any potential underlying relationship between the outcome $log(Y_{it})$ and ε_{city} near the June 1 implementation date. I suggest two versions of this regression: one where $f(date)_t$ represents a linear time trend and one where $f(date)_t$ represents a quadratic time trend.

Results

Tables 1 through 4 display the regression results from my DiD and triple difference (DDD) specifications from two separate control groups. The DiD specification identifies the causal relationship of the RFG program in the Denver nonattainment area with ground-level ozone by comparing pollution levels in 2024 to previous years in treated compared to untreated counties. The DDD specification identifies the same causal relationship, adding a third comparison variable: season, where non-summer ozone levels are compared to summertime ozone levels.

Difference-in-differences results

Table 1: Effect of RFG on ambient ozone levels

VARIABLES	(1) Compared to rest of Colorado	(2) Compared to rest of Colorado	(3) Compared to other Western cities	(4) Compared to other Western cities
(Treat*2024)	0.0465**	0.0378*	0.0302*	0.0262
	(0.0186)	(0.0187)	(0.0163)	(0.0178)
2024	0.000434		0.0167*	
	(0.0128)		(0.00897)	
Treat	0.0967***		0.0281	
	(0.0202)		(0.0167)	
Weather controls		X		X
Gas price controls		X		X
Day of week fixed effects		X		X
Year fixed effects		X		X
County fixed effects		X		X
Observations	15,691	15,066	24,500	22,496
R-squared	0.093	0.263	0.011	0.220

Note: *** p<0.01, ** p<0.05, * p<0.1. Standard errors are clustered at the county level at which the policy is applied.

Table 1 displays the regression results from my DiD specifications with and without added controls, comparing the counties in the nonattainment area to both comparison areas (counties in the rest of Colorado and counties in comparable Western Cities). Coefficients of the DiD specifications can be interpreted as a 2.62 to 4.65 percent additional increase in ground-level ozone pollution in 2024 compared to previous years in treated compared to untreated counties in the summertime. This does not necessarily mean that RFG caused ozone levels to increase in treated counties in 2024. However, it shows that RFG was not effective enough to outweigh other factors that contributed to an increase in ozone that year.

Difference-in-difference-in-differences results

Table 2: Effect of RFG on ambient ozone levels (Compared to the rest of Colorado)

VARIABLES	(1) Summer time DiD	(2) Wintertime DiD	(3) DDD
(Summer*Treat*2024)			-0.0213

			(0.0232)
(Treat*2024)	0.0465**	0.0678**	0.0678**
	(0.0186)	(0.0310)	(0.0310)
(Treat*Summer)			0.161***
			(0.0321)
(Summer*2024)			-0.0322**
			(0.0151)
Summer			0.180***
			(0.0141)
Treat	0.0967***	-0.0639*	-0.0639*
	(0.0202)	(0.0342)	(0.0342)
2024	0.000434	0.0327	0.0327
	(0.0128)	(0.0206)	(0.0206)
Observations	15,691	43,513	59,204
R-squared	0.093	0.015	0.176

Note: *** p<0.01, ** p<0.05, * p<0.1. Standard errors are clustered at the county level at which the policy is applied.

Table 3: Effect of RFG on ambient ozone levels (Compared to the other Western cities)

VARIABLES	(1) Summer time DiD	(2) Wintertime DiD	(3) DDD
(Summer*Treat*2024)			-0.0152
			(0.0188)
(Treat*2024)	0.0302*	0.0455*	0.0455*
	(0.0163)	(0.0240)	(0.0240)
(Treat*Summer)			0.0568
			(0.0491)
(Summer*2024)			-0.0383***
			(0.00614)
Summer			0.284***
			(0.0398)
Treat	0.0281	-0.0288	-0.0288
	(0.0167)	(0.0508)	(0.0508)
2024	0.0167*	0.0550***	0.0550***
	(0.00897)	(0.00600)	(0.00600)
Observations	24,500	71,413	95,913
R-squared	0.011	0.006	0.180

Note: *** p<0.01, ** p<0.05, * p<0.1. Standard errors are clustered at the county level at which the policy is applied.

Table 4: Effect of RFG on ambient ozone levels

VARIABLES	(1) Compared to rest of Colorado	(2) Compared to rest of Colorado	(3) Compared to other Western cities	(4) Compared to other Western cities

(Summer*Treat*2024)	-0.0213	-0.0249	-0.0152	-0.00214
	(0.0232)	(0.0232)	(0.0188)	(0.0182)
(Treat*2024)	0.0678**		0.0455*	
	(0.0310)		(0.0240)	
(Treat*Summer)	0.161***		0.0568	
	(0.0321)		(0.0491)	
(Summer*2024)	-0.0322**		-0.0383***	
	(0.0151)		(0.00614)	
Weather controls		X		X
Gas price controls		X		X
Day of week fixed effects		X		X
County-by-year fixed effects		X		X
County-by-season fixed effects		X		X
Season-by-year fixed effects		X		X
Observations	59,204	56,584	95,913	88,053
R-squared	0.176	0.337	0.180	0.409

Note: *** p<0.01, ** p<0.05, * p<0.1. Standard errors are clustered at the county level at which the policy is applied.

Tables 2 and 3 (one table for each comparison area) display three specifications without controls. The original DiD specification (same as columns 1 and 3 of Table 1) alongside a DiD restricted to dates excluding summertime and a DDD. We can interpret the key coefficient of the non-summer DiD specification as a 4.55 to 6.78 percent additional increase in ground-level ozone pollution in 2024 compared to previous years in treated compared to untreated counties throughout the rest of the year (excluding summertime dates). That is, wintertime ozone concentrations, which are not affected by RFG requirements, increased in treated counties in 2024. Columns 1 and 2 of this table help us interpret the DDD for which the coefficient of interest (Summer*Treat*2024) is equal to the key coefficient of column 1 minus the key coefficient of column 2. From this, we gather that the ozone pollution from wintertime to summertime in 2024 compared to past years increased by 1.52 to 2.13 percent less in treated counties compared to untreated counties.

Table 4 reports DDD specification results for both comparison groups, including specifications both with and without control variables. The key coefficient here can be interpreted as a 1.52 to 2.49 percent lower increase in the change in ozone pollution levels from winter to summer time in treated counties compared to untreated counties in the year 2024 compared to past years. However, the coefficient is not statistically significant in any of the DDD models.

Although we learn from the DiD specifications that ozone levels in the summer of 2024 in treated counties compared to untreated counties were higher compared to past years, we can also say that the increase from winter to summer time for these groups decreased by a small percentage in 2024. Essentially, RFG requirements may have helped to reduce ozone, but estimates are imprecise and not large enough to offset factors that generally increased ozone in treated counties in the summer of 2024.

Discussion

The EPA standard for ozone is 0.070 parts per million (ppm) as the fourth-highest daily maximum 8-hour concentration, averaged across three consecutive years. This average over the years 2021 to 2023 (immediately before the implementation of RFG) in the Denver nonattainment area was 0.0719333 ppm. This would require a decrease of more than 2.688% in ambient ozone levels to be within EPA standards. Most generously, I estimate that RFG decreased ozone by 2.49%, not enough to help the Denver area meet EPA standards given a similar summer to previous years. Moreover, with high ozone levels in the summer of 2024, we can see that ambient ozone levels have further surpassed standard limits with an average of 0.0725667 ppm as the average across 2022-2024 fourth-highest eight-hour maximum readings.

To meet EPA ozone standards, this will require even stronger RFG reduction strategies, with more than a 3.54% reduction in ambient ozone concentrations.

It is important to consider why the coefficient of interest in my results changes signs between the DiD and DDD specifications. The DDD specification absorbs year-long trends that the DiD specification misses due to its restricted time frame. One likely explanation is that overall traffic levels increased in the year 2024, increasing ozone levels at both times of the year, with substantially more ozone observed in the summertime when ozone precursors (NOx, VOCs, etc.) interact with sunshine and high temperatures (other crucial components of ozone). This seems feasible, considering the steady increase in population in the Denver area over the sample period, with the highest population levels recorded in 2024 (Macrotrends, n.d.). Additionally, the pandemic work-from-home and post-pandemic return-to-work trends have undoubtedly influenced traffic patterns. Return-to-work trends, in combination with an increasing population, provide good reason to believe that traffic levels may have been differentially increasing in treated counties compared to untreated counties over the sample period.

For this reason, it would be useful to include a control variable for traffic, which would be expected to be positively correlated with ozone. We can expect that the bias due to this omitted variable would be positive, meaning that the omission of a traffic control would cause the estimation of the key coefficient representing RFG to be closer to zero than the true value. In other words, if I included a control variable for traffic, I could expect the key coefficients for RFG to be more negative.

One concern presented earlier in the paper pertains to cross-border purchasing, a case in which Denver residents would travel out of the nonattainment/RFG geographic area to purchase gasoline in an effort to avoid high RFG prices. However, this is likely not a confounding factor in this study because results are consistent across multiple control groups, and it is highly unlikely that Denver area RFG has affected ozone levels in other Western Cities compared to Denver.

I would be more confident in my estimations with more robust EPA air quality data provided. Given that I have 15 monitors across 10 counties that meet my criteria for the number of days with observations in the treated area and that tropospheric ozone varies at a local level, my estimations of ozone levels themselves are imperfect. Ozone levels would be considerably higher if a monitor is located near a highway versus in a more residential or rural part of a county, so a perfect measure of ozone would require an even spread of monitors among higher and lower traffic areas in each county.

To further my research, I also suggest conducting a regression discontinuity in time, which I outline in the methodology section of this paper. This would allow us to understand if there was an immediate decrease in ozone concentrations with the implementation of RFG requirements. This regression eliminates comparisons between 2024 and past years, which may be useful, knowing that 2024 was a relatively high year for ground-level ozone in general. Unlike DiD and DDD models, this model allows for unobservable nonlinear trends over time, which might affect ozone levels, provided they are continuous during the implementation of RFG.

Conclusion

The state of Colorado faces significant ground-level ozone pollution during the summer months. To combat this issue, RFG was implemented in the Denver area starting in the summer of 2024, aimed at lowering ozone precursor emissions during critical ozone months. This paper is the first to empirically study RFG in the Front Range and is the first paper to use a triple difference regression specification to evaluate RFG's effectiveness.

Using ground-level ozone data from EPA monitor networks to compare the Denver Metro/North Front Range nonattainment area to the Rest of Colorado and comparable Western cities, we find that RFG can have a small but insignificant effect on ambient ozone levels, similar to findings from Auffhammer & Kellogg (2011). Difference-in-differences results show that ozone increased somewhat significantly by 2.62-4.65% during the RFG implementation period. However, triple difference specifications estimate a non-significant decrease of 1.52–2.49% in ground-level ozone in the nonattainment area during the same period. The most generous triple difference specification suggests that RFG did not reduce ozone enough for the Denver area to meet EPA standards. However, there is reason to believe that including a traffic level control variable would give more accurate estimates, making the key coefficient in my triple difference more negative and indicating a larger reduction in ozone than I estimate in this paper.

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