Concentration Effects of Heterogenous Standards: Refinery response to the Clean Air Act Amendments

Matt Butner[†]
University of Colorado Boulder, Economics

May 1, 2019

Abstract

Environmental regulations can alter the geographic and product markets in which firms compete. This can impact a firm's ability to exercise market power, and profits subsequently. The boutique fuel standards related to the 1990 Clean Air Act Amendments is one such regulation that did this to the petroleum refining industry by mandating unconventional, cleaner burning, gasoline to be sold in certain counties of the United States. While the production of the cleaner fuel increased the fixed and variable cost of refineries, it also allowed them to recuperate lost profits by selling their product in a more concentrated market with a higher markup. I use a simulation to show evidence that the concentration effect can offset investment cost, and provide empirical evidence to suggest the refineries most exposed to the boutique fuel standards benefited the most from the policy.

JEL classification codes: L13, Q58, L71

[†]256 UCB, Boulder, Colorado, 80309; matt.butner@gmail.com

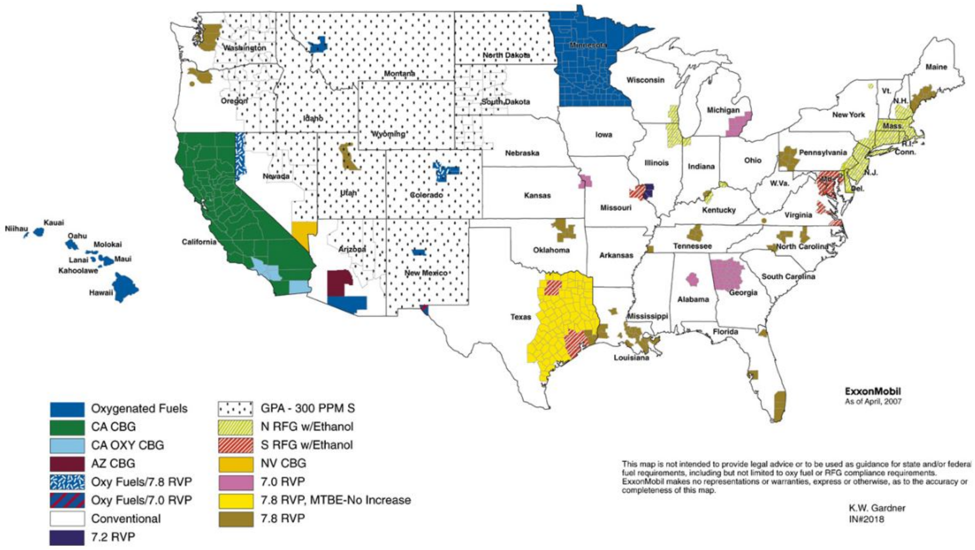
1 Introduction

Environmental policies have the goal of increasing total welfare by correcting for an externality that is not addressed by the market. More often than not there are unintended economic consequences that result from the implementation of an environmental policy. These unintended consequences have the potential to be large, and can influence much of the political economy regarding the implementation of differing policies. In this paper I document one such policy, the boutique fuel standards associated with the 1990 Clean Air Act Amendments (CAAA). I show how this policy influenced the market structure for petroleum refineries by segmenting the product market, and what the implications were for the profitability of refineries that were exposed to the standard.

These standards required specialized, cleaner burning, fuel to be sold in a patch work of densely populated areas within the United States, illustrated by Figure 1. These specialized fuels had a higher variable cost of production and required investment into particular production technologies (Office of Technology Assessment, 1990; Sweeney, 2014). Industry publications at the time claimed this regulation had "a more significant impact on refinery operations and capital expenditures than any environmental legislations since ... 1976" (Scherr et al., 1991). Typically, an increase in the cost of production would cause more firms to exit the market in the long run. Industry publications painted a grim picture, with one editorial column stating petroleum refineries "either retooled ... or shutdown ... invested ... or shutdown ... bought oxygenate or the ability to make it or shut down" (Oil & Gas Journal, 1997). In this paper, I show that the concentration effect associated with segmented product markets offset some of these industry concerns.

Although the boutique standards associated with the 1990 CAAAs did increase the costs of production, they also segmented the product market into "conventional" gasoline and "reformulated" gasoline. The segmentation of the product market, in addition to the costly investment in production technologies, allowed petroleum refineries to compete in more concentrated markets where they could exert more market power and charge a higher markup of price over the cost of production. We might expect the "concentration effects" of these standards to be large as the number of refineries has decline over time (shown in Figure 2) and these refineries already compete in

Figure 1: Product Markets Resulting from the 1990 CAAAs.



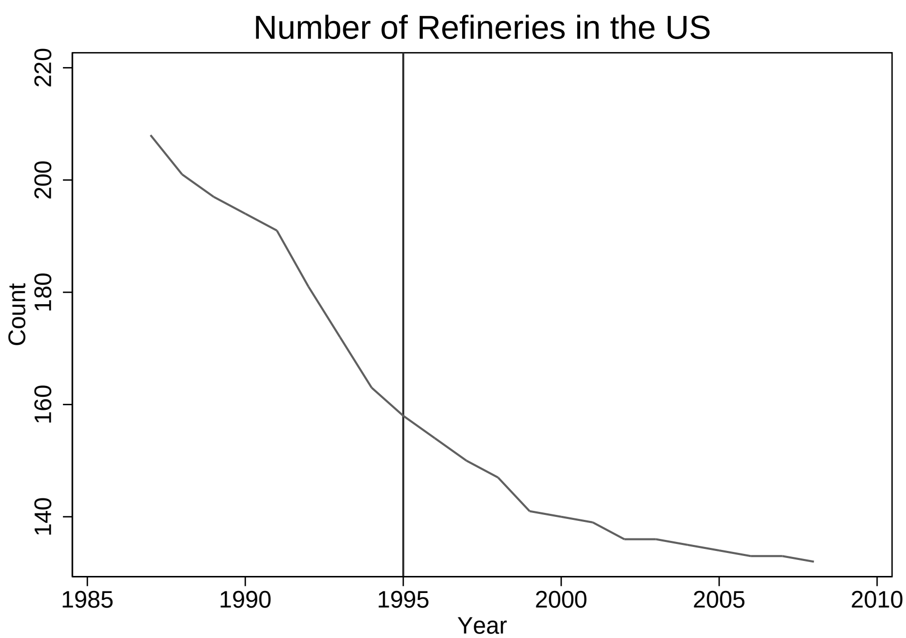
Map is from Brown et al. (2008).

relatively concentrated markets.[1]

In the paper, I explore the extent to which the concentration effects of the boutique fuel standards offset the higher cost of production in influencing the profitability of petroleum refineries in the United States (US). I do this by first considering a simple model of Cournot competition in which petroleum refineries can sell two different products to geographic markets. In this model I explicitly model transportation costs, so the geography of production and consumption is important. I use this model to focus on the dynamics of investment in a technology that allows production of the higher cost good, and how the profitability of different refineries changes under different investment scenarios. Next, I turn to annual data of refinery capacity and operation status from the Energy Information Agency to look for evidence consistent with the theory. Using a hazard function approach in a difference-in-differences type framework, I show that refineries that were most exposed to Boutique Fuel Standards were the least likely to exit the market after the standards went into place. Interpreting this from a latent profits perspective, the additional profits

[1]Using data on petroleum refinery capacity by Unit States state from 1987 to 2008, the average Herfindahl–Hirschman Index is approximately 0.56, indicating high concentration.

Figure 2: Number of Operating Refineries in the US by Year.



The vertical bar approximates the introduction of Boutique Fuel Standards associated with the Clean Air Act Amendments. Source: EIA-820.

from market segmentation offset investment and production costs.

Most directly, this research addresses the dynamic implications of environmental policies and the spatial issues relating to environmental federalism. The use of dynamic industry models to understand the long term implications of environmental regulations is "[p]erhaps the most striking gap in the literature" despite investment, research and development, and entry-exit decisions being the major mechanism in which a regulation can impact industry (Millimet et al., 2009, p.113). Recent work, using the dynamic discrete choice framework of Maskin and Tirole (1988); Ericson and Pakes (1995), has been used to simulate the resulting change in market power due to environmental regulations (Ryan, 2012; Fowlie et al., 2015). While informative, this type of analysis requires data that are often confidential and a number of assumptions regarding market conduct and economic primitives.[2] Though less structured, similar dynamic information can be inferred from robust reduced form specifications or through the use of survival analysis as in Deily and Gray (1991); Helland (1998); Snyder et al. (2003).

From a regulatory perspective, the CAAAs and their impact on refinery closures can be conceived as an issue within Environmental Federalism (Millimet, 2014). The boutique fuel standards were primarily designed to reduce ozone, and since ozone pollution depends on the *local* mix of nitrogen oxides (NO_x) and volatile organic compounds (VOCs), heterogeneous fuel standards at the county level make sense in the context of Oates' Decentralization Principle - the scale of the regulation should match the scale of the externality (Oates, 1972). For this policy in particular, however, the production and transportation network do not match the scale of the regulation. The incongruence between policy and production can create risk of supply interruptions, and contribute to other distortions that have economic consequence.[3]

From a policy perspective, my study contributes to the evaluation of the CAAAs transportation fuel standards' impact and efficacy. States subject to the fuel mandate have been associated with

[2]The data to do this analysis for the petroleum industry exists, however the EIA has changed its data sharing policy as of 2017.

[3]Muehlegger (2006) shows the boutique fuel standards can explain 70-90% of a price spike caused by an unexpected refinery outage in California, Illinois, and Wisconsin. This is driven by the difficulties in sourcing alternative fuels that meet the local standard.

a positive and statistically significant increase in retail gasoline price when controlling for other factors (Chouinard and Perloff, 2007). Using a paired differences approach at the city level, Brown et al. (2008) shows that these boutique fuels cost an additional 3 cents per gallon in retail price on average. This cost is substantial given that the policy has been shown to have little to no impact on pollution levels except in the most strictly regulated state of California (Auffhammer and Kellogg, 2011). The extent to which this price increase is driven by an increase in the cost of production, or increased concentration, is a great avenue of future research.

This paper proceeds as follows, section 2 describes some key details on the regulation and industry. Section 3 presents an analytical model of spatially differentiated multi-product Cournot competitors who choose to invest in a new technology to produce a higher cost good, while subsection 3.4 simulates this model. Section 4 shows empirical evidence to support the model and the simulation. Section 5 concludes.

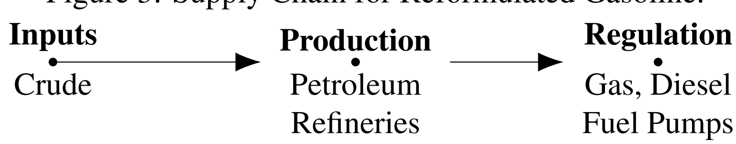
2 Background on the Regulation and Industry

The CAAAs consist of three petroleum relevant regulations including maximum Reid vapor pressure to decrease volatile organic compounds, minimum added Oxygenate to reduce carbon monoxide, and a reformulated gasoline (RFG) standard to address ozone formation. While all three are significant, RFG has been most directly associated with increased costs and a change of refinery operations (Sweeney, 2014). My analysis will exclusively consider the impact of RFG, but can easily be extended to encompass alternative fuel policies.

Promulgated in 1990, Phase I RFG fuels were mandated in counties of severe ozone nonattainment in 1995. It is important to note there is a lag between policy creation and implementation, during which firms had the opportunity to adapt. The RFG standard consists of a fuel with a level of benzene, volatile organic compounds, and toxic air pollutants that is less than those of average gasoline products, however there are multiple ways a fuel can achieve this standard. Some counties opted into the fuel standard as part of their state's implementation plan to achieve ozone compliance, while a few other counties chose to opt out.[4] Notably, the entire state of California adopted reformulated fuel standards and enforced a standard stricter than Federal guidelines. Because these regulations were mandated in disproportionately populated areas, over 30% of domestic consumption of gasoline includes these fuels. Phase II introduced in 2000 involved stricter standards addressing NO_x. The implications for refineries consist of increased fixed and variable costs as well as the segmentation of a once homogeneous product market into a patchwork of specialized fuels.

As an industry, refining possess unique characteristics. It is the intermediate production process between crude extraction and retail sale of petroleum products (predominately distillate, gasoline, diesel, jet fuel), as shown in Figure 3. Firms in this industry are both vertically and horizontally integrated, owning upstream exploration, downstream retail, and multiple refineries. Gasoline accounts for the most significant share of output from a refinery, typically over 40%, while distillate fuels (diesel) typically account for an additional 30%. Various technologies are employed at variable capacities to transform crude into refined products. The basic process involves a distillation tower to separate elements of crude oil, an upgrading of the distillation vapors, and then a host of process to purify the product. While certain technologies, such as upgrading and desulpherization, have been associated with RFG, there is no singular technology that produces RFG exactly (Office of Technology Assessment, 1990). This is in part due to the various ways in which fuel can meet RFG requirements in addition to the ambiguous engineering relationship between technologies and pollutants.[5]

Figure 3: Supply Chain for Reformulated Gasoline.

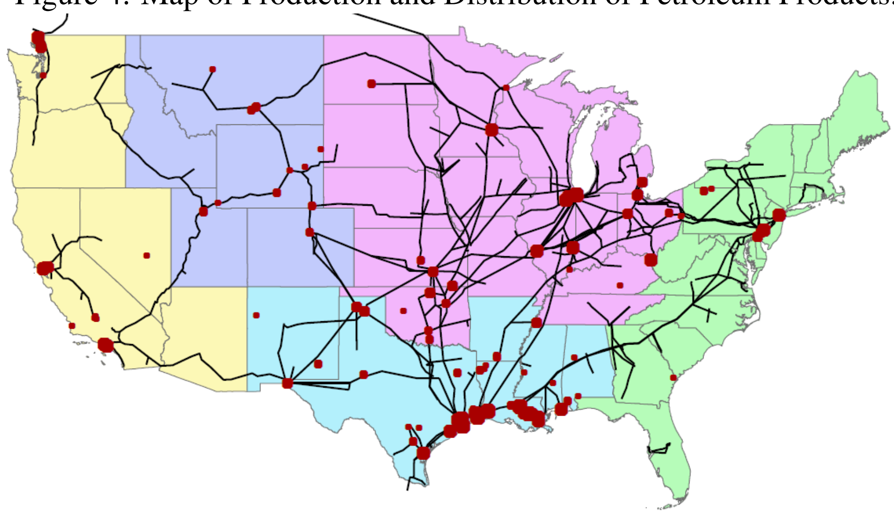


[4]A complete list of counties and their adoption date is available at `http://www.epa.gov/gasoline-standards/reformulated-gasoline`, accessed 2/28/2016

[5]For example, hydro-treating reduces aromatics (good) and hydro-cracking increases concentration of olefin (bad), catalytic reforming increases aromatics (bad) and reduces the concentration of olefin (good) (Office of Technology Assessment, 1990).

The geography of petrol production and distribution is not uniform across the US and incongruent with RFG markets. Figure 4 shows the refinery locations in addition to operating pipelines for finished products. Aggregate markets commonly used in analysis are referred to as Petroleum Administrative Defense Districts (PADD). A majority of production is accomplished in PADD 2 (Midwest) and PADD 3 (Gulf Coast), primarily because these market's proximity to waterways that are connected to crude production areas. PADD 4 (Rockies) and PADD 5 (West Coast) are largely isolated, in part because of the difficulty crossing the Pacific Ocean and the Rocky Mountains. The largest net importer is PADD 1 (East Coast), as there is not much conventional oil produced in this area, and there is a high demand for oil products. During the study period gasoline was predominately transported via petroleum product pipelines, however shipments by barge, rail, or transport truck do happen, albeit with higher transportation costs.

Figure 4: Map of Production and Distribution of Petroleum Products.



Data is publicly available from the EIA. Colors represent PADD regions, dots represent refinery with the diameter proportion to refinery capacity, and the lines represent pipelines for transporting crude and gasoline products.

The dynamics of this industry are particularly interesting, the number of refineries has declined considerably and consistently since domestic price supports and subsidies were dismantled in 1981 as shown in Figure 2.[6] Chesnes (2009) considers the dynamic investment decision of refineries, emphasizing the high capacity utilization rates despite a declining number of plants. Empirical work looking at the refining industry from 1947 to 2013 finds refinery size and the degree of multiple plant ownership as major drivers of plant closure, with multiplant owners choosing to close the smaller plants (Meyer and Taylor, 2015). Considering the importance of policy, Chen (2002) uses survival analysis to determine plants that were subsidized in the 1970s were more likely to close once the subsidies were dismantled in the 1980s. Breaking down the number of refineries by PADD, as in Figure 5, shows the geographic distribution of exit varies more after the Phase 1 or RFG was implemented. Exit trends since the end of the price supports equalize across PADDs. Most of the refineries that exited were in PADD 3, while very few refineries exited in PADD 1 and PADD 4.

3 Modeling Refinery Response

3.1 Baseline Model

I model N petroleum refineries competing in M geographic markets.[7] Refinery n chooses to sell q_{nm} units of gasoline to market m, however incurs a transportation costs equal to τ_{nm} for every unit sold. Inverse demand in each market, m, is given by $P(Q_m)$ where $Q_m = \sum_n q_{nm}$ denotes aggregate gasoline sold in market m with $P'(Q_m) < 0$. The cost of producing gasoline is convex, to characterize the capacity constraints associated with petroleum refineries, and a function of the total amount of gasoline sold by firm n: $C(q_n)$ where $q_n = \sum_m q_{nm}$ and $C'(q_n) > 0$ and $C''(q_n) > 0$.

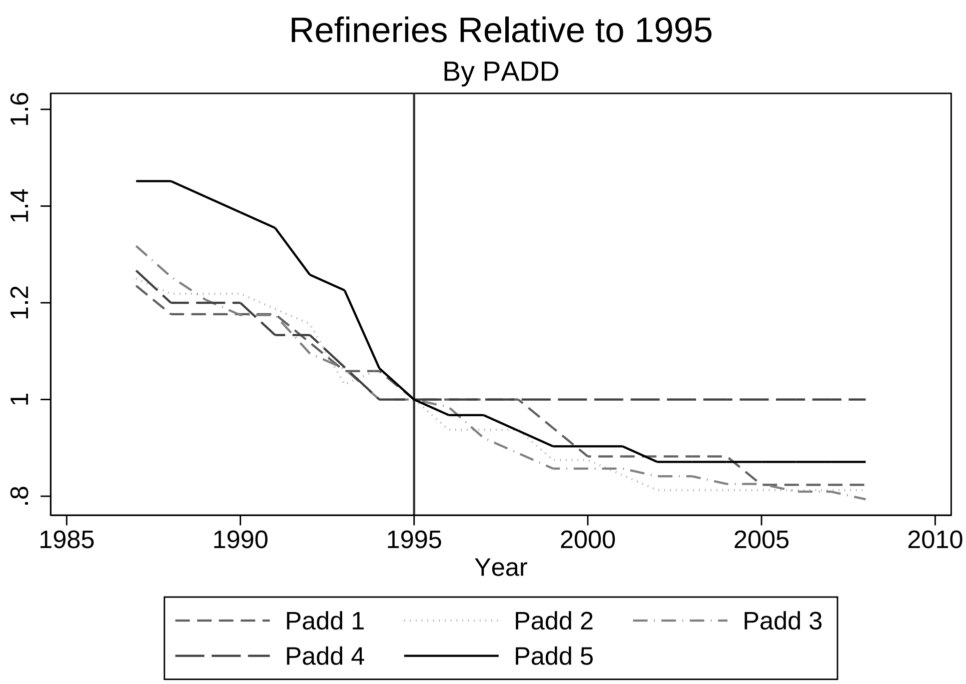
All together, this implies the profits of firm n can be characterized by $\mathbf{q_n} = [q_{n1} \dots q_{nM}]'$

$$\pi_n(\mathbf{q_n}) = \sum_m [(P(Q_m) - \tau_{nm})\, q_{nm}] - C(q_n) \tag{1}$$

[6]For a detailed description of refinery genealogy see `http://www.eia.gov/finance/genealogy/` Accessed 4/3/2016

[7]The geographic markets can be thought of as counties within the United States.

Figure 5: Number of Refineries by PADD.



This figure shows the number of refineries by PADD per year as a percentage of the number of refineries in that PADD in 1995 when RFG Phase I went into effect.

Because demand is identical across markets, and cost of production are identical across refineries, the refineries are only differentiated by their transportation cost. The difference in transportation costs could be thought of firm's having different costs of production to sell in different markets. The refinery will choose the set of $q_{n1},\ldots,q_{nM}$ to maximize their profits taking the quantities from the other refineries as given. The m first order conditions for firm n are

$$P(Q_m)+P'(Q_m)q_{nm}-\tau_{nm}=C'(q_n), \quad \forall m$$

This set of first order conditions depends on the production of other refineries in the same market through Q_m, but also the production of this refinery in other markets, through q_n. From this first order condition we can see that the refinery will set the marginal revenue net transportation costs equal to the same marginal cost across all markets. If competitors supply the same amount to market i and market j, firm n will sell more in market i if $\tau_{ni}<\tau_{nj}$. So each refinery will sell more gasoline to closer markets, all else equal.

The set of first order conditions for all refineries, across all markets, characterize the equilibrium quantities q^*_{nm}. The prices per market will be determined by $P(Q^*_m)$ and profits will be be given by equation 1. Because of the asymmetry in transportation costs, an analytical Nash equilibrium is difficult to solve for. However, because transportations costs determine the quantity produced by every refinery, the aggregate quantity in a market Q^*_m will depend on the transportation costs of all firms selling to that market, $\tau_{1m},\ldots\tau_{Nm}$, and markets with smaller total transportation costs will have lower prices.

If inverse demand is linear, of the form $P(Q_m)=a-bQ_m$, and costs are quadratic, of the form $C(q_n)=cq_n^2$, the first order condition can be expressed as a system of equations in matrix form:

$$A=BQ_{N\times M}+Q_{N\times M}C \tag{2}$$

where element (n,m) of $Q_{N\times M}$ is q_{nm}. Here $A=[\mathbf{1}_{N\times M}a-\tau_{N\times M}]$, $B=b\,[\mathbf{1}_{N\times N}+\mathbf{I}_N]$, and $C=2c\,[\mathbf{1}_{M\times M}]$ where element (n,m) of $\tau_{N\times M}$ is τ_{nm}, $\mathbf{I}_N$ is an identity matrix of size N and $\mathbf{1}_{N\times M}$ is a matrix of ones. This is a Sylvester equation and has a solution as long as the B and $-C$ do not share an eigenvalue.

3.2 Introduction of New Product

I now model the market structure after a new, more expensive, product is mandated in some geographic markets. In the context of the reformulated gasoline standards of the 1990 Clean Air Act Amendments, this represents the counties in which only a cleaner burning fuel could be sold. I denote these markets by $M^r \subset \{1,\ldots,M\}$, and the conventional markets are denoted by $M^c = \subset \{1,\ldots,M\} \setminus M^r$. The refinery now chooses how much to produce of each type of product, where q^r_{nm} denotes the new product sold by refinery n to market $m \in M^r$, and q^c_{nm} is the quantity of the conventional fuel type sold by firm n to market $m \in M^c$.

I first assume that it is costless to acquire the technology to produce and sell this product, however this product has an additional marginal cost of production c_r. Refineries now have the following profit function

$$\pi_n(\mathbf{q}_n) = \sum_{m\in M^r} [(P(Q_m) - \tau_{nm} - c_r)\, q^r_{nm}] + \sum_{m\in M^c} [(P(Q_m) - \tau_{nm})\, q^c_{nm}] - C(q_n)$$

Choosing q_{nm} to maximize their profits results in first order conditions

$$P(Q_m) + P'(Q_m) q^c_{nm} - \tau_{nm} = C'(q_n), \quad \forall m \in M^c$$
$$P(Q_m) + P'(Q_m) q^r_{nm} - \tau_{nm} - c_r = C'(q_n), \quad \forall m \in M^r$$

This can be incorporated into the Sylvester Equation 2 by redefining $A = [\mathbf{1}_{N\times M} a - \tau_{N\times M}] - c_r \mathbf{1}_{N\times 1} R_{1\times M}$ where element m in $R_{1\times M}$ equal 1 if market m is subject to the regulation and 0 if it is not.

From these first order conditions we see that the refinery will choose to sell *less* in the markets where the higher cost gasoline is mandated ($m \in M^r$), all else equal, because the cost of production has increased in these markets. Because the quantity sold in markets $m \in M^r$ has reduced, the firm will increase in the quantity sold in $m \in M^c$. This happens because the marginal cost of production is a function of total quantity produced, and producing less in $m \in M^r$ decreases this marginal cost of total production, $C'(q_n)$, because costs are convex. In the markets where costs have not changed, $m \in M^c$, the refinery will choose to increase their quantity sold to match marginal revenue to the lower marginal cots. This static result of cross-product spillovers is the premise of Sweeney (2014).

3.3 New Product Requires Investment

I now consider the dynamic effects of the new product mandate by considering the incentives of refineries to expend a fix cost F_r to have the *ability* to sell in the geographic markets where the more costly product is mandated. I denote whether refinery n invests in the technology to produce the new product by the binary indicator variable I_n which equals to 1 if refinery n invests F_r and 0 if they do not. As a result, there will two types of refineries, those that invest, and those that don't. The refineries that invest receive revenue from both product markets, while those that don't only receive revenue from the conventional product markets. So the general profit function is of the form

$$\pi_n(\mathbf{q}_n) = I_n \left[\sum_{m \in M^r} [(P(Q_m) - \tau_{nm} - c_r)\, q^r_{nm}] - F_r \right] + \sum_{m \in M^c} [(P(Q_m) - \tau_{nm})\, q^c_{nm}] - C(q_n)$$

The refinery's decision to invest in the technology will depend on the additional variable profit they receive selling into $m \in M^r$, the fixed cost F_r, and how they substitute production away from $m \in M^c$ and towards $m \in M^r$. For a refinery to decide to invest, not only must the additional profit less the fixed costs be positive, but it must also be larger than the reduction in profits from selling less in the conventional markets. In equilibrium the decision to invest will not only depend on this trade off, but also the number of firms that are already selling into the reformulated market, as the revenues in the new product market will decrease with less market concentration.

Because the firms are only differentiated by their transportation costs, this will create a ranking that will determine which refineries will invest and which ones will not invest. For each refinery there is a vector of transportation costs $[\tau_{n1} \dots \tau_{nM}]$. These vectors can be ordered based on the sum of total transportation costs to the markets with the new product $m \in M^r$. The refinery that has the lowest total transportation costs to the new product market will invest first, followed by the refinery with the second most total transportation costs, and so on. This will continue until the marginal refinery becomes strictly worse off by expending the amount F_R to have access to the market.

I assume that the fixed costs are sufficiently high that there will be at least some refinery that will not want to invest in the new product. As a result, there will be less firms competing in the new product market. This *concentration* of the product market allows the refineries to charge a higher mark up than they would in the absence of the increase in the cost of production. This is because the new product has segmented the market. This increased mark up increases the profitability of the refinery, and reduces the probability that they will shutdown and exit the market. As a result, the refineries that are most exposed to the regulation can benefit the most by investing into the new product, which will be a more concentrated market. I will now illustrate this with a numerical example.

3.4 Numerical Simulation of the Model

I assume that there are three refineries spaced between two geographic markets, $n \in \{1,2,3\}$, $m \in \{A,B\}$. The transportation costs from firm n to market m are such that firm 1 is near market A, firm 3 is near market B, and firm 2 is in the middle. Illustratively, market A is a county in Wyoming and market B is Brooklyn, NY. Firm 1 would be a refinery in Denver, firm 2 would be a refinery in Louisiana, and firm 3 would be a refinery in New Jersey. Numerically, I choose

$$\tau_{1A} = \tau_{3B} = 10$$

$$\tau_{2A} = \tau_{2B} = 20$$

$$\tau_{3A} = \tau_{1B} = 30$$

Inverse demand is identical at each geographic market and given as $P(Q_m) = 100 - 10Q_m$. A firm produces a total of q_n in the absence of any policy, considered to be the baseline and incurs a cost of $C(q_n) = \frac{1}{2}q_n^2$. After the policy has been put in place, only a more expensive product can be sold in market B. Now, the total amount of quantity produced can be decomposed into the conventional product and the higher cost product: $q_n = q_n^c + q_n^r$. The marginal cost of producing this more expensive unit is 10 dollars so that costs are now $C(q_n, q_n^r) = \frac{1}{2}q_n^2 + 10q_n^r$.

I consider alternative investment scenarios and solve for the optimal quantity produced by each firm using according to Equation 2 with matrix A taking into account the additional marginal cost of producing the good for the regulated market. First I consider a "baseline" scenario in which there is no policy that mandates a cleaner product be sold in certain geographic areas. Next, I consider the variable profits when all three firms invest in the technology to produce the new product, when just the two closest firms invest in the technology to produce the new product, when only the closest firm invests, and finally when no firm invests. If firm n invested, then $I_n = 1$. I denote $I = \{I_1, I_2, I_3\}$. The results are presented in Table 3.4.

Table 1: Profits from Numerical Simulation.

I	Baseline	$\{1,1,1\}$	$\{0,1,1\}$	$\{0,0,1\}$	$\{0,0,0\}$
Firm 1	99.82	95.47	92.35	91.0	85.9
Firm 2	79.82	70.47	77.79	43.48	39.98
Firm 3	99.82	85.47	97.56	158.8	11.4

Notes: The Baseline simulation assumes there is only one product sold in all markets with identical costs. The other columns are the corresponding variable profits depending on which of the refineries, 1, 2, or 3, invested in the technology to produce the more expensive good, $I = \{I_1, I_2, I_3\}$

We see that all firms are better off in the baseline scenario than when the higher cost product is mandated in certain counties and they all invest in the technology to produce the new product. This is because the cost of production has increased. As expected, the refinery that is most exposed to the regulation, firm 3, loses the most profit after the policy has been put into effect and all firms decide to invest. If only the two refineries closest to the regulation decide to invest in the new technology, both of them will do better than if all three were to have invested in the technology, and firm 3 does better than firm 1. Although firm 3 is worse off relative to the baseline case, they are the most profitable of all three firms. This is because they are able to compete in a more concentrated market, and have the lowest transportation cost to this more concentrated market.

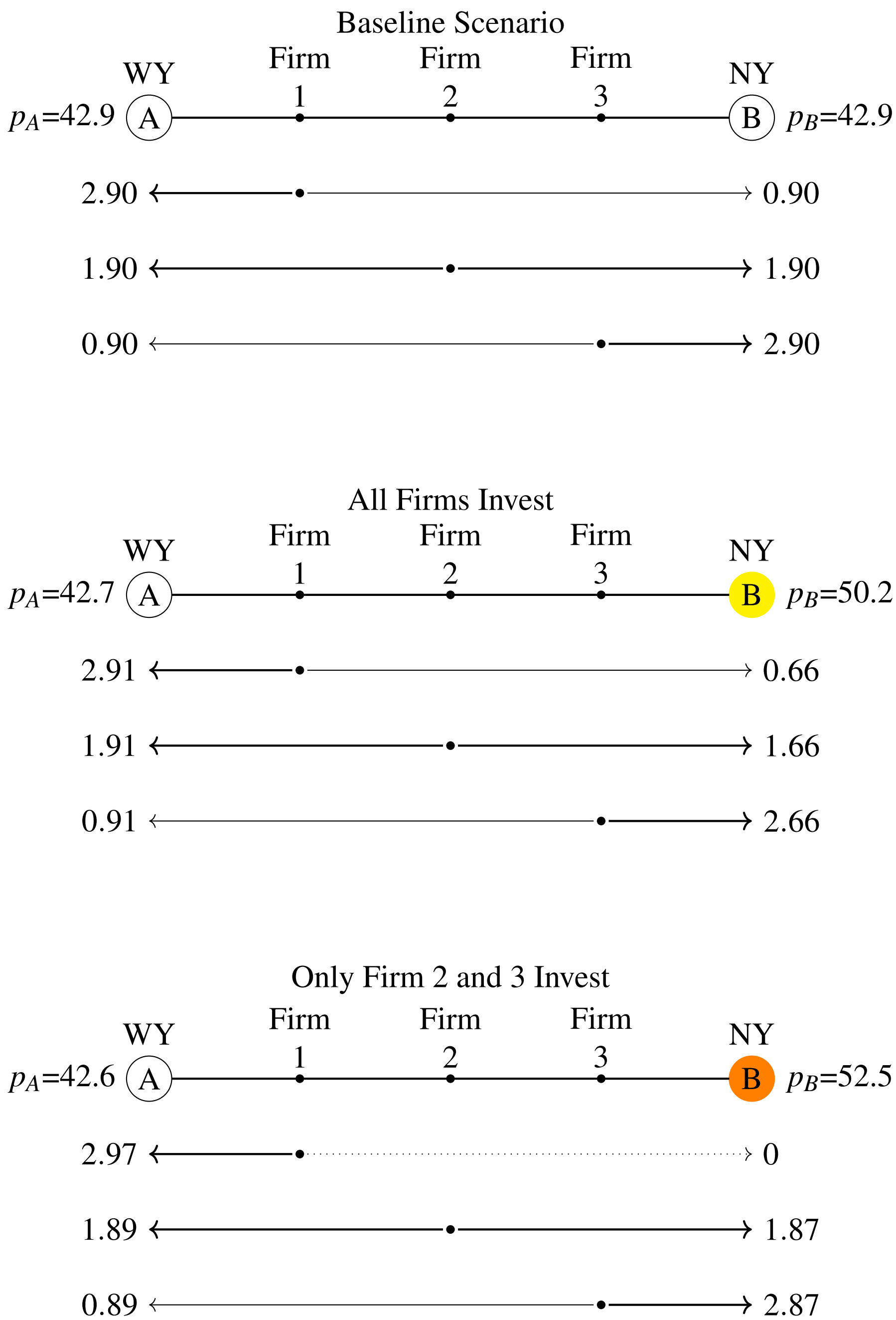
In the situation when only the closest refinery will sell into the new product market, their profit is the largest. It is even larger then the profit they would receive in the baseline scenario, when no higher cost product is mandated. This is because firm 3 is able to operate as a monopolist in market B. In the scenario in which no one invests in the technology to produce the higher cost market, all refineries are worse off because market B is effectively closed.

Which investment decision, and profits, are realized depends on the fixed cost F_r. In this simulation, firm 3 will invest as long as the fixed costs doesn't exceed the increase in their profits relative to $I_n = \{0,0,0\}$, a total of \$147.4. Knowing that firm 3 has the bigger incentive to invest, and will invest first, firm 2 will only want to invest when the fixed costs is less than how their profits change going from $\{0,0,1\}$ to $\{0,1,1\}$, which equals \$34.31. In this particular scenario, firm 3's variable profit are larger after the regulation goes into place as long as $34.31 < F_r < 147.4$. For their total profit, including the fixed costs, to be larger than the baseline, the fixed costs must not exceed \$58.98.

The quantities each firm produces under the base line scenario, $I = \{1,1,1\}$, and $I = \{0,1,1\}$ are shown in Figure 6. This model illustrates how the segmentation of the product market associated with an environmental policy can offset the cost of compliance. Because a new product is introduced, and it is costly to obtain the ability to produce the new product, not all of the producers will decided to produce the new good. Although the variable costs of the new good are higher, the firms that decided to produce the good do so in a more concentrated industry. This concentration effect can increase the profits of the firm that is the most exposed to the policy, mitigating industry concern regarding the impact of the environmental policy.

Although it is not the main objective of this paper, it is worth while pointing out the total welfare effects of this policy taking into account the change in market structure. Although firm 3 is best off when $I = \{0,0,1\}$, consumers are worse off, as the prices are higher in market B.

Figure 6: Prices and Quantities from Simulation.



The arrows indicate the quantity supplied of to each market by each firm.

These higher prices are due to the higher cost of production *and* the concentration of the product market. Although the prices decrease in market A, the magnitude is much smaller relative to the price increase in market B. Overall, total welfare goes down because of the market concentration (not taking into account the benefits of reduced pollution). Because implementing environmental policies that harm industry are often more difficult, the reduction in consumer welfare due to market power might be admissible given political economy concerns.

4 Empirical Evidence

I now look at annual data on refinery operations in the United States from 1987 to 2008 to show evidence consistent with the theory outlined in section 3. Although the theoretical predictions in section 3 are regarding the profits of refineries with different exposure to the policy, I have limited information on the quantities prices of refinery sales, and the cost of operation. Instead, I take a latent profit approach and consider a refineries decision to shut down to be indicative of their profits.[8] In what follows, I take a few approaches to estimate the relationship between exposure to reformulated gasoline standards and the refineries decision to exit the market.

4.1 Data

EIA-820, published annually by the Energy Information Agency, provides firm-level data on operating status and capacity for various technologies of all refineries of the United States. While the refinery's name and location is available for all years, the exact spelling varies significantly over time due to inconsistent form filing, mergers and acquisitions, and re-branding by the refinery's parent company. I write an algorithm that probabilistically matches refineries based on the observation year, the refinery's location, and a measure representing the similarities in name character string and capacity levels. This identifies all but 20 firms, who were subsequently identified manually. While a measure of exit can be inferred from these data, some firms still submit reports years

[8]The latent profits approach is motivated by Bresnahan and Reiss (1991).

after official closure. To ensure that refineries have exited, EIA-820 is cross referenced with closure listings from the American Petroleum Institute (API) annual data book. The present sample covers a period of 21 years from 1987 to 2008, with 211 plants in the beginning of the sample and a total of 147 in the final year. Of the 64 plants that exited the market during the sample period, 42 were before RFG phase I was implemented in 1995.

To measure capital technology, I calculate a index commonly used in the industry, the Nelson Complexity Index. Introduced in the 1960s, this index represents the financial investment per unit capacity and has often been used to measure refinery sophistication. Relative weights for capacity of different technologies are shown in Table 4.1. In general, less sophisticated refineries should be at a greater risk of exit. I measure investment of a refinery as the year-to-year change in the Nelson Index.

Table 2: Nelson Complexity Index.

Refining Process	Index per Unit Capacity
Distillation Capacity	1
Vacuum Distillation	2
Thermal Process	2.75
Coking	6
Catalytic Cracking	6
Catalytic Reforming	5
Catalytic Hydrocracking	6
Catalytic Hydrorefining & Hydrotreating	2.5
Alkylation/Polemerization	10
Aromatics/Isomerization	15
Lubes	60
Asphalt	1.5
Hydrogen (MCfd)	1
Oxygenates (MTBE/TAME)	10

Adopted from Nelson (1976)

To measure the exposure of refineries to markets where the boutique fuels were mandated I use GIS to calculate a unit-less measure representing the proportion of the refinery's consumer base that are in counties with fuel standards. Explicitly I calculate

$$Exposure_n = \frac{\sum_{m \in M^r} \frac{Population_m}{\tau_{nm}}}{\sum_{m \in M} \frac{Population_m}{\tau_{nm}}} \tag{3}$$

for every refinery n, where $Population_m$ is the population of county m from the 2014 census and τ_{nm} is the transportation cost from refinery n to market m taking the least cost path through pipelines, barges, and highways. $Exposure_n$ varies over time as a few counties adopted boutique fuel standards after 1995, and is equal to zero prior to the implementation of the boutique fuel standards.

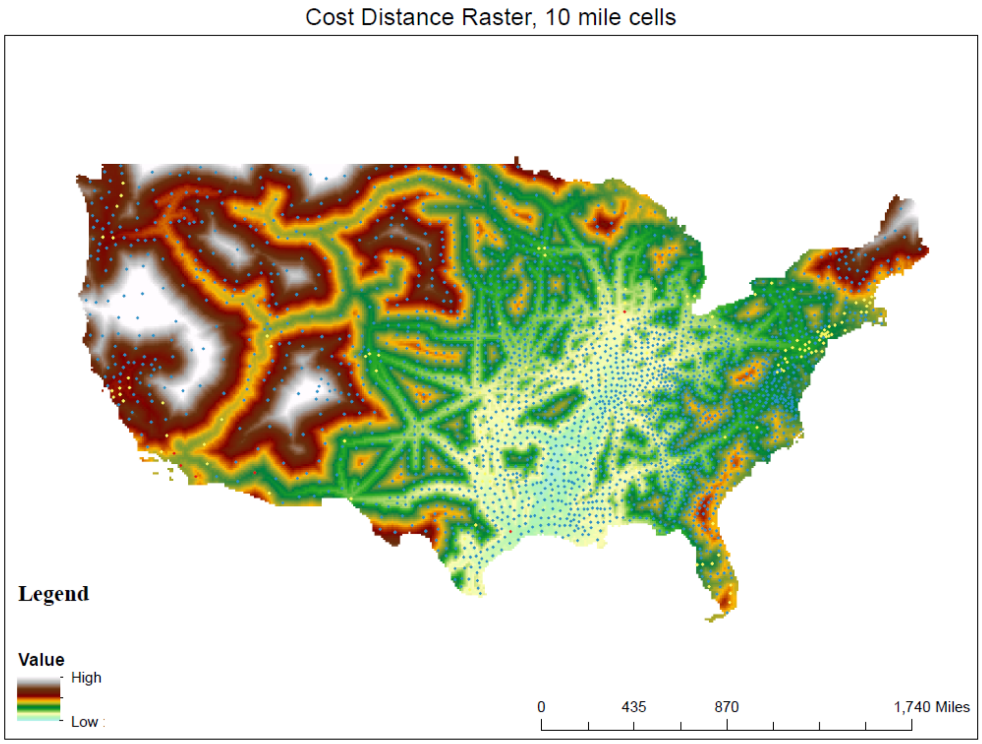
Following Muehlegger (2006), transportation costs are 2 and 4.5 cents per thousand mile-gallon (in 2003 dollars) for pipeline and barge respectively. Although Muehlegger (2006) employs a transportation cost of 30 cents per thousand mile-gallon of ground transportation, I separate this into 25 cents for major US highways and 40 cents for terrain absent of pipelines, barges, or highways. This reflects the difference in city and highway fuel economy. Lastly, elevation data are incorporated into transportation cost by multiplying the horizontal distance traveled by $1/cos(\theta)$, where θ is the slope of elevation derived from a Digital Elevation Model raster file. Figure 7 show examples of the cost distance maps used to calculate this measure for the a refinery in the Gulf Coast and California.

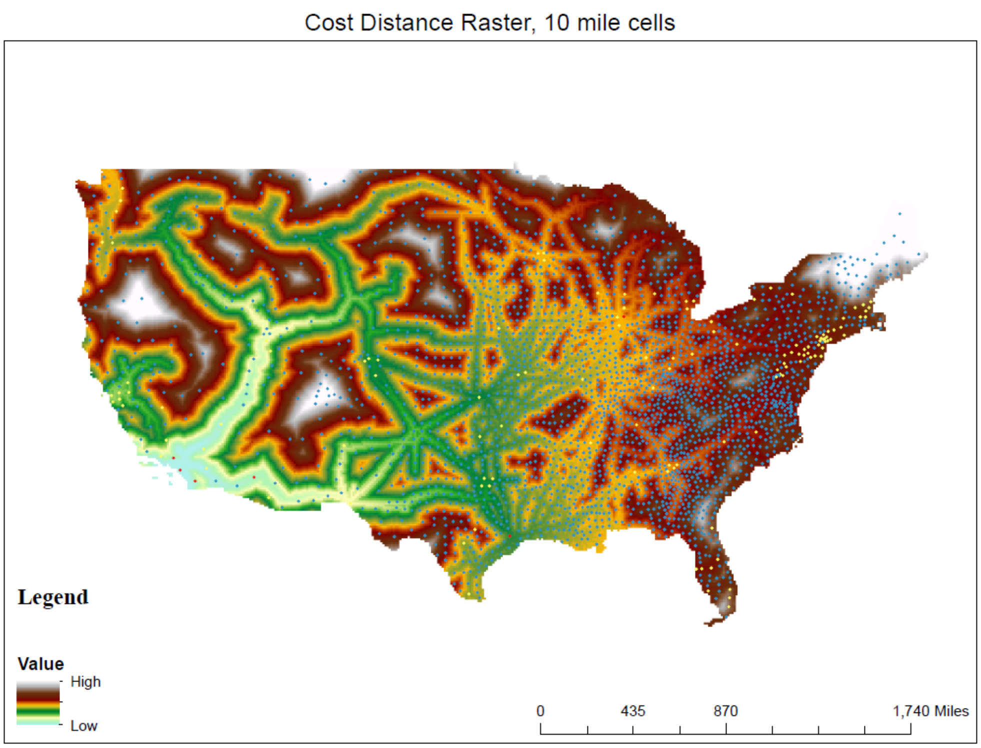
Other variables of interested include a PADD-level measure of profitability known as "crack spread" as well as industry specific cost factors such crude quality, electricity and natural gas prices sourced from the EIA.[9] Although age is typically an important variable in exit analysis, is it hard to find public and reliable data on the age of refineries in the US. Further, papers estimating the determinants of refinery exit do not find age to be a statistically significant factor (Chen, 2002; Meyer and Taylor, 2015).

Table 3 and Table 4 show some summary statistics of the data. We see refineries vary greatly in the sophistication, as measured by the Nelson Index. Change in the Nelson Index, measured as

[9] 3 barrels of crude typically product 2 barrels of gasoline and 1 barrel of distillate. The crack spread typically measures $2 \times (Price\ of\ gas) + (Price\ of\ distillate) - 3 \times (Cost\ of\ Crude)$. I use a ratio of revenue to cost instead of the difference.

Figure 7: Cost Distance Map.





The color represents the cumulative cost path from the refinery to the county, taking the least cost path. The points in these maps represent counties, with the color of the point signifying if a fuel standard was ever required in that county.

Table 3: Refinery - Year Summary Statistics.

	Mean	Std. Dev.	Minimum	Maximum	Observations
Nelson Index	.794	.931	0	5.39	3,539
Investment	.0116	.0916	-1.7	1.64	3,327
Operating Capacity	102,369	106,028	0	590,500	3,539
Max Exposure to RFG	.263	.131	.102	.726	3,539

Table 4: State - Year Summary Statistics.

	Mean	Std. Dev.	Minimum	Maximum	Observations
State HHI	.555	.339	0	1	685
Crack Spread	1.68	.185	1.28	2.32	685
Crude Gravity	32	2.47	24.9	36.2	685
Crude Sulfur Content	1.18	.212	.76	1.7	685
Price of Gasoline	.892	.278	.48	1.82	563
Price of Electricity	5.3	.493	4.56	6.15	563

Investment, also seems to vary significantly in the sample. The maximum exposure of refineries to RFG, $Expose_n$, during the sample period varies from 10 percent of the refineries cost discounted consumer base to up to 73 percent of the refineries cost discounted consumer base, showing a good deal of variation in exposure to the policy. The Herfindahl-Hirschman Index within a state varies from zero (no refineries exist in that state) to one (one refinery exists in that state), with an average of 0.55, indicating high concentration of the refinery markets at the state level on average.

4.2 Empirical Framework

The continuous decline of refineries since 1981 as shown in Figure 2 motivates the use of survival analysis to determine how RFG impacts a firm's risk of exit. Survival analysis considers the risk of instantaneous exit conditional on the fact that the firm is still alive. The objective is to estimate a hazard function of the form

$$\lambda(t) = \frac{f(t)}{1-F(t)} \tag{4}$$

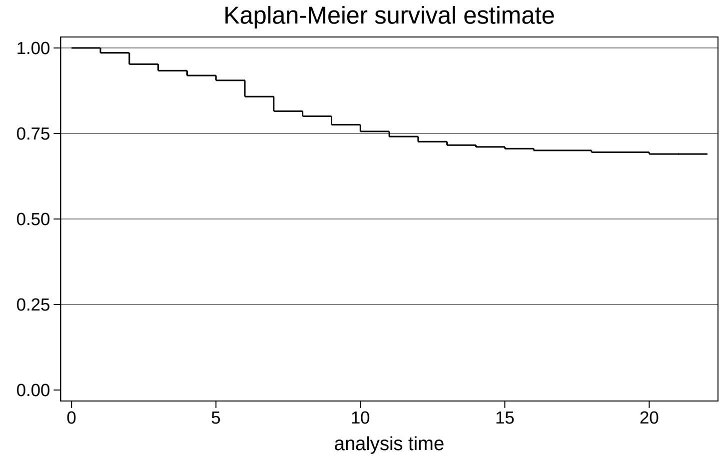
where $F(t)$ and $f(t) = \frac{d}{dt}F(t)$ are the cumulative and instantaneous probability of exit at time t. The denominator is often called the survivor function. A key feature of hazard function is the assumption placed on the distribution of t. A correct specification is necessary for consistent estimates. Broadly, there are two types of models employed is survival analysis. The proportional hazard and accelerated failure time model.

The proportional hazard specification is of the form $\lambda(t|X'\beta) = \lambda_0(t)\phi(X'\beta)$ where $\lambda_0(t)$ is the baseline hazard, independent of $X'\beta$, X is matrix of control characteristics, and β is a vector of parameters. $\phi(X'\beta)$ shifts the baseline hazard up or down, depending of the parameter values and the values of X. The distribution of t determines the functional form of the baseline hazard, $\lambda_0(t)$. If t is exponential, the baseline hazard is constant, while a Weibull distribution of t implies a baseline hazard that is monotone increasing or decreasing. It is also possible to estimate a semi-parametric Cox Proportional Hazard model, where the estimates of β are recovered without specifying the functional form of $\lambda_0(t)$.

In contrast to the proportional hazard model, the accelerated failure time model is of the form $\lambda(t|X'\beta) = \lambda_0(t\phi(-\mathbf{X}'\beta))\phi(\mathbf{x}\beta)$, allowing for a non-monotonic λ_0. Common distributions employed include Log-normal or Gamma. Although the Weibull proportional hazard is most frequently used in the literature, the empirical distribution of the hazard function should help determine which specification is appropriate. Figure 8 shows the non-parametric estimate of the Kaplan-Meier survival function for the full sample. The linear trend over time suggest the Weibull proportional hazard function is an appropriate specification.

I specify $\phi(\mathbf{X}'\beta)$ to be of the form $e^{X'\beta}$ where X consists of determinants of a refinery's decision to exit the market. This includes state level measures of crude quality and the crack spread, a PADD-specific indicator variable, an indicator variable for if the year is before RFG phase I (1995) or a year-specific indicator variable, as well as a measure of refinery exposure to RFG, Equation 3, the exposure measure squared, and the maximum refinery level exposure during the sample period. The coefficients of interest are on the measure of refinery exposure, and the measure of refiner exposure squared. I include a squared term because of the non-linear relationship between refinery

Figure 8: Kaplan-Meier Survival Estimate from the Full Sample.



Non-parametric estimates of the cumulative probability a firm is still operating. Analysis time is an annual count normalized such that 1986 is year zero.

exposure to RFG and profits illustrated in section 3. One row in $X'\beta$ looks like

$$\beta_1 Expose_{nt} + \beta_2 Expose_{nt}^2 + \beta_3 MaxExposure_n + \beta_4 Sulfur_{st} + \beta_5 Gravity_{st} + \beta_6 CrackSpread_{st} + \gamma_t + \delta_P$$

Where $Expose_{nt}$ is the exposure of refinery n to the fuel mandate at time t which equals to zero in the pre-period. $MaxExpose_n$ is a refinery specific measure of the maximal eventual exposure to the fuel standard. $Sulfur_{st}$, $Gravity_{st}$, and $CrackSpread_{st}$ are state-year control variables. Finally, γ_t denotes a time period fixed effects (either yearly fixed effects or a pre-post fixed effect), and δ_P is a PADD specific fixed effect.

Identification of the effect RFG on the propensity of a refinery to shutdown comes from a difference in difference type argument in the potential outcomes framework. The variable $Expose_{nt}$ measures the intensity of treatment for each refinery, and is time varying as new counties adopt boutique fuel standards, and zero prior to the policy implementation. By controlling for the pre and post policy average rate of exit (or annual average rate of exit), as well as the maximum eventual

Table 5: Summary Statistics by Exposure Quartile.

	Quartile 1	Quartile 2	Quartile 3	Quartile 4	Total
Nelson Index	.706	.343	.392	.915	.582
	(.67)	(.583)	(.655)	(1.04)	(.788)
Investment	.00937	.00675	.003	-.000824	.0045
	(.0181)	(.0176)	(.0241)	(.0461)	(.029)
Operating Capacity	94,975	53,497	53,827	114,273	78,353
	(83,391)	(75,658)	(80,157)	(114,379)	(92,973)
Max Exposure to RFG	.164	.201	.226	.455	.264
	(.0279)	(.00559)	(.0119)	(.118)	(.13)

Standard errors are in parenthesis.

exposure of the refinery to the mandate, $MaxExpose_n$, I am able to estimate how more exposure to the regulatory fuel standard impacted the decision to exit taking into account general trends in the exit rate over time as well as time invariant determinants of exit that might be correlated with $Expose_{nt}$. The PADD fixed effects take into account the time invariant average exit rate within a PADD, so that I am using the spatial variation in exposure to reformulated gasoline within a PADD.

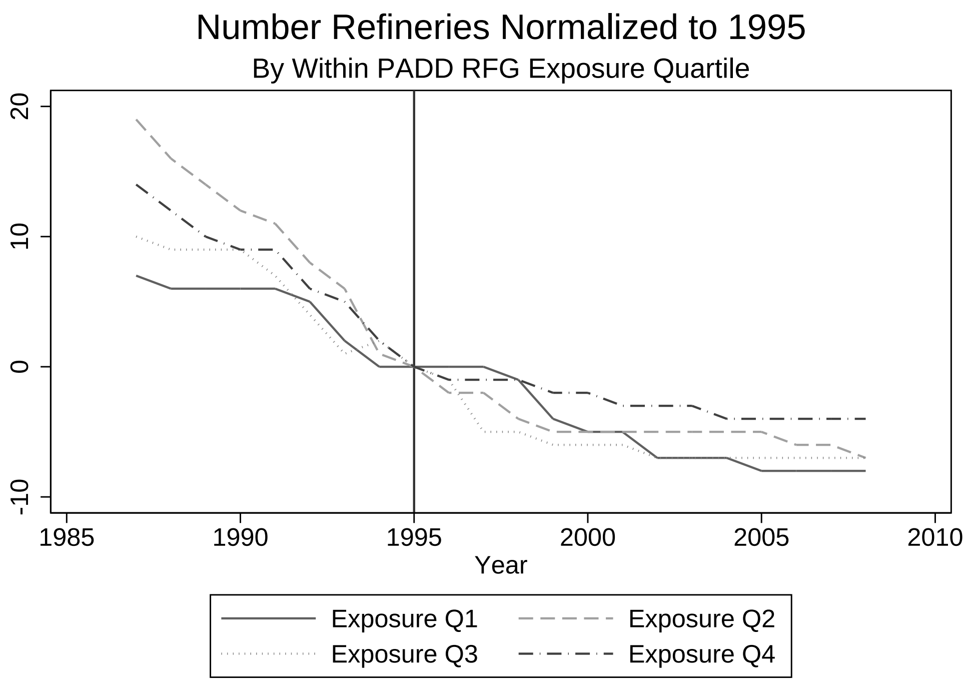
Credible identification requires that there is no other determinant of exit that is correlated with a refineries exposure to the fuel standards. Table 5 shows that refineries are similar across quartiles of $MaxExpose_n$, suggesting that they are similar on unobservable measures as well. One threat to identification is that the policy is endogenous, as emphasized by Besley and Case (2000).[10] Overall this is not a major concern; as the policy was federally mandated and on a downstream product. There are some concerns where counties opted in or out of the policy, or refineries lobbied for the policy, especially in the case of California. However, this concern only speaks to rent seeking behavior of the refineries, and is consistent with the results presented in section 3.

As in all difference in differences approaches, the key to valid estimates is that the treated

[10]To address this concern, non-attainment in National Ambient Air Quality Standards would be a source of exogenous variation, as it determines policy implementation but not the exit rate of refineries.

group acts like the control group in the absence of treatment. We can look for similarities in the pre-treatment trends as done in Figure 9. All expect the lowest quartile of exposure to RFG shows similar trends prior to RFG Phase 1. Though it is clear that the post treatment trends differ from the pre-treatment, with less exits for the refineries in the outer quartiles. This suggest a non-linear effect of RFG exposure on refiner exit which can be tested in the data.

Figure 9: Differential Exit by RFG Exposure Quartile.



Annual level is the number of operating firms divided by the number of operating firm in 1990. Quartiles are defined by the RFG exposure measure described in the text.

4.3 Empirical Results

I estimate the model using the annual data from EIA-820 with the Cox and Weibull proportional hazard specification, as well as with a probit and linear probability specification. The coefficients in the proportional hazard and probit specifications are estimated using maximum likelihood and the coefficients in the linear probability model are estimated using ordinary least squares. The results, in terms of marginal effects, are presented in Table 6. Across all specifications the qualitative relationship between exposure to RFG and the hazard rate, or probability of exit, are similar.

Table 6: Regression Results.

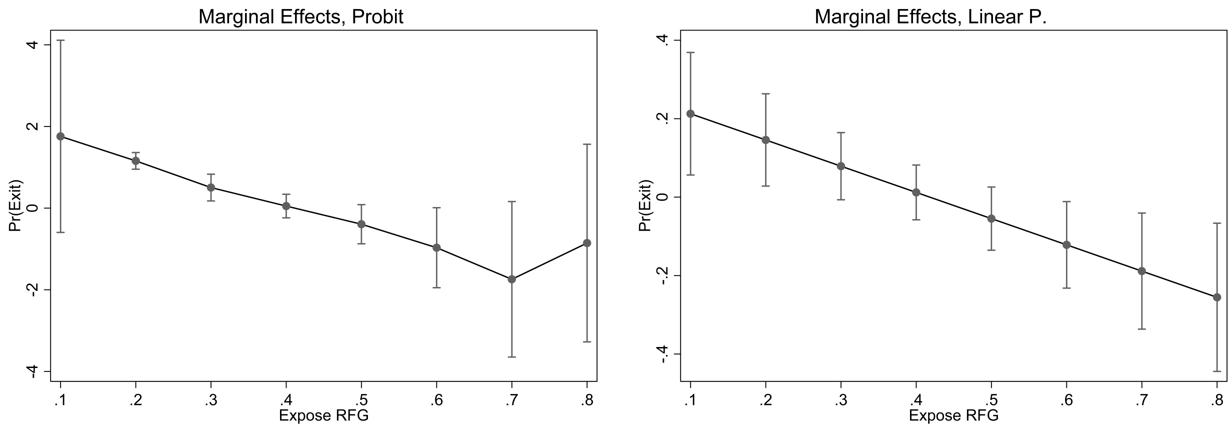
	Cox PH	Weibull PH	Probit	Linear P.
Exposure to RFG	37.66*	34.86*	18.25**	0.280**
	(20.38)	(18.66)	(8.297)	(0.101)
Exposure to RFG × Exposure to RFG	-47.28*	-44.77*	-22.17**	-0.334***
	(27.16)	(24.11)	(10.50)	(0.115)
Nelson Index	-4.638***	-4.724***	-2.176***	-0.0158***
	(0.739)	(0.758)	(0.335)	(0.00217)
Crack Spread	-0.808	1.250	-0.149	-0.0170
	(2.587)	(0.783)	(1.430)	(0.0436)
Crude API gravity	-0.363	-0.529**	-0.188	-0.00242
	(0.259)	(0.214)	(0.127)	(0.00259)
Crude sulfur	-2.460	-6.021***	-1.241	-0.0282
	(2.340)	(1.539)	(1.025)	(0.0247)
Max Exposure to RFG	1.988	2.543	1.002	0.0297
	(1.496)	(1.630)	(0.705)	(0.0313)
PADD Fixed Effects	Yes	Yes	Yes	Yes
Pre/Post Fixed Effects	Yes	Yes	No	No
Year Fixed Effects	No	No	Yes	Yes
Observations	3,495	3,495	3,004	3,539
R-squared				0.02

Robust standard errors in parenthesis. $*$, $**$, and $***$ denote 0.1, 0.05, and 0.005 level of significance respectively.

Interpreting the marginal effects for the proportional hazard models is not straight forward. These estimates represent the effect of a one unit increase in $Expose_{nt}$ (going from 0 to 1) on the hazard ratio shown in Equation 4. While the units themselves are not meaningful, we can see the point estimates suggest the relationship is an inverted-U shape, with a peak at approximately $Expose_{mt} = 0.39$.[11] This general relationship can be said for the probit and linear probability model. This relationship is illustrated in Figure 10, where I've plotted the marginal effect of $Expose_{nt}$ on the probability of exit for the probit and linear probability models. In these models,

[11]For a polynomial of the form $y = ax^2 + b$, the global maximum is $-\frac{b}{2a}$. Taking the point estimates from columns one and two we find the maximum at $34.86/(2*44.77)$ or $37.66/(2*47.28)$.

Figure 10: Marginal Effect of RFG Exposure on Exit.



the coefficients are statistically significant from zero with a level of significance equal to 0.05.

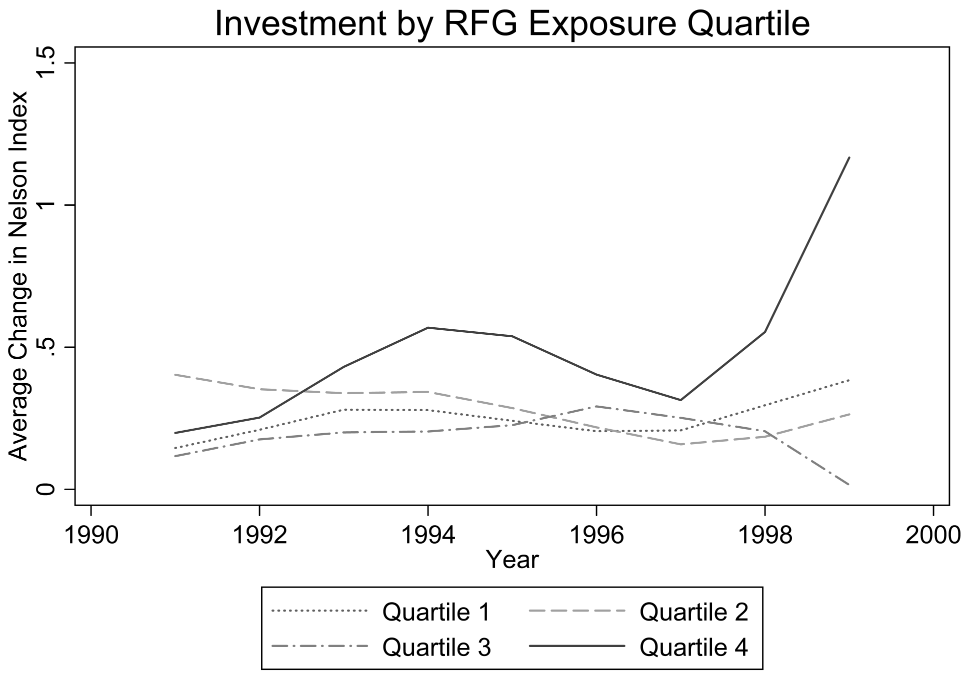
These estimates suggest that the refineries that were most exposed to the reformulated fuel standards were *less* likely to exit the market, which would imply that they were relatively more profitable after the policy went into place. This is consistent with the model presented in section 3, where some refineries would invest in the technology to produce the higher cost product, but others would not. This market segmentation leads to concentration in the new product market, where refineries can now sell the product with a higher markup over the cost of production.[12] As a final note of evidence, Figure 11 shows the average year-to-year change in the Nelson Index by quartile of $Expose_n$. This represents the investment of refineries in new, more sophisticated technologies. We see that the quartile of refineries most exposed to RFG fuels invested much more than the others and this coincides with the RFG phase I and phase II, suggesting only they were able to sell the new product.

5 Conclusion

In this paper I show how environmental policies can impact the market structure in which firms compete. Looking at the Boutique Fuel Standards associated with the 1990 Clean Air Act Amendments, I show how the mandate of a cleaner burning fuel creates a new product market that seg-

[12]Effectively a pass-through rate of the higher cost of production greater than one

Figure 11: Average Investment by RFG Exposure.



ments the market. Using a model of Cournot competition, I simulate how the new standard can impact the profitability of refineries when producing the cleaner burning fuel requires a costly investment. Because not all refineries will decide to invest in the new technology, the new product market is more concentrated and refineries in this market can now charge a higher markup. Using data on annual refinery operations in the United States I show empirical evidence consistent with the theoretical predictions. The refineries that were most exposed to the environmental policy were less likely to exit the market.

References

Auffhammer, M. and Kellogg, R. (2011). Clearing the air? the effects of gasoline content regulation on air quality. *The American Economic Review*, pages 2687–2722.

Besley, T. and Case, A. (2000). Unnatural experiments? estimating the incidence of endogenous policies. *The Economic Journal*, 110(467):672–694.

Bresnahan, T. F. and Reiss, P. C. (1991). Entry and competition in concentrated markets. *Journal of Political Economy*, 99(5):977–1009.

Brown, J., Hastings, J., Mansur, E. T., and Villas-Boas, S. B. (2008). Reformulating competition? gasoline content regulation and wholesale gasoline prices. *Journal of Environmental economics and management*, 55(1):1–19.

Chen, M.-Y. (2002). Survival duration of plants: Evidence from the us petroleum refining industry. *International Journal of Industrial Organization*, 20(4):517–555.

Chesnes, M. (2009). Capacity and utilization choice in the us oil refining industry. Technical report, Working Paper.

Chouinard, H. H. and Perloff, J. M. (2007). Gasoline price differences: Taxes, pollution regulations, mergers, market power, and market conditions. *The BE Journal of Economic Analysis & Policy*, 7(1).

Deily, M. E. and Gray, W. B. (1991). Enforcement of pollution regulations in a declining industry. *Journal of Environmental Economics and Management*, 21(3):260–274.

Ericson, R. and Pakes, A. (1995). Markov-perfect industry dynamics: A framework for empirical work. *The Review of Economic Studies*, 62(1):53–82.

Fowlie, M., Reguant, M., and Ryan, S. P. (2015). Market-based emissions regulation and industry dynamics. *Journal of Political Economy*.

Helland, E. (1998). The enforcement of pollution control laws: Inspections, violations, and self-reporting. *Review of Economics and Statistics*, 80(1):141–153.

Maskin, E. and Tirole, J. (1988). A theory of dynamic oligopoly, i and ii. *Econometrica: Journal of the Econometric Society*, pages 571–599.

Meyer, D. W. and Taylor, C. T. (2015). The determinants of plant exit: The evolution of the us refining industry. *FTC Working Paper No. 328*.

Millimet, D. L. (2014). Environmental federalism: A survey of the empirical literature. *Case W. Res. L. Rev.*, 64:1669.

Millimet, D. L., Roy, S., and Sengupta, A. (2009). Environmental regulations and economic activity: Influence on market structure. *Annu. Rev. Resour. Econ.*, 1(1):99–118.

Muehlegger, E. (2006). Gasoline price spikes and regional gasoline content regulation: A structural approach. *KSG Working Paper No. RWP06-015*.

Nelson, W. (1976). Complexity-1: The concept of refinery complexity. *Oil & Gas Journal*, Sept. 13.

Oates, W. E. (1972). Fiscal federalism. *Books*.

Office of Technology Assessment (1990). *Replacing Gasoline: Alternative Fuels for Light-Duty Vehicles*. US Government Printing Office.

Oil & Gas Journal (1997). Cost of the clean air act. *Oil & Gas Journal: Anonymous Editorial*, 95(52):17.

Ryan, S. P. (2012). The costs of environmental regulation in a concentrated industry. *Econometrica*, 80(3):1019–1061.

Scherr, R. C., Smalley Jr, G., and Norman, M. E. (1991). Clean air act complicates refinery planning. *Oil and Gas Journal;(United States)*, 89(21).

Snyder, L. D., Miller, N. H., and Stavins, R. N. (2003). The effects of environmental regulation on technology diffusion: the case of chlorine manufacturing. *American Economic Review: Papers and Proceedings*, pages 431–435.

Sweeney, R. L. (2014). Environmental regulation, imperfect competition and market spillovers: The impact of the 1990 clean air act amendments on the us oil refining industry. *Working Paper*.