DOES THE U.S. BIOFUELS MANDATE INCREASE THE PRICE AT THE PUMP?

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ABSTRACT

The Renewable Fuel Standard (RFS) as amended by the *Energy Independence and Security Act of 2007* created a federal mandate for blending conventional biofuels like corn-based ethanol and advanced biofuels like biodiesel and renewable gasoline into the United States transportation fuel supply. The RFS established yearly blending standards for the obligated parties—refiners and importers of petroleum products—that increase progressively until reaching a high of 36 billion gallons by 2022. Each ethanol-equivalent gallon of biofuel blended is assigned a unique Renewable Identification Number (RIN) through the Environmental Protection Agency's (EPA) Moderated Transaction System (EMTS). At year's close, obligated parties must submit their allotted RIN obligations to the EPA to demonstrate compliance. In the case of under-compliance or over-compliance, RINs can be traded between obligated parties freely through the EMTS or carried over for use in the next year. It follows, then, that a RIN carries a market value reflective of the cost of complying with RFS regulations. Indeed, most biofuels cost more than their fossil-based equivalents. When the price of a corn ethanol RIN went from 2-3 cents each in 2012 to nearly $1.50 in July of 2013 due to a perceived shortage in corn ethanol RINs, obligated parties faced the prospect of multimillion-dollar compliance cost increases. Arguing that RFS makes fuel significantly more expensive for consumers, petroleum companies have begun to advocate for the full repeal of the RFS, winning over some allies in

Congress. The future of this program is uncertain. In an attempt to quantify the concerns of RFS critics, this thesis estimated the effect that RIN prices have on the wholesale cost of diesel fuel. Using daily price data from January 2011 through August of 2013 on RINs and crude oil, I specified twelve OLS regression models that predict the passthrough of the diesel RIN price to wholesale diesel price. My statistical analysis suggests that the diesel RIN price is a useful predictor of wholesale diesel price; however, my analysis also casts some doubt on the claims of obligated parties that they pass the cost of compliance onto the consumer, thereby increasing fuel prices significantly.

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Special thanks to Micah Jensen, my graduate thesis adviser at Georgetown University, for helping me learn the best practices in econometrics and seeing me through to the very end.

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Many thanks,
Stephen R. Bolotin

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SECTION I: INTRODUCTION

The future of the United States' Renewable Fuel Standard (RFS) hangs in the balance. The RFS, which mandates the blending of 36 billion gallons of biofuel into the transportation fuel supply by 2022 (see **Figure 1**), has come under fire by petroleum, food manufacturer, and livestock trade groups who argue the mandate distorts markets and increases consumer prices.[1] Uniquely, the RFS is the only fully implemented U.S. federal energy policy that mitigates climate change through greenhouse gas (GHG) reductions.[2] These mandated gallons come from a variety of first-, second-, and third-generation biofuel technologies derived from edible and non-edible plant-based sources. The first iteration of this standard was amended into the *Clean Air Act* by the *Energy Policy Act of 2005* (EPAct) as a federal mandate to blend corn-based ethanol into gasoline and meet established national oxygenate requirements that make fuels burn cleaner, previously achieved by methyl tertiary butyl ether (MTBE). The RFS was then greatly expanded by the *Energy Independence and Security Act of 2007* (EISA) to include second- and third-generation biofuel technologies (collectively referred to as advanced biofuels) like biodiesel, biogas, butanol, cellulosic ethanol, and renewable diesel, all of which deliver significantly better reductions in GHG emissions on an energy density basis.[3] A number of unforeseen developments in the transportation fuels market, however, have cast doubt on the future viability of the RFS.

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[1] See testimony in House Energy & Commerce Committee hearing "Overview of the Renewable Fuel Standard: Stakeholder Perspectives" from 23 July 2013.

[2] The Obama Administration's *Climate Action Plan*, which aims to regulate GHG emissions form existing and new power plants, is poised to become the second such policy. Unlike the RFS, however, which was passed into law legislatively, these power plant regulations are being enacted through the regulatory rule making process of the Environmental Protection Agency (EPA). (WH-A 6)

[3] The RFS statute defines "advanced biofuels" as reducing GHG emissions over a 2005 baseline of gasoline by at least 50%. Corn ethanol, by contrast, reduces GHG emissions over the same baseline by 20% and is defined as a "conventional biofuel." These calculations are based on "field-to-wheels" impact lifecycle analyses. (GPO-B 29-30)

When the RFS was expanded in 2007, the outlook for U.S energy security was widely perceived as bleak, with a barrel of petroleum hitting a high $144.96 on July 11, 2008 (EIA-A). Congress intended the RFS, in addition to its climate benefits, to expand and diversify domestic sources of transportation fuel.[4] Since then, to the surprise of many market and policy analysts, worldwide energy market dynamics have been transformed by the North American oil and gas shale revolution, driven by technological breakthroughs and historically high oil prices that make unconventional extraction methods economically viable. Hydraulic fracturing, horizontal drilling, and three-dimensional seismic imagining have reversed a decades-long downward trend in oil and gas production in the U.S. In fact, the U.S passed both Saudi Arabia as the world's largest petroleum producer and Russia as the world largest fossil fuel producer in 2013 (EIA-C).

At the same time, U.S. gasoline consumption has steadily declined since 2009, inadvertently causing an infrastructure compatibility issue with the mandated levels of ethanol. The decline in fuel consumption has been driven by two primary factors: the Great Recession and improved Corporate Average Fuel Economy (CAFE) standards in cars (EIA-B). When Congress wrote the RFS, however, it assumed increasing fuel consumption year over year. Starting in 2013, the RFS began to statutorily mandate volumes of ethanol in gasoline above 10% (see **Figure 3**), which has the potential to damage older automobile engines.[5] This ethanol saturation limit in gasoline is popularly referred to as the ethanol "blend wall."

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[4] See EPA rule making "Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program; Final Rule" in 75 Federal Register 14683 (26 Mar 2010).

[5] The EPA has only approved ethanol blends of greater than 10% in car engines made in 2001 and later. See EPA rule making "Regulation To Mitigate the Misfueling of Vehicles and Engines With Gasoline Containing Greater Than Ten Volume Percent Ethanol and Modifications to the Reformulated and Conventional Gasoline Programs" in 76 Fed. Reg. 44406 (25 Jul 2011).

This ethanol compliance issue has been further exacerbated by insufficient commercial supply of some advanced biofuels. The production of cellulosic biofuels--constituting 16 billion of the 36 billion gallons mandated in 2022 (GPO-B 31-32)--has missed every statutory milestone outlined in the RFS.[6] This combination of unforeseen changes to energy markets and the perceived failure of cellulosic biofuels have provided ammunition to the petroleum industry trade groups like the American Petroleum Institute and the American Fuel and Petrochemical Manufacturers--along with a coalition of livestock, restaurant chain, and food manufacturing groups--to advocate for its repeal entirely. Their central argument is that the RFS needlessly increases consumer prices in food and fuel. The groups have repeatedly petitioned and sued the Environmental Protection Agency (EPA), tasked with implementing the RFS, to waive the biofuel mandate.[7] There have also been numerous bills introduced in the House of Representatives and Senate to repeal or modify the RFS.[8]

These efforts to dismantle the RFS have cast a long shadow over advanced biofuels producers and have the potential to create a self-fulfilling prophecy. The entire advanced biofuels industry (save for biodiesel) emerged following the biofuels mandate itself. These pioneering fuel producers courted investors through the guarantee of a market for their products. One of the unique challenges facing biofuel producers is that they must sell their products to their competitors: the petroleum companies. Given the doubt over the future of the RFS, capital

[6] The challenges of scaling up cellulosic biofuels are broadly indicative of new energy technologies in general. The innovations that have ushered in shale energy revolution, for instance, have their roots in U.S. Department of Energy research and development efforts in the 1970s and received over two decades (1980 to 2002) of federal subsidies through the tax code. (Begos)

[7] See RFS waiver petitions: 75 Fed. Reg. 76790 (Dec. 9, 2010), 77 Fed. Reg. 1320 (Jan. 9, 2012), 78 Fed. Reg. 49794 (Aug. 15, 2013), 73 Fed. Reg. 47168 (Aug. 13, 2008), 77 Fed. Reg. 70752 (Nov 27, 2012), 78 Fed. Reg. 49411 (Aug. 14, 2013). Also, see *American Petroleum Institute v. Environmental Protection Agency*, 43 ELR 20026. No. 12-1139, (D.C. Cir., 01/25/2013).

[8] See proposed legislation H.R. 1461, H.R. 1462, and S. 1195 of the 113th Congress.

investment has since dried up almost entirely and put the industry into “suspended animation” (McAdams). Without enough liquidity to make it across the “valley of death” in scaling up commercially, these producers of non-cellulosic advanced biofuels like renewable diesel and gasoline are poised to fail—not because their technologies do not work, but because of the successful efforts by RFS opponents to cast the entire industry as a failure. Ironically, these other advanced biofuels do not have the same blending limits as ethanol and further, not only made up for, but also exceeded the shortfall in cellulosic biofuels in 2013.

This thesis, then, is an attempt to shed light on the one remaining charge of the petroleum interests in their fight against the RFS: that it needlessly increases consumer fuel prices. Using price data from January of 2011 through August of 2013, I attempt to estimate the price premium on diesel fuel as a consequence of biofuel blending mandates through OLS multivariate regression analysis. I do not attempt to sort out if any price premium is justified given the potential benefits of the RFS. The rest of this study is organized accordingly. Section II dives deeper into how the RFS is operationalized. Section III establishes the rationale for analyzing biofuel substitutes for diesel fuel as opposed to gasoline. Section IV reviews related literature. Section V outlines my dataset, research methodology, and hypotheses. Section VI delivers my results. Section VII discusses the implication of these results. Section VIII concludes.

SECTION II: THE RENEWABLE FUEL STANDARD

The Renewable Fuel Standard (RFS) is a federal law amended into the *Clean Air Act* that mandates the blending of increasing volumes of biofuel into the transportation fuel supply by up to a total of 36 billion gallons in 2022 (see **Figure 1**). The obligated parties under the RFS, those who are tasked with demonstrating compliance on yearly basis, are the refiners and importers of petroleum-based fuels within the U.S. By design, the RFS is operationalized to give preferential treatment to plant-based fuels with superior performance and environmental characteristics.[9] It is also designed to provide obligated parties with flexibility in demonstrating compliance. These features of the RFS are achieved through the nesting of three distinct sub-targets or fuel pools, within the Total Renewable Fuels mandate (see **Figure 2**). Of these, the Total Advanced Biofuels pool designates a specific number of gallons each year that must be met by biofuels that achieve a minimum of 50% greenhouse gas (GHG) reductions off a 2005 baseline of gasoline based on a "field-to-wheels" impact lifecycle analysis. Conventional biofuels, namely corn-based ethanol, which achieve only a minimum of 20% GHG reductions, play a proportionately decreasing role in the mandate, capped at 15 billion gallons in 2015, and can only fulfill the mandate for the Total Renewable Fuels pool (GPO-B 28-30). Within the Total Advanced Biofuel pool, there are two further sub-targets for Biomass-Based Diesel and Cellulosic Biofuels.

Each pool within the RFS has its own unique characteristics based upon biomass source, finished fuel molecule, and/or GHG reductions. The Biomass-Based Diesel pool consists of biodiesel (mono-alkyl esters) and renewable diesel (fungible hydrocarbons) produced from renewable feedstocks like waste fats and greases or vegetable oils. The Cellulosic Biofuels pool consists mainly of advanced ethanol (alcohol not from corn) and renewable gasoline and diesel (fungible hydrocarbons) produced from the lignocellulose in plants. Specific cellulosic biomass sources include agricultural and forestry residues (wastes) like corn stover and felled trees. Cellulosic biomass sources also include dedicated energy crops like switchgrass, napier grass,

[9] The effectiveness of the RFS's design to this end has been the subject of much criticism by environmental groups. Again, see House Energy & Commerce Committee hearing "Overview of the Renewable Fuel Standard: Stakeholder Perspectives" from 23 July 2013.

and giant cane. The Biomass-Based Diesel and Cellulosic Biofuels pools are nested within a Total Advanced Biofuels pool, which includes other biofuels that meet the definition of advanced, such as butanol and ethanol from sugars, renewable crude oil from algae, and biogas produced in landfills.[10] Crucially, the nesting of the pools allows advanced biofuels with superior GHG reductions to meet the target for conventional biofuels but not vice versa. The nesting also places a premium on advanced biofuels for the flexibility they provide in meeting overall targets. On a yearly basis, the U.S. Environmental Protection Agency (EPA) sets volumetric blending requirements for all four pools, using either the quantity of available biofuels or the statutory targets, whichever is less.

The EPA tracks compliance with the RFS through a market-based compliance mechanism of tradable biofuel credits known as the Renewable Identification Numbers (RINs). Like a barcode or serial number, the RIN is a unique, 36-digit identification number assigned to every ethanol-equivalent gallon of biofuel that is blended into the transportation fuel supply. Since most advanced biofuels have greater energy densities than ethanol, one such gallon generates more than one RIN based on predetermined energy density multipliers. Also, RINs are categorized through a system of D-codes numbered D3-D7 that delineate which fuel pool certain RINs can apply to. A summary of energy density multipliers and D-codes can be seen in **Table 2**. Each year, obligated parties submit their RIN allotment to the EPA to demonstrate compliance. If obligated parties blend more biofuel than required under that year's volumetric blending requirement, the RINs are separable and can either be banked for use the subsequent

[10] There is a pending rule at EPA that would allow biogas--that is methane captured from landfills and used for transportation--to qualify as a cellulosic biofuel. This rule is expected to be finalized in 2014. (EPA-D and McAdams)

year or sold to another obligated party. As with any free market, a surplus of RINs reduces their value while a deficit increases it. Surpluses and deficits in RINs are generally driven by the relative cost of producing biofuels to that of petroleum fuels. The present value of a RIN, then, is reflected in the present value of the biofuel, which generated it. It follows that RINs also behave as a sort of market-based subsidy of biofuels, rising and falling to make them cost competitive with their petroleum-based counterparts. RINs, therefore, carry a real dollar value that reflects the relative price premium that come with biofuels, as well as serving as a proxy for the cost of compliance with the RFS.

As mentioned in the previous section, unforeseen developments in U.S. energy markets--breakthroughs in unconventional extraction techniques and declining fuel consumption--have created an issue where, beginning in 2013, the RFS mandated more ethanol blended into gasoline than is compatible with many engines, especially for automobiles made before 2001. This infrastructure compatibility issue has become popularly referred to as the ethanol "blend wall" and is depicted in **Figure 3**. Although advanced biofuel RINs can and did makeup for the shortfall in corn ethanol RINs by virtue of the nested targets, nervousness in the market over an inadequate supply of RINs drove the average price of a corn ethanol RIN from just $0.02-0.03 in 2012 to $1.47 in July of 2013, collapsing the spread between the different RINs and driving up the price of advanced biofuel RINs as well (see **Figure 4**). This historical spread between the advanced and conventional biofuel RINs reflected the higher costs of producing advanced biofuels relative to conventional biofuels, which have existed for over a century (Graetz 127-132). Beginning in 2013, however, RIN prices began to reflect these infrastructure induced supply limits.

When Congress enacted the RFS in 2007, lawmakers had not foreseen corn ethanol reaching its potential saturation limit until 2015, when the mandate for corn ethanol is capped 15 billion gallons (GPO-B 31-32). If obligated parties are forced to purchase large quantities of RINs valued at over $1 due to the lack of any other viable compliance options, they could potentially face hundreds of millions if not billions of dollars in increased operational costs. In 2013, the RFS mandated a total of 16.55 billion RINs or ethanol-equivalent gallons of biofuel. RINs have become the crux of the debate with respect to whether or not the RFS is significantly increasing consumer fuel prices. Obligated parties claim that they pass these costs directly onto the consumer in the form of higher fuel prices. RINs have therefore become a lightning rod issue within the Capitol Beltway and amongst commodity market analysts. Industry publications characterized the run up in RIN prices in mid-2013 as "RINsanity" and "RINdemonium" (Gerlach 4).

SECTION III: THE BIOMASS-BASED DIESEL POOL

As previously mentioned, the RFS is divided into nested pools differentiated by biomass feedstock, molecule, and/or GHG emissions reductions (see **Figure 2**). Since this is a study about diesel price, I'm principally concerned with the Biomass-Based Diesel pool because, as the name implies, this is where almost all plant-based diesel fuels generate RINs. According to the EPA's Moderated Transaction System (EMTS), the Biomass-Based Diesel pool consists first and foremost of biodiesel (a methyl ester produced largely from soybean oil) and various non-ester renewable diesels (most of which are fungible hydrocarbons and produced from waste fats and greases). While there are some gallons of diesel producing RINs in the conventional ethanol pool (coded D6) and the generic advanced pool (coded D5), these volumes are miniscule when compared to the overall pools.

For instance, there were 12,986,547,479 gallons of corn ethanol in the D6 pool in 2012 but only 1,118,519 ethanol-equivalent gallons of biodiesel, constituting just 0.0086% of the pool. Likewise, there were 603,461,683 gallons of sugarcane ethanol, 2,874,046 ethanol-equivalent gallons of biogas (produced from landfills), and 196,124 ethanol-equivalent gallons of heating oil in the D5 pool in 2012 but just 20,532,873 ethanol-equivalent gallons of renewable diesel, constituting just 0.034% of the pool. Because of the superior value of the biomass-based diesel RIN (coded D4) to the D5 or D6 RINs throughout 2012, these diesels only entered the D5 and D6 pools because they either were grandfathered into the RFS or did not have qualifying pathways into the D4 pool.[11] Consequently, the RIN that is most relevant to studying the impact of the RFS on diesel price is the D4 RIN.

There are four main reasons to study the Biomass-based Diesel pool beyond its immediate relevance to diesel. First, the Biomass-Based Diesel RIN (code D4) has historically been the highest priced RIN of the fuel producing pools;[12] therefore, one could hypothesize that these RINs ought to individually have the greatest measurable impact on fuel prices. Second, to date, most advanced biofuels produced are various forms of plant-based diesel. As previously

[11] Biodiesel in the conventional pool (D6) has been grandfathered into the RFS; it does not qualify as an advanced biofuel because it does not meet the minimal threshold of 50% GHG reductions. Furthermore, fuels must have an approved pathway in order to participate in the RFS. Pathways are determined by looking at feedstock, conversion technology, GHG reductions, and finished fuel molecule. EPA has been historically slow to approve new pathways, putting pressure on advanced biofuel producers who have limited to no means of selling their fuel until a pathway is approved. At the time of this study, EPA had 34 outstanding pathways, many of which have been waiting for more than 2 years. (EPA-D)

[12] I do not factor in cellulosic biofuel RINs (coded D3 or D7) because less than 1 million gallons of cellulosic biofuel have produced RINs in the RFS to date; by contrast, there were over 2.75 billion gallons of advanced biofuels produced in 2013 alone. (EPA-C)

mentioned, the RFS was specifically enhanced in 2007 by EISA to promote advanced biofuels with superior energetic and environmental performance characteristics. Cellulosic biofuels, which were touted as the fuels of the future by President George W. Bush (WH-B), have proven extremely difficult to scale-up and commercialize, missing virtually every milestone set in the RFS. The plant-based diesels, however, have managed to fill in for cellulosic biofuels every year to date and meet the statutory mandate. Third, the biomass-based diesel pool is nested within two other pools. D4 RINs provide the more flexibility than the D5 or D6 RINs to obligated parties in fulfilling their regulatory obligations. Finally, previous literature on biofuels has looked at ethanol in gasoline. This study then deliberately aims to start exploring the other, overlooked biofuels that are now starting to constitute significant portions of the U.S. fuel supply.

The prices of biodiesel and renewable diesel, while market-based, also reflect the value of the RIN and any applicable tax credits. This is exceedingly straightforward for renewable diesel, where the price is simply that of ultra-low sulfur diesel (ULSD) plus the RIN and tax credit values, since it is a fungible hydrocarbon. For instance, in August 8, 2013, the wholesale price of ultra-low sulfur diesel was $2.92 and the D4 RIN price was $0.76; therefore, the price of renewable diesel was then $0.76 times 1.7 (the energy density multiplier) plus the $1.00 tax credit plus the price of ultra-low sulfur diesel, totaling $5.21. The price of biodiesel is similarly established but is not the same as renewable diesel since it is a methyl ester as opposed to a hydrocarbon, thus having a lower energy density value. Furthermore, while biodiesel prices do vary regionally in the U.S., prices are also influenced by demand in the European Union from countries with similar mandates for biodiesel (McAdams). Given the existence of the RFS and regulations limiting sulfur content in diesel, demand is guaranteed to biofuel producers allowing them to price a gallon to sufficiently cover their production costs, which are higher than the fossil-based alternative.

It is possible to estimate the theoretical passthrough of the D4 RIN price to the wholesale price of ULSD if one assumes the RIN is fully monetized and ignores any potentially mitigating market forces like arbitrage between refiners and importers of diesel. For argument's sake, I assumed a B5 diesel blend (that is biodiesel blended at 5% into petroleum diesel), a realistic assumption given the consumption of biodiesel relative to petroleum diesel in 2013.[13] Using the mean prices of wholesale ULSD ($2.944) and biodiesel ($4.741) in my data set, I calculated the *neat* price of diesel fuel, that is, pure fossil-based diesel before blending with renewable fuels, and then subtracted the neat price from that of ULSD. These calculations follow:

$$\text{ULSD} = \text{neat} \times 0.95 + \text{biodiesel} \times 0.05$$

$$\$2.944 = \text{neat} \times 0.95 + \$4.741 \times 0.05$$

$$\text{neat} = \$2.849$$

$$\$2.944 - \$2.849 = \$0.0946$$

Based on mean prices in 2013, these calculations suggest that, absent any market arbitrage or other mitigating forces, the RFS would have increased the wholesale price of a gallon of ULSD by 9.46 cents. This figure will serve as a hypothetical point of comparison in the regression analysis of RIN passthrough I preform in this study.

SECTION IV: LITERATURE REVIEW

The central question of how RINs impact the fuel prices broadly and gasoline specifically was first taken up by Goldman Sach's Global Investment Research division in a publication on

[13] Given total diesel fuel consumption in 2013 and total biodiesel consumption, the penetration of renewable fuels in diesel was about 4.7%. (EIA-D)

April 4, 2013 entitled "Navigating the labyRINth." The report has framed the discussion among commodity traders and policy makers on the risks and opportunities posed by the unregulated RIN market. The report focuses on the passthrough of the corn ethanol RIN, due to the spike in price and the large volumes of corn ethanol mandated under the RFS, but its logic applies to the other RIN categories as well. Industry stakeholder groups on both sides of the debate have used the report to make their case. The report states:

> We believe that obligated parties, either refiners or importers, are likely passing on the cost of RINs down to the retail gasoline level. While the cost likely remains modest for now, $0.07/gal currently if we assume a 10% pass through of the price of a D6 [corn ethanol] RIN, further increases in RIN and in turn gasoline prices would start to matter. For example our US economists' modeling suggests that a 10% increase in a gasoline prices shaves 0.9% of US real GDP growth in the year that it occurs. This would likely be the case should D6 RIN prices reach $3. (Sachs 11)

The report bases its assumption of a 10% passthrough on feedback it has received from refiners; however, it does not establish a model that can predict RIN price passthrough and help policy makers more precisely weigh the costs and benefits. The report correctly notes that RIN prices were always intended to drive innovation but the mismatch between ethanol mandated and infrastructure compatibility has pushed prices higher than anticipated when the legislation was passed into law. Rather than trying to sort out the precise effect of RIN prices, the report principally tries to identify larger trends in the fuels market and how it sees the blend wall eventually being resolved through legislative reform (Sachs 14). My study is the first to empirically estimate the impact of RIN prices on diesel fuel prices, as a measure of the compliance cost passthrough to the consumer.

The impact of a biofuels mandate like the RFS on gasoline prices has also been explored through economic modeling. In 2009, Gorter and Just published a paper accounting for how biofuels mandates can both increase or decrease gasoline prices. Gorter and Just set up a simplified model of supply and demand curves that assumed an exogenous oil-based gasoline price, a single gasoline supply curve (representing both domestic and imported gasoline supply), and no imports of biofuels (e.g. sugarcane ethanol from Brazil). They found that an increase in ethanol mandated will, at first, increase the price of the ethanol, but this increase will then drive down the price of neat gasoline through a decrease in gasoline demand in a fuels market that perceives gasoline and ethanol as perfect substitutes. It is possible for the latter decline to overpower the former increase, resulting in a net decrease in consumer gasoline prices. Gorter and Just's model presents some issues for my research. First off, gasoline and ethanol are not perfect substitutes, as ethanol can only be blended up to 10%. Second, the authors do not account for the role a market-based compliance mechanism like RINs have on the price of consumer gasoline. My thesis takes the next logical step of modeling how a biofuels mandate works when alternative fuels are substitutes up to a certain percentage in addition to factoring RINs into the larger supply and demand forces that drive a biofuels mandate and fuel prices.

Relatedly, Du and Hayes explore the impact that increasing ethanol production has on wholesale/retail gasoline prices in a journal article in 2009 along with two follow-up working papers that incorporate recent data. Their analysis centers on two dependent variables: the crack ratio and crack spread, both measures of gasoline price relative to crude oil price and both commonly used metrics of refinery profits. Because the Du and Hayes anticipate regional variation in ethanol production impacts, they estimate the crack ratio and crack spread using price data from January 1995 to December 2011 (including the article and both working papers) from price data obtained from the the U.S. Energy Information Administration (EIA) both nationally and by production region. Their selected time frame includes data both before and after the implementation of the RFS, although corn-ethanol has existed in transportation fuel supply consistently since the 1970s (Graetz 127-132). They separately regress the crack ratio and crack spread on a number of cost and price shifting variables, namely, seasonality, market conditions, refinery capacity, market concentration, supply disruptions, gasoline imports, and ethanol production through a combination of interval-ratio, indicator, index, and instrumental variables. They find that ethanol production has a significant and negative impact on retail gasoline prices both regionally and nationally.

While my research found no other academic studies directly related to the RFS, there are several that sought to model the fuel price premium associated with a variety of gasoline content regulations. They specifically utilized geographical and/or temporal variation in regulations to estimate the effect on wholesale gasoline. In the first of these studies, Vita in 2000 estimated the impact that gasoline divorcement regulations had on wholesale prices in six states including the District of Columbia. Divorcement regulations aim to prevent the vertical integration of fuel companies in the name of fostering competition. Vita hypothesized that such regulations could reduce efficiency seen in economies of scale, leading to higher fuel prices. He regressed average monthly retail gasoline prices, obtained from EIA's *Petroleum Marketing Annual* reports, on a number of demand shifters, cost shifters, regulatory variables, and other control variables. His demand shifters included income per capita, population, age, and number of vehicles on the road. His cost shifters included average consumer transportation costs, spots prices of crude oil, and the percentage of oxygenated gasoline. Key were his regulatory variables on divorcement, especially his indicator variable coded for states with divorcement regulations. He also lagged his crude oil variable to reflect the delay that changes in refiner costs have on retail prices. Vita concluded that divorcement regulations are associated with a statistically significant increase in the price of gasoline of 2.6 cents.

The other relevant studies specifically analyzed regulations associated with the *Clean Air Act* (CAA) Amendments of 1990. Under the CAA, the EPA required areas that do not meet minimal air quality standards—termed *non-attainment* areas—to implement clean gasoline programs, primarily Reformulated Gasoline (RFG) or Oxygenated gasoline (OXY). The CAA amendments gave license to states to implement the programs more broadly than only in designated non-attainment areas, which lead to the proliferation of unique fuels blends or boutique fuels and the segmentation of the fuels market into so-called fuel islands. While these studies acknowledge the role that increased input costs may play, they focus mainly on the role that segmentation plays in increased prices and price volatility.

Papers by Erich Muehlegger in 2002 and 2006 sought to define and analyze the relevant variables that impact gasoline price regionally, with particular attention to isolated price spikes such as in California. Market segmentation following the CAA amendments has increasingly concentrated supply amongst a select number of refiners per region. Shortages or refinery outages lead to localized price spikes, as other gasoline supply cannot meet a region's specific content regulations. Specifying a structural model based on refiner profit optimization, Muehlegger concluded in 2006 that this fragmenting of the gasoline market likely accounts for 90% of all regional price spikes between 1992 and 2002.

In 2006, Brown, Hastings, Mansur, and Villas-Boas studied the effects of content regulation at the city level, using a differences-in-differences approach by matching regulated and unregulated fuel markets under the CAA Amendments of 1990. They hypothesized that, in addition to increased marginal production costs, content regulations increase prices for two reasons: one, the segmentation of once contiguous geographic fuel markets, and two, the reduction in competition associated with fewer suppliers to each market. Their study used weekly price data from the Oil Price Information Service (OPIS) of unbranded wholesale gasoline at distribution terminals located near regulated and unregulated cities from 1994 to 1998. Brown et. al. regressed wholesale gasoline prices of regulated cities on prices of unregulated cities including a variable for the number of local fuel suppliers and indicators for each type of content regulation. They found statistically significant increases in prices of regulated cities at an average of 3 cents/gallon.

In the same year, Chakravorty, Nauges, and Thomas took up the same issue but with a different approach. Instead of employing a treatment and control model, Chakravorty et. al. compared annual, average wholesale gasoline prices from 1995-2002 in neighboring states using simultaneous equation system (three stage least squares). They obtained their data from the EIA's *Petroleum Marketing Annual* reports. For each state, they regressed the log of wholesale gasoline on the log of crude oil, along with proxy variables for cost and regulatory effects, variables for refinery concentration and capacity, and a variable for the average distance to refineries. Notably, they found that OLS regression systematically underestimated the effects on gasoline price, due to the endogeniety of the regulatory variables. Like Brown et. al, Chakravorty et. al. concluded that there is a statistically significant increase in the price of wholesale gasoline associated with content regulations, in part because of increased production costs, but predominately as a result of market segmentation.

Reviewing this literature on the price premium associated with content regulations generally, it appears that there is no consensus or best practice on how to approach modeling a federal biofuel mandate, as previous studies have exploited cross-state or cross-city variation. That said, I do have an example of dealing with serial correlation in Brown et. al. and an example of logarithmic functional form on price variables in Chakravorty et. al. All relevant peer-reviewed studies employ some form of regression analysis. Using my preliminary calculations of a fully monetized biomass-based diesel (D4) RIN at 9.46 cents, which establishes a hypothetical range for what RIN price passthrough should be in the absence of potentially confounding market forces, I then employ a wide variety of specifications in order to hone in on the best fit.

SECTION V: DATA, METHODOLOGY & HYPOTHESES

This paper attempts to answer the question: Does the U.S. biofuels mandate increase the price at the pump? In doing so, my analysis estimates the price premium associated with the Renewable Fuel Standard (RFS) on diesel fuel. Section II provided an overview of how the RFS is operationalized and Section III provided the rationale for focusing on the impact to diesel fuel as opposed to gasoline. The market-based compliance mechanism of tradable biofuel credits known as Renewable Identification Numbers (RINs) serves as a proxy for the cost of complying with the RFS to refiners and importers of consumer fuel. These obligated parties are legally required to blend increasing volumes of biofuel on a yearly basis. To perform this analysis, I obtained price information on the biomass-based diesel RIN (D4), the generic advanced biofuel

RIN (D5), the conventional biofuel RIN (D6), wholesale biodiesel, and wholesale ultra-low sulfur diesel (which contains between 2-5% biofuel varying by year) from the Oil Price Information Service (OPIS) for each business day in 2011 and 2012 and from January through August in 2013. See **Table 2** for a breakdown of the RFS' fuel classification system of D-codes and energy density multipliers. I also obtained West Texas Intermediate (WTI) crude oil price information for each business day of the same time period from the Federal Reserve Bank of St. Louis.[14] Finally, I included monthly data on total vehicle miles traveled (VMT) nationally from the National Highway Traffic Safety Administration (NHTSA).[15]

Descriptive statistics of these key variables are provided in **Table 1**. The greatest variation in my time series data is seen in the prices of the three RINs and biodiesel, while the least variation is seen in the prices of ULSD and WTI. The D4 reaches its high mark in 2011 at $1.99 per RIN, the D5 in 2013 at $1.47, the D6 in 2013 at $1.46, and biodiesel in 2011 at $7.05 per gallon. The highest mean prices follow the same pattern with the D4 at $1.30 in 2011, D5 at $0.84 in 2013, D6 at $0.71 in 2013, and biodiesel at $6.25 in 2011. By contrast, the D4 falls to its low mark at $0.44 in 2013, D5 at $0.33 in 2012, D6 at less than $0.01 in 2011, and biodiesel at $4.00 in 2012. For ULSD, its high and low marks are set in 2011 at $3.34 and $2.46 respectively, with its highest mean price set at $3.05 in 2012. For WTI, its high and low marks are also set in 2011 at $113.39 and $75.40 respectively but with its highest mean price set at $97.18 in 2013. Given this set of high-level descriptive statistics, no obvious patterns emerge.

[14] The price data for biodiesel, ULSD, and WTI crude represent national averages determined at the close of trading for each business day. By contrast, the RIN data are price quotes as opposed to averages provided by OPIS for each business day. The RINs marketplace, which is contained in the EPA's Moderated Transaction System (EMTS), does not have the same transparency as national commodities exchanges and therefore hinders more precise price data.
[15] Data on national VMT is estimated and published by NHTSA on a monthly basis. My dataset is coded such that price observations for each business day are matched with that month's average VMT estimate.

The highest mean price of D4 in 2011, which corresponds with the highest mean price of biodiesel in 2011, does not correspond with the highest mean price of ULSD in 2012. The lack of obvious patterns is likely reflective of the complexity of market dynamics at work.

In terms of the D4 RIN specifically, the full passthrough to the wholesale price of ULSD is limited by market arbitrage and fluctuations in the prices of neat (unblended) diesel fuel and WTI crude. As in most commodity markets, RFS obligated parties are predominantly price takers with a few price setters. Because refiners and importers have markedly variable operational costs, only the most cost efficient operators will have profit margins that allow them to increase fuel prices up to the point of the lowest priced competitor. Nevertheless, since the RFS impacts the entire transportation fuels market in the U.S., there is likely to be some collective effect of refiners increasing or lowering prices based on variations in input costs. In short, some of the RIN price is passed along to the consumer and some is absorbed by the obligated parties.

My study began from two testable hypotheses. First, I hypothesized that the price of the D4 RIN is a useful predictor of wholesale ULSD fuel prices after controlling for confounding price factors in the transportation fuels market. I expected to find a statistically significant association between the D4 RIN and ULSD prices. Second, I hypothesized that the actual passthrough of the D4 RIN to the wholesale ULSD prices is less than the fully monetized RIN, controlling for confounding factors, due to arbitrage in the transportation fuels market. In Section III, I estimated that the full monetization of a $1.00 D4 RIN, assuming 5% of ULSD is biomass-based diesel, is 9.46 cents. If true, I expected to find the regression estimates would predict that a

$1.00 increase in D4 RIN price, holding all else constant, increases ULSD by less than 9.46 cents. I've tested these hypotheses as follows.

In my statistical estimations, I regressed the D4 RIN price on the wholesale price of ULSD, controlling for the prices of the D5 RIN, the D6 RIN, and WTI crude. My dependent variable was the wholesale price of ULSD measured in dollars for each business day. I ultimately decided to exclude biodiesel price from my estimations altogether for two reasons. First, the D4 RIN and biodiesel prices are both proxies for the same cost of compliance of the RFS with respect to diesel fuel. Biodiesel, however, is just one type of plant-based diesel used in the RFS, making the D4 RIN arguably reflective of all biomass-based diesels broadly. Second, the D4 RIN price represents the isolated cost of the RFS mandate as opposed to biodiesel price, which also reflects the costs of feedstocks and adverse weather events like droughts (McAdams). In addition, my estimations also included indicator variables to control for the presence of applicable tax credit provisions and the market dynamics of the ethanol blend wall reached in 2013. I utilized interaction terms to control for the relative impact of RINs before and after the blend wall is reached. I employed two different methods for addressing serial correlation in my time series data: including a lagged dependent variable and the Prais-Winsten estimation procedure. Finally, all dependent and independent pecuniary variables were included in both their linear forms (**Table 3**) as well as logarithmic forms (**Table 4**), by taking the natural log of each price observation. My results, discussion, and conclusions are provided in the subsequent three sections.

SECTION VI: RESULTS

My estimation results for how the RFS impacts the wholesale price of diesel fuel are presented in **Tables 3** and **4**. **Table 3** specifically presents my results in linear form, and **Table 4** presents my results when they are in logarithmic form. Each table has six specifications that move from a bivariate regression of the D4 RIN price on ULSD price with basic controls to a fully specified model that includes all key independent variables and interactions in addition to addressing serial correlation in my time series data. I will now go through all six sets of specifications comparing the linear and logarithmic interpretations and evaluating my hypotheses against these regression results. As estimated in Section III, the full monetization of a $1.00 RIN into ULSD that is blended with 5% plant-based diesels is about 9.46 cents. This figure will serve as a theoretical baseline comparison for evaluating my second hypothesis specifically.

In my first set of specifications from both tables (Models 3.1 and 4.1), I regress ULSD on D4 controlling for the tax credit, blend wall, and vehicle miles traveled (VMT). My linear estimation results (Model 3.1) predict that a $1.00 increase in D4 RIN price, holding all else constant, causes a 6.7 cent increase in the price of ULSD, statistically significant at the 1% level. This finding clearly supports my first hypothesis that the D4 RIN price is a useful predictor of ULSD price. Furthermore, this figure is less that my estimated 9.46 cents of a fully monetized $1.00 RIN and supports my second hypothesis that the D4 passthrough to ULSD is not fully monetized, as some part of the RIN price is absorbed by the consumer and some part by the obligated parties. In my logarithmic estimation of my first specification (Model 4.1), a 1% increase in D4 RIN price, holding all else constant, causes a predicted increase in ULSD of 0.0133%, statistically significant at the 5% level. In 2013, the D4 RIN went from a low price in

$0.44 early in the year to a high of $1.465 in July, an increase of $1.025 or 333%. According to Model 4.1, an increase of 333% in D4 causes a 4.43% increase in ULSD. Based on the mean price of ULSD in 2013 of $2.979 (see **Table 1**), the $1.025 D4 price increase from $0.44 to $1.465 is predicted to increase ULSD by 13.2 cents to $3.11. By comparison, going from a $1.00 D4 RIN to a $1.993 RIN, the high price seen in 2011 or a 99.3% increase, is predicted to cause ULSD at a 2011 mean price of $2.973 to increase by 1.32% or 3.93 cents to $3.012. Like Model 3.1, Model 4.1 supports my first hypothesis. The implications for my second hypothesis are less clear, although not altogether inconclusive, given the high probability that the passthrough is nonlinear and depends upon relative RIN prices. While these logarithmic predictions, like my linear predictions, are similar to my calculations of a fully monetized $1.00 RIN passthrough, my first set of specifications do not account for other confounding variables that may be biasing these estimates.

In my second set of specifications (Models 3.2 and 4.2), I incorporate the price of WTI crude oil. Crucially, this inclusion changes the sign on D4's effect from positive to negative with coefficients on D4 and WTI statistically significant at the 1% level in both my linear and logarithmic estimations, suggesting that the omission of crude oil was biasing my estimates in Models 3.1 and 4.1. Model 3.2 estimates a $1.00 increase in the price of a D4 RIN, holding all else constant, *lowers* the wholesale price diesel fuel by 5.43 cents. By comparison, Model 4.2 predicts that a 1% increase in D4 RIN price, holding all else constant, decreases ULSD by 0.0319%. While Models 3.2 and 4.2 support my first hypothesis, they do not support my second hypothesis that RIN values increase the price of fuel by some amount less than a fully monetized passthrough. One possible explanation for why controlling for crude oil price turns the estimate for D4 negative could be that an increase in biofuels utilization in the transportation fuels market increases the elasticity of crude oil. In effect, this development might theoretically allow fuel producers to substitute away from crude oil when prices rise relative to biofuels, blunting the impact of crude oil price volatility over the long-term and leading to a lower price of diesel. Nevertheless, there is still reason to believe that the other RIN classes could have a confounding effect on Models 3.2 and 4.2 and need to be controlled for.

In my third set of specifications (Models 3.3 and 4.3), I include the D5 and D6 RINs, within whose pools the D4 RIN is nested. In both models, coefficients on all independent variables except for VMT are statistically significant again at the 1% level, supporting my first hypothesis. In my third set of specifications, however, the sign of the D4 RIN changes back to positive, supporting the argument that omitting the D5 and D6 RINs from the model was biasing my estimates. By contrast, the coefficient on WTI changes only slightly from 0.0151 to 0.0116, pointing to a specific bias on the D4 coefficient estimate caused by the omission of D5 and D6. In Model 3.3, a $1.00 increase in the price of the D4, holding all else constant, has the predicted effect of increasing ULSD by 17.9 cents, and a $1.00 increase on the price of the D5 or D6 RINs, holding all else constant, has the predicted effect of decreasing the ULSD by 38.8 cents and 11.4 cents respectively. In Model 4.3, a 1% increase in D4 price, holding all else constant, is predicted to increase ULSD by 0.0487%. Using the same historical examples of an approximate $1.00 increase in RIN price as before, Model 4.3 predicts that the 333% rise in D4 price from $0.44 to $1.465 observed in 2013 increases ULSD by 16.2% or 48.3 cents given a mean price of $2.979 and the 99.3% rise in D4 price from $1.00 to $1.993 observed in 2011 increases ULSD by 4.84% or 14.4 cents given a mean price of $2.973. Predictions from Models 3.3 and 4.3 cast doubt on my second hypothesis. Given the historical penetration of biofuels into the diesel market at no more than 5%, it is difficult to accept predictions of 17.9 cent, 48.3 cent, or 14.4 cent increases in diesel price for a $1.00 RIN. Furthermore, there is also reason to believe that my third set of specifications are biased as they do not control for the dramatic change observed in RIN prices once the ethanol blend wall was reached in 2013.

In my fourth set of specifications (Models 3.4 and 4.4), then, I interact all three RINs types with my blend wall indicator variable to account for the fact that the effect of the RINs varies with whether or not ethanol has reached its maximum saturation limit into the gasoline market. As a reminder, even though the blend wall is a gasoline issue, the nesting of the RFS mandates mean that the blend wall impacts demand for plant-based diesel substitutes in addition to plant-based gasoline substitutes. In Models 3.4 and 4.4, coefficients on all three RINs and WTI are statistically significant at the 1% level, again supporting my first hypothesis. Coefficients on the interaction variables are all significant at the 1% level in the linear model, but in the logarithmic model the D4 and D5 interactions are statistically significant at the 1% level while the D6 interaction is not statistically significant at any conventional level. In both models, coefficients on all RINs change, with the most dramatic changes observed on the D5 and D6 RINs, suggesting that the omission of the interaction terms was biasing my estimates in the earlier specifications. While the new coefficients on D4 in both models are again hard to make sense of, given that they are comparable or even higher than in previous specifications, controlling for the interaction with the blend wall adds a new dynamic in how D4 RIN prices impact ULSD prices.

In Models 3.4 and 4.4, the D4 RIN is predicted to increase the price of wholesale diesel fuel until the blend wall is reached; after that, it begins to have the predicted effect of decreasing the price of fuel. The D5 and D6 RINs are predicted to work in the opposite direction to that of the D4 RIN, lowering the price of diesel fuel before the blend wall and increasing it after. This finding does make some sense in light of the fact that isolated increases in the D5 or D6 RIN prices, both in pools that consist almost entirely of gasoline substitutes, would likely draw gallons away from the Biomass-Based Diesel pool, consisting exclusively of diesel substitutes, and perhaps lower the price of ULSD. These findings again cast doubt on my second hypothesis, as both model's predicted effects before and after the blend wall are outside my estimations of a fully monetized RIN. Moreover, the predicted decrease in ULSD price after the blend wall is so large relative to the price and quantity of D4 RINs in both models that it is hard to view these estimates as plausible. The estimation of the magnitude of the effect of the D4 RIN has been consistent challenge in my modeling experiments. As I've introduced control variables into my models, the magnitude of predicted D4 returns to ULSD has generally increased, reaching levels that are difficult to explain. While this is suggestive of persistent omitted variable bias, I believe that the direction of predict effects is still an important finding. This is discussed in more detail in the next section.

Finally, in my fifth and six sets of specifications (Models 3.5-6 and 4.5-6), I attempt to control for serial correlation in my price variables stemming from the lag between when prices inputs rise and when refiners and importers can practically increase wholesale prices. In Models 3.5 and 4.5, I use the procedure of lagging my dependent variable—ULSD—by one business day and including the lagged variable as a regressor. Given the technological sophistication of modern refinery operations, I argue that one business day is a realistic time frame in which refineries could adjust their behavior to market signals. Alternatively, Models 3.6 and 4.6, I use the Prais-Winsten procedure to control for serial correlation. While the merits and pitfalls of either approach are beyond the scope of this analysis, my fifth and sixth specifications produce significant improvements in goodness of fit as measured by the adjusted "R-squared" estimations. The adjusted R-squared in Models 3.4 and 4.4 of 0.600 and 0.607 respectively rise to 0.940 in both Models 3.5 and 4.5 and to 0.987 and 0.989 in Models 3.6 and 4.6 respectively. Unlike with the Prais-Winsten procedure, however, the lagged dependent variable approach considerably alters the statistical significance and magnitude of most of the key interpretive and interaction variables, especially in Model 4.5 where only the D5 RIN variable remains statistically significant apart from the lagged dependent variable. With the D4 RIN coefficient statistically significant in three out of four models, however, my first hypothesis that the D4 RIN price is a useful predictor of ULSD price remains generally supported by the evidence.

The D4 coefficients in Models 3.6 and 4.6 predict price effects on ULSD appreciably similar to Models 3.4 and 4.4, but Models 3.5 and 4.5 with lagged ULSD as an independent variable diverge substantially. Model 3.5 predicts a $1.00 increase in D4 price passes 1.97 cent through to the wholesale price of ULSD, significant at the 10% level. Notably, the interaction of the D4 RIN with the blend wall is no longer statistically significant. The predictions of Model 3.5 support both of my hypotheses about the D4 RIN. However, Model 4.5 supports neither of these hypotheses, as the D4 RIN variable is not statistically significant at any conventional level. Still, given that D4 RIN price is statistically significant in eleven out of twelve models employed in this study, there is reasonable evidence to accept my first hypothesis.[16] In terms of my second hypothesis, the evidence is more mixed but perhaps tentatively supportive of the idea that some of the RIN price is absorbed by the obligated parties and some passed on to consumers.

SECTION VII: DISCUSSION

The results of this study analyzing the impact of diesel (D4) RIN prices on the wholesale price of ultra low sulfur diesel (ULSD) points to an effect dependent upon market forces. In 2011 and 2012 before the ethanol blend wall is reached, most of my regression estimates suggest that the D4 RIN increases diesel fuel prices; however, after the blend wall is reached in 2013, the sign on the D4 coefficient reverses direction suggesting that it now decreases diesel prices. Moreover, the blend wall marks a reversal in signs for all three RIN types. These findings imply that reaching the saturation limit of ethanol in gasoline fundamentally alters the dynamics of the biofuels mandate in the fuels market broadly.

To illustrate this point, assume a market price of ULSD at $3.00 per gallon and D4 price of $1.00. Model 3.6 predicts that a 100% increase in D4 price from $1.00 to $2.00 before the blend wall (a realistic increase in historical terms) increases ULSD by 21.2 cents from $3.00 to $3.212 or an approximate 5.9% increase from $3.00 to $3.177 per Model 4.6. Yet after the blend wall, the same 100% increase in D4 price predicts a decrease in ULSD of 10.5 cents from $3.00 to $2.895 or an approximate 5.1% decrease from $3.00 to $2.847 using Models 3.6 and 4.6 respectively. Given that biodiesel penetrates the diesel market at no more than 5% throughout the

[16] An F-test of the joint-significance of the D4 RIN and D4 interaction variables in my fourth, fifth, and sixth sets of specifications found my fourth and sixth sets to be statistically significant at the 1% level but not the fifth set at any conventional level.

history of the RFS, the direction of the predicted effects are perhaps more illuminating than the absolute magnitudes.

Critically, there are two reasons to be cautious in considering the magnitudes of the coefficients in these estimates. The first is that they vary considerably based on model specifications—control variables, logarithmic transformations (functional form), and attempts to correct for serial correlation—a sensitivity that suggests bias may remain in the estimates despite the best of efforts. Due to the controversial nature of the RFS as a policy instrument, highlighted in Section I, stakeholders such as petroleum companies, livestock companies, and restaurant chains have made repeated and sustained attempts to repeal, weaken, or alter the mandate, thereby casting a long shadow of doubt over the future of RFS and likely impact RIN prices themselves.

Second, the seemingly implausible predictions derived most of the models may not be too surprising given the incongruence of interpreting one coefficient holding all others constant. There is no historical example of the D4 RIN moving independently of the others, (see **Figure 4**) but this is what interpreting the D4 coefficient entails. An increase in the D4 RIN has always coincided with an increase in the generic advanced biofuels (D5) RIN and, beginning in 2013, the ethanol (D6) RIN as well. I specifically chose to include my biased first and second sets of specifications because, although running against the norms of econometrics, they do not partial out the impacts of the other two RINs, which may better reflect what is actually being observed in the RINs market. In reality, the RINs may be highly collinear, given the nesting of mandates for the different molecules (see **Figure 2**). Perhaps, there is some value in interpreting the simpler statistical model, as it does not hold each of the RINs constant.

Nevertheless, it is my belief that the value of my regression model specifications are not in the absolute magnitudes of the coefficients but in the estimated direction of the predicted effects given by the coefficient signs. The fact that the biofuels mandate has an ambiguous effect on fuel prices is supported by other relevant research (Gorter 742-743) as highlighted in Section IV. There are two potential explanations in economic theory as to why the signs reverse on the RIN variables once the blend wall is reached. Neither is about the ethanol saturation limit in gasoline *per se* but rather altered market dynamics due to this saturation limit driving gallons of biodiesel into the diesel fuel pool. In fact, there is a 70 percent increase in volume of biodiesel consumed from 2012 to 2013.

First, it could be that a large and rapid increase in biodiesel consumed by the market drives down the demand for petroleum-based diesel. Given the relatively inelastic supply of diesel fuel holding gasoline supply constant (a consequence of the fixed percentage of diesel produced in the distillation process at refineries), the surplus of petroleum diesel supply over and above demand may lower the wholesale price by an amount that surpasses the price premium of biodiesel, a market dynamic observed by Du and Hayes in their related study on ethanol and gasoline prices. In contrast to petroleum diesel, biodiesel has a relatively elastic supply due large and under utilized production capacity of 2.8 billion gallons per year.[17] The RFS mandated 1.3 billion gallons of biodiesel in 2013, yet the diesel fuel market consumed over 1.7 billion as a direct result of the blend wall. In 2012, the fuel market consumed just 1 billion gallons of biodiesel, matching that year's volumetric obligation (EPA-C).

[17] See EPA rule making "Regulation of Fuels and Fuel Additives: 2013 Renewable Fuel Standards; Final Rule" 78 Fed. Reg. 49813 (15 Aug 2013).

The second explanation has to do with how increases in biofuel utilization increases the elasticity of oil demand itself, a consequence of providing substitutes in the transportation fuel market for which there is no real historical precedent. As **Figure 1** illustrates, the statuary requirements of the RFS increased biofuel consumption by 1.35 billion gallons from 2012 to 2013. The question of whether such an increase in a combined diesel and gasoline fuel pool of about 160 billion gallons can impact elasticity is beyond the scope of this study. Yet, basic economic theory suggests that increased availability of substitutes for petroleum-based fuels could blunt price volatility in the oil markets, given the inelastic demand for transportation fuel in the U.S. (Gorter 742). What happened when WTI crude price was added in Models 3.2 and 4.2 may be evidence of this, since it reversed the sign on D4 from positive to negative.

SECTION VIII: CONCLUSIONS

This study began from two hypotheses. First, I hypothesized that the price of the biomass-based diesel RIN (D4) is a useful predictor of the price of ultra-low sulfur diesel (ULSD). Second, I hypothesized that the passthrough of the D4 RIN value to ULSD is some amount less than if it were fully monetized at 9.46 cents, assuming 5% of ULSD is biofuel, due to arbitrage in the transportation fuel market. The findings of this study generally support my first hypothesis and to some extent my second. Specifically, I found the price impact of the D4 RIN on diesel fuel prices to be statistically significant, somewhat predictable, and possibly less than the full passthrough prior to the blend wall being reached. For the models that predicted an effect on fuel prices greater than my 9.46 cent estimate of a fully monetized $1.00 RIN, this result may be the consequence of multicollinearity from the nesting of the fuel pools. After the blend wall is reached, however, my estimates vary wildly in direction and magnitude, suggesting that the blend wall alters how RINs affect diesel prices in ways that are perhaps difficult to understand.

These findings cast some doubt on the assertions made by opponents of the Renewable Fuel Standard (RFS) that RINs prices are passed onto the consumer and increase fuel prices significantly. I have found some evidence that compliance costs are absorbed in some part by obligated parties. Further, increased biofuel utilization may have the ability to reduce or blunt petroleum prices. Most importantly, however, these findings may provide a basis for arguing the RFS needs to be legislatively reformed, given the ethanol blend wall issue. There is already bipartisan interest in a reform bill in the committees of jurisdiction in both chambers of Congress (McAdams).

Given the far reaching impacts of energy prices and the uncertainty surrounding the future of the RFS, a more comprehensive study is called for. Subsequent research would benefit from utilizing the most recent price data, given the relatively limited time frame that the RFS had been implemented at the time of this study. Also, future research may benefit from including and controlling for gasoline market data, in addition to diesel market data, seeing as the ethanol blend wall has a statistically significant effect on the transportation fuel market broadly. Finally, the best way to estimate the price premium on fuel produced by the RFS may indeed be a control-treatment approach, utilized effectively in other studies (see Section IV) of fuel content regulations. Hawaii and Alaska, the two states exempted from the RFS by virtue of being disconnected from the infrastructure that makes blending biofuels practically feasible, could be potential counterfactuals.

APPENDIX A: TABLES

Table 1. Descriptive statistics of key interpretative variables by year.

		ULSD	D4 RIN	D5 RIN	D6 RIN	WTI crude	Biodiesel
	Mean	2.97332	1.301091	.7493625	.0257801	94.87279	6.247645
2	**Max**	3.33895	1.9925	1.275	.0415	113.39	7.045
0	**Min**	2.46025	.72	.42	.0025	75.4	5.335
1	**Std. Dev.**	.1691542	.251126	.2011735	.0108072	8.093871	.4023145
1	**Skewness**	-.6047614	.0693969	.7481114	-.7984693	.0795979	-.2825767
	Kurtosis	3.160154	3.65921	3.127942	2.523741	2.432042	2.237594
	Mean	3.051343	1.097191	.6177689	.0287088	94.08139	4.481515
2	**Max**	3.33065	1.595	.855	.059	109.39	4.96
0	**Min**	2.59005	.43375	.325	.01125	77.72	3.995
1	**Std. Dev.**	.1809703	.3567369	.1620994	.0120026	7.730498	.2843344
2	**Skewness**	-.6363397	-.5439828	-.249157	.5245924	.1590062	-.2079774
	Kurtosis	2.645871	1.824546	1.465458	2.097319	1.949001	1.761724
	Mean	2.979389	.8606473	.8362723	.7142815	97.17869	4.79738
2	**Max**	3.2862	1.465	1.465	1.455	110.17	5.4
0	**Min**	2.71835	.44	.37	.06925	86.65	4.2925
1	**Std. Dev.**	.1264743	.2303345	.2453708	.3198053	5.563617	.2214057
3	**Skewness**	.3163935	-.0309938	-.0281748	-.4213811	.7363458	-.1465893
	Kurtosis	2.65103	2.628214	2.67474	2.757518	2.406182	2.884496

Price information comes form the Oil Price Information Service (OPIS) and the Federal Reserve Bank of St. Louis and includes observations for each business day of the calendar year for 2011 and 2012 and from January through August for 2013. Each statistic is given in dollars per unit of analysis. For ultra-low sulfur diesel (ULSD) and biodiesel, the figure is dollars per gallon. For the three RIN types, the figure is dollars per RIN. For WTI crude, the figure is dollars per barrel (42 gallons).

Table 2. RIN D-codes and energy density multipliers by fuel type and pool.

General Fuel Type	Specific Fuel Type	RIN D-Code	Total Gallons in 2013	Energy Density Multiplier	Total RINs in 2013	Fuel Pool or Category	D-Codes That Satisfy RVO
Cellulosic Biofuels	Renewable Gasoline	D3	281,819	1.6	422,740	**Cellulosic Biofuels**	D3, D7
	Renewable Diesel	D7	232,808	1.7	395,777		
Biomass-Based Diesels	Renewable Diesel	D4	230,487,597	1.7	391,828,924	**Biomass-Based Diesel**	D4, D7
	Biodiesel	D4	1,533,077,991	1.5	2,299,645,343		
Other Advanced Biofuels	Sugarcane Ethanol	D5	457,302,194	1.0	457,302,194	**Advanced Biofuels**	D3, D4, D5, D7
	Biogas	D5	25,903,595	1.0	25,903,595		
	Naptha	D5	2,311,157	1.5	3,466,737	**Total Renewable Fuel**	D3, D4, D5, D6, D7
Conventional Biofuels	Corn Ethanol	D6	13,095,953,766	1.0	13,095,953,766		
	Biodiesel	D6	36,778,740	1.5	55,168,362		

Production data comes from the Environmental Protection Agency's (EPA) Moderated Transaction System (EMTS): http://www.epa.gov/otaq/fuels/rfsdata/2013emts.htm

Table 3. Linear regression results for different specifications on ultra low sulfur diesel (ULSD).

VARIABLES	**(3.1)** **D4** ULSD	**(3.2)** **WTI** ULSD	**(3.3)** **All IVs** ULSD	**(3.4)** **Interactions** ULSD	**(3.5)** **LDV** ULSD	**(3.6)** **P-W** ULSD
Biomass-Based Diesel (D4) RIN	0.0670*** (0.0204)	-0.0543*** (0.0199)	0.179*** (0.0370)	0.189*** (0.0376)	0.0197* (0.0115)	0.212*** (0.0491)
Other Advanced Biofuel (D5) RIN			-0.388*** (0.0564)	-0.291*** (0.0591)	-0.0360* (0.0189)	-0.346*** (0.0792)
Conventional Biofuel (D6) RIN			-0.114*** (0.0408)	3.472*** (0.526)	0.374* (0.202)	2.231*** (0.810)
West Texas Intermediate (WTI) Crude Oil		0.0151*** (0.000650)	0.0116*** (0.000770)	0.0128*** (0.000779)	0.000553 (0.000376)	0.00687*** (0.00104)
Tax Credit Indicator	-0.0907*** (0.0174)	-0.0783*** (0.0127)	-0.0742*** (0.0105)	-0.0794*** (0.0101)	-0.00226 (0.00428)	-0.0736*** (0.0239)
Ethanol Blend Wall Indicator	0.0371** (0.0188)	-0.0515*** (0.0164)	0.168*** (0.0301)	0.496*** (0.0759)	-0.00626 (0.0267)	0.172** (0.0858)
Vehicle Miles Traveled (VMT)	-0.000611 (0.000473)	-0.000322 (0.000387)	0.000766** (0.000364)	0.000706** (0.000353)	-9.14e-05 (0.000127)	-0.000166 (0.000514)
D4 Blend Wall Interaction				-1.367*** (0.224)	0.0186 (0.0894)	-0.317** (0.147)
D5 Blend Wall Interaction				1.052*** (0.278)	0.0705 (0.0875)	0.398** (0.154)
D6 Blend Wall Interaction				-3.511*** (0.542)	-0.443** (0.205)	-2.313*** (0.815)
Lagged Ultra-Low Sulfur Diesel (ULSD)					0.925*** (0.0140)	
Constant	3.128*** (0.116)	1.773*** (0.110)	1.822*** (0.108)	1.544*** (0.105)	0.190*** (0.0503)	2.361*** (0.162)
Observations	669	669	669	669	665	669
Adjusted R^2	0.054	0.452	0.554	0.600	0.940	0.987

All price variables in U.S. dollars. Robust standard errors in parentheses. Statistical significance indicated by: *** p<0.01, ** p<0.05, * p<0.1.

Table 4. Logged regression results for different specifications on ultra low sulfur diesel (ULSD).

VARIABLES	**(4.1)** **D4** ULSD	**(4.2)** **WTI** ULSD	**(4.3)** **All IVs** ULSD	**(4.4)** **Interactions** ULSD	**(4.5)** **LDV** ULSD	**(4.6)** **P-W** ULSD
Biomass-Based Diesel (D4) RIN	0.0133**	-0.0319***	0.0487***	0.0440***	0.00533	0.0590***
	(0.00657)	(0.00600)	(0.0115)	(0.0115)	(0.00329)	(0.0160)
Other Advanced Biofuel (D5) RIN			-0.0997***	-0.0634***	-0.00783**	-0.0775***
			(0.0104)	(0.0115)	(0.00365)	(0.0164)
Conventional Biofuel (D6) RIN			0.00622***	0.0208***	0.00217	0.0162**
			(0.00233)	(0.00323)	(0.00138)	(0.00629)
West Texas Intermediate (WTI) Crude Oil		0.500***	0.372***	0.426***	0.0195	0.226***
		(0.0221)	(0.0252)	(0.0237)	(0.0119)	(0.0342)
Tax Credit Indicator	-0.0284***	-0.0230***	-0.0186***	-0.0232***	-0.000564	-0.0220**
	(0.00597)	(0.00434)	(0.00383)	(0.00364)	(0.00143)	(0.00858)
Ethanol Blend Wall Indicator	0.00888	-0.0241***	0.00313	-0.0776***	-0.00663	-0.0376
	(0.00619)	(0.00531)	(0.0124)	(0.0172)	(0.00611)	(0.0301)
Vehicle Miles Traveled (VMT)	-0.000135	6.60e-05	2.51e-05	0.000388***	-2.56e-05	2.75e-05
	(0.000163)	(0.000127)	(0.000133)	(0.000121)	(4.33e-05)	(0.000177)
D4 Blend Wall Interaction				-0.349***	-0.0100	-0.110***
				(0.0451)	(0.0182)	(0.0377)
D5 Blend Wall Interaction				0.198***	0.0104	0.100***
				(0.0453)	(0.0168)	(0.0345)
D6 Blend Wall Interaction				-0.00702	-0.00414	-0.0307**
				(0.00936)	(0.00308)	(0.0121)
Lagged Ultra-Low Sulfur Diesel (ULSD)					0.923***	
					(0.0146)	
Constant	1.147***	-1.174***	-0.614***	-0.873***	0.00757	0.0986
	(0.0391)	(0.106)	(0.115)	(0.102)	(0.0493)	(0.156)
Observations	669	669	669	669	665	669
Adjusted R^2	0.043	0.462	0.548	0.607	0.940	0.989

All price variables logged (e^x) including my dependent variable ULSD. Robust standard errors in parentheses. Statistical significance indicated by: *** p<0.01, ** p<0.05, * p<0.1

APPENDIX B: FIGURES

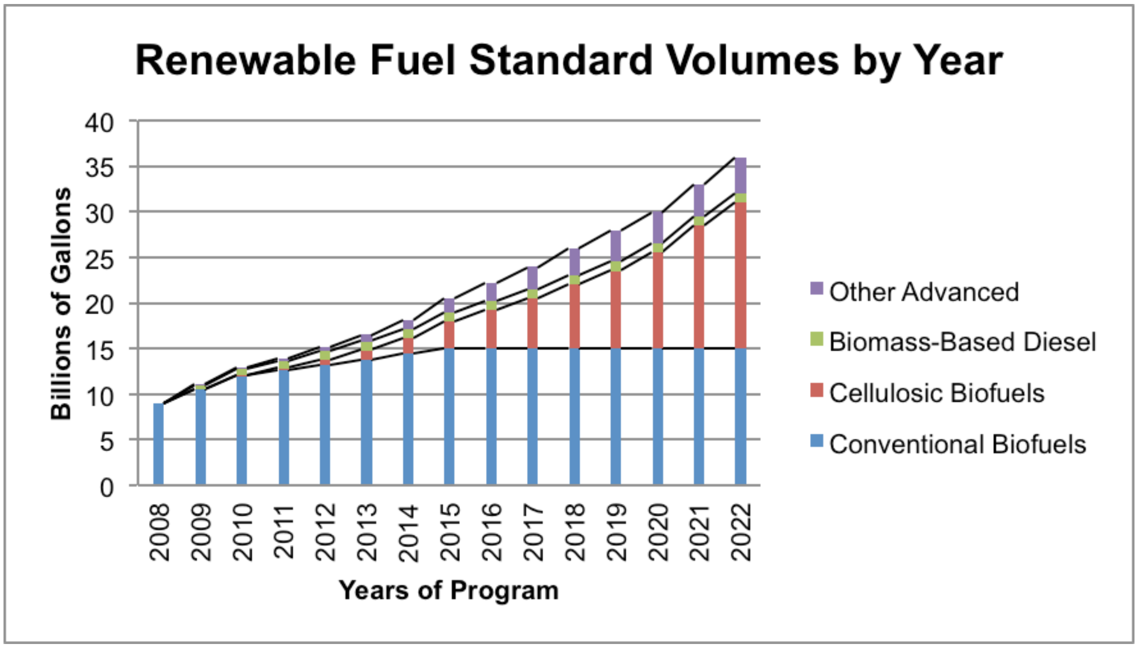

Figure 1: The Renewable Fuel Standard (RFS), as amended by the Energy Independence and Security Act (EISA) of 2007, mandates increasing volumes of conventional and advanced biofuels be blended into U.S. transportation fuel each year, reaching a total of 36 billion gallons in 2022. Towards the beginning of the program, most of the RFS consists of conventional biofuels or corn ethanol, reaching its maximum of 15 billion gallons in 2015. By the end of the program, the RFS consists mostly of advanced biofuels, including 16 billion gallons of cellulosic biofuels in 2022. **Source:** Gallons are all ethanol-equivalent and come from the statutory blending requirements as established in EISA.

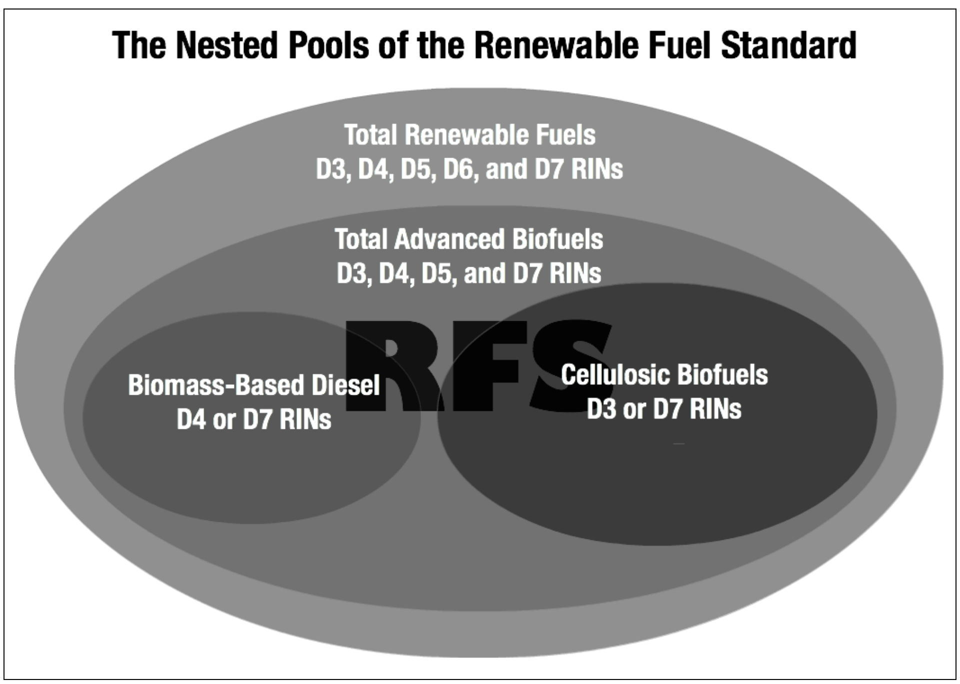

Figure 2: The RFS consists of four nested pools that give preferential treatment to fuels with greenhouse gas reductions of 50% or more off a 2005 baseline for gasoline. Corn ethanol (D6 RINs) can only fulfill the mandate for Total Renewable Fuels. Sugarcane ethanol (D5 RINs) can fulfill the mandate for Total Renewable Fuels and Total Advanced Biofuels. Biodiesel (D4 RINs) can fulfill the mandate for Biomass-Based Diesel, Total Advanced Biofuels, and Total Renewable Fuels. **Source:** Advanced Biofuels Association, Washington, D.C.

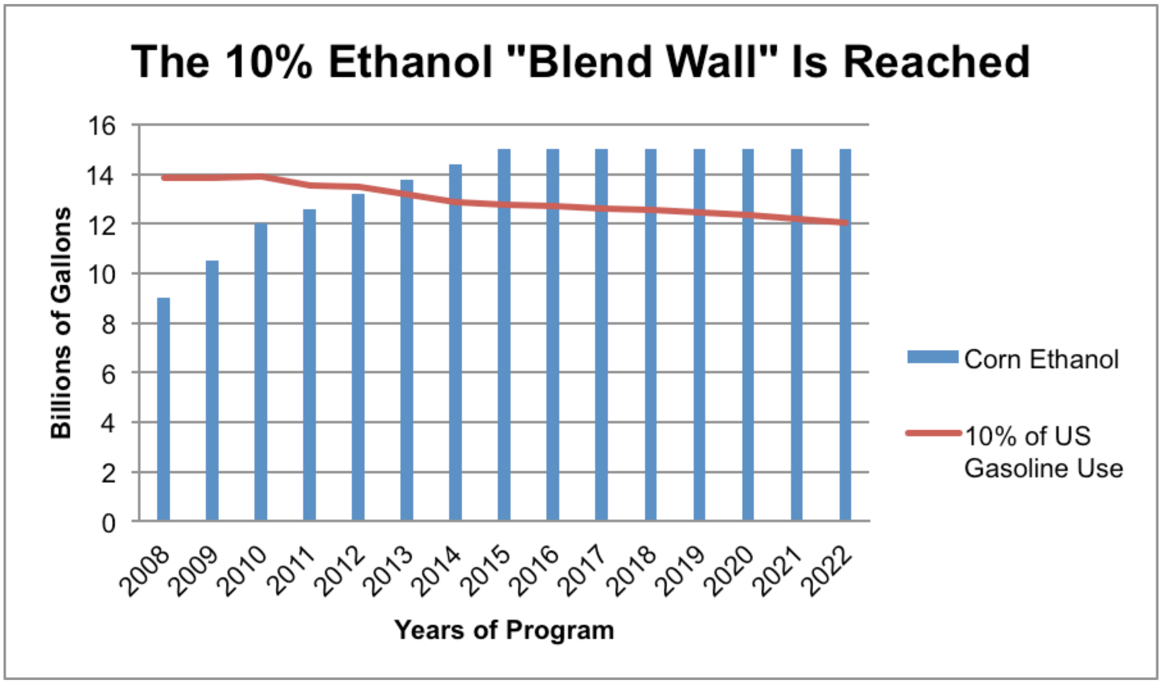

Figure 3: The 10% ethanol "blend wall" in motor gasoline is reached in 2013. The compliance gap, indicated by the red line passing below the tops of the blue bars, widens significantly by 2015. Reaching this blend limit coincided in 2013 with unprecedented spikes in corn ethanol RIN credit prices. **Sources:** Gallons of corn ethanol come from the statutory blending requirements as established in in the Energy Security and Independence Act (EISA) of 2007, and historical and projected data on U.S. gasoline consumption come from the U.S. Energy Information Administration's (EIA) *Annual Energy Outlook 2013 Early Release*.

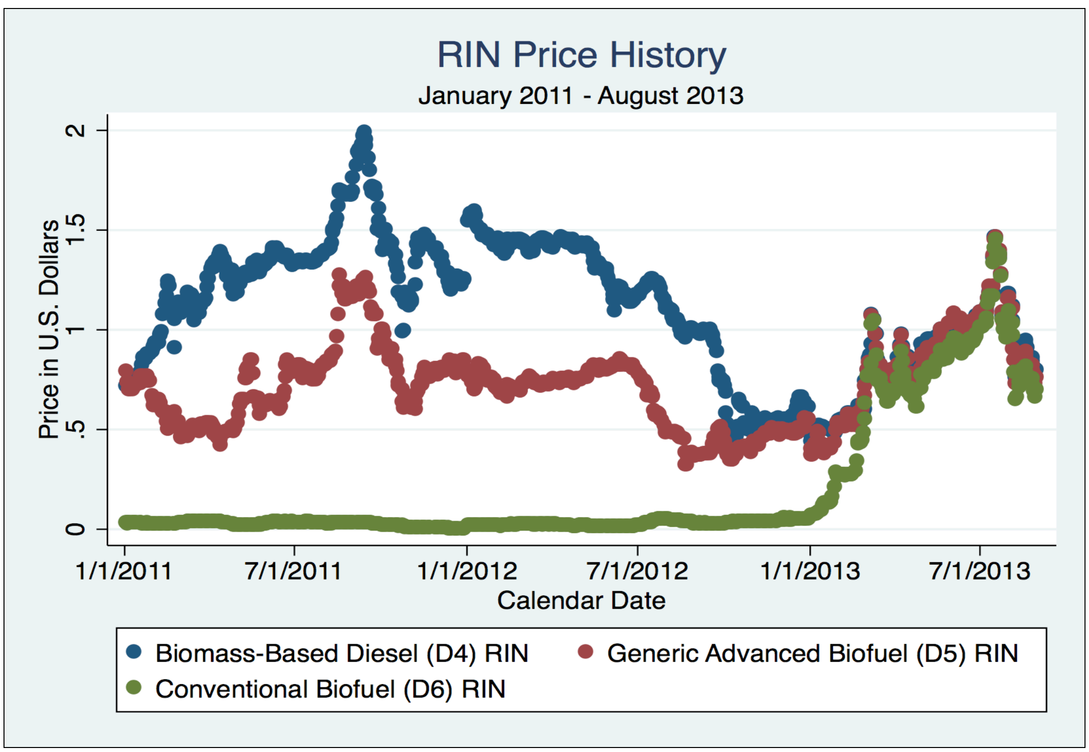

Figure 4: The price of biofuel compliance credits or Renewable Identification Numbers (RINs) has a volatile history. RINs became "RINsanity" and "RINdemonium" in 2013 when all prices climbed by more than $1.00 within a year that the RFS mandated a total of 16.55 billion RINs. **Sources:** Price information comes form the Oil Price Information Service (OPIS). Industry reaction comes from *A/C Trading Commodity Futures.*

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