MARKET EFFECTS AND WELFARE IMPACTS OF THE RENEWABLE FUEL STANDARD

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EXECUTIVE SUMMARY

This report presents the results of our analysis of the market effects and welfare impacts of the Renewable Fuel Standard under USDA Cooperative Agreement 58-0111-15-018.

The key objectives of the cooperative agreement are threefold: to develop a theoretical model of RIN price determination; to explain its relation to the various means of overcoming the blend wall; and to assess the impact of the EPA adjusting the annual RFS mandate requirements down since 2014.

To address these questions, we propose a partial equilibrium model of U.S. fuel markets capturing the joint compliance base and nested mandate structure of the RFS2 and simulate it using carefully calibrated demands for high-ethanol blends from the literature (Pouliot & Babcock (2014), Pouliot & Babcock (2016)). This approach allows us to evaluate the incidence of varying biofuels mandate levels taking into account the stringent demand constraints posed by the ethanol blend wall. Our findings can be categorized into (i) data driven insights about the severity of the blend wall constraint and the channels commonly used to overcome it; (ii) structural findings relating to the mechanism of the RFS2 such as the determination of RIN prices and an analysis of available compliance channels and their relative importance at varying mandate levels; and (iii) simulation results concerning the impact of the RFS2 on fuel market participants.

Three insights about the nature of the RFS2 are of particular interest: First, as summarized in Korting & Just (2017), we provide a new formula for the core value of RINs. The value of a RIN in equilibrium is shown to reflect the marginal cost of compensating the blender for employing one additional ethanol-equivalent unit of biofuel. This contrasts with existing research equating the price of RINs to the gap between ethanol supply and demand evaluated at the mandate level. In the same paper, we highlight four available compliance channels: an increase in the ethanol blend ratio in E10; increased E85 sales; higher biodiesel blending; and a reduction in the overall compliance base by supplying less petroleum

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gasoline and petroleum diesel to the U.S. market.[1] We discuss their activation and importance at varying mandate levels. Finally, simulation results reported in Korting, de Gorter and Just (2017) highlight that the independent effects of the nested mandate structure and the joint compliance base under the RFS2 effectively operate as a *dual link* between motor gasoline and diesel fuel markets.

Korting, de Gorter and Just (2017) summarizes our assessment of the welfare impacts of the RFS2. Surprisingly, we find that the cost of increasing biofuel mandates given a binding ethanol blend wall will fall disproportionately on diesel fuel consumers. We show that most of the burden on diesel fuel consumers can be directly attributed to the ethanol blend wall. We support this result by highlighting that (i) in a model without a blend wall, the effect of rising total renewable mandates is largely borne by motor gasoline consumers; and (ii) neither the more inelastic diesel fuel demand nor the effect of the biodiesel tax credit can explain the extent of the burden placed on diesel fuel consumers.

Our results underscore the importance of information campaigns targeted at FFV drivers as well as of E85 infrastructure projects at the pump and distribution level. The Renewable Fuel Standards were designed to be 'technology forcing', inducing blenders and refiners to provide adequate infrastructure to achieve mandate compliance. From this perspective, the EPA's decision to alleviate short-term pressure by cutting 2014-2016 mandate requirements was potentially self-defeating. On the other hand, diesel fuel consumer surplus losses are likely to have important general equilibrium ramifications: since heavy trucks and trains account for most of the diesel fuel consumption in the U.S., the increased cost of transportation will likely be passed on in the form of higher consumer price inflation. It is important to note that our analysis only addresses welfare effects in fuel markets; we do not evaluate the impact of the RFS on other stakeholders such as corn and soybean growers, livestock feeders, and automakers. Nor do we consider the economic value of the GHG benefits from using renewable fuels instead of petroleum.

It is therefore becoming increasingly clear that industry and policy makers need to find a joint way forward to keep the mandates both physically and economically feasible. The USDA's commitment of USD 100mn towards industry projects investing in additional E15 and E85 infrastructure under its Biofuel Infrastructure Partnership (BIP), requiring matching contributions from industry partners, may prove to be an important first step in that direction.[2]

Our results also highlight the importance of evaluating the incidence of the RFS in a holistic framework taking both ethanol and biodiesel into account. While ethanol-only models can add important intuition about the nature of blend mandates, they do not adequately capture the nuances of the burden share between consumer groups implied by the dual link generated by both the nested mandate structure and the joint compliance base under the RFS. Our model provides a convenient starting point to explore these interactions and to study the effects of additional market interventions such as the subsidized expansion of E85 capacity.

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[1] We discuss additional compliance mechanisms such as banked RINs and RINs from non-transportation biofuels in the empirical section of this report. Our model abstracts away from the multi-period setting under uncertainty for tractability.

[2] https://www.fsa.usda.gov/programs-and-services/energy-programs/index

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NOTATION AND ABBREVIATIONS

A	Advanced biofuels mandate category
BBD	Biomass-based diesel
D	Diesel (from fossil fuels)
DF	Diesel fuel (final blend of biodiesel or renewable diesel and fossil-based diesel)
ϵ	Elasticity parameter
E	Ethanol
E*	Ethanol consumption forecast
E0	Motor gasoline blend containing no ethanol
E10	Motor gasoline blend containing up to 10% ethanol
E15	Motor gasoline blend containing up to 15% ethanol
E85	Motor gasoline blend containing up to 85% ethanol
EISA	Energy Independence and Security Act
EPA	Environmental Protection Agency
EPAct	Energy Policy Act
EV	Equivalence value (used to convert biofuel quantities into their ethanol equivalent on an energy basis; for example, biodiesel has an EV of 1.5)
FFV	Flexible-fuel vehicle
G	Gasoline (from fossil fuels)
G*	Gasoline consumption forecast
GHG	Greenhouse gas
κ	Percentage blend mandate
LHS	Left hand side
MG	Motor gasoline (final blend of ethanol and fossil-based gasoline)
p	Price
q	Quantity
RFS	Renewable Fuel Standard
RHS	Right hand side
RIN	Renewable Identification Number
RVO	Renewable Volume Obligation
TBD	To be determined
TR	Total renewable mandate category
USDA	U.S. Department of Agriculture

Background

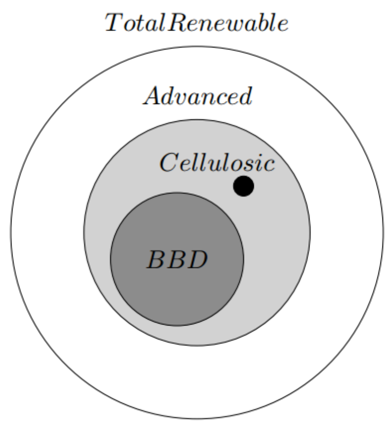
The Renewable Fuel Standards of 2005 (RFS1) and 2007 (RFS2), passed as part of the Energy Policy Act (EPAct) and the Energy Independence and Security Act (EISA) respectively, mandate the use of specific amounts of biofuels in the transportation sector. The RFS2sets a series of annual volumetric targets, and the EPA is responsible for setting regulations that will ensue that these volumes are used in U.S. supplies of gasoline and diesel fuel. The RFS rulemaking is an annual process; EPA's goal is to have standards in place by November 30 of the preceding year. Part of the process is an evaluation of the availability of renewable fuels; if the targeted volumes are not expected to be available, EPA can reduce the volumes to conform to the volumes that are likely to be available. EPA subsequently converts the renewable volume requirements into percentage blend mandates for the year ahead using gasoline and diesel consumption levels forecasted by the Energy Information Administration.

Each obligated party's renewable volume obligation (RVO) is calculated by applying the percentage blend mandate requirements to their total imports or production of the petroleum-derived portions of gasoline and diesel. The sum of gasoline and diesel therefore represents the *joint compliance base* of the mandates under the RFS2. As noted in the 2010 final rule, the EPA considered maintaining separate standards for gasoline and diesel, but deemed this alternative mandate structure unnecessarily more complex to implement (EPA (2010), p. 14716). Blend mandates are thus given by the fraction of volumetric mandates divided by the joint compliance base.

The obligated parties are refiners and importers of fossil fuels who often do not directly control the final blend of consumer motor fuels. As noted in the 2010 final rule, this choice of obligated party was based on a desire to minimize the number of obligated parties (EPA (2010), p. 14722). Compliance is monitored through financial instruments called Renewable Identification Numbers (RINs) which represent one ethanol gallon-equivalent unit of biofuel blended. Each gallon of ethanol produced by an acceptable process receives one RIN; other biofuels receive RINs in proportion to the energy content relative to ethanol. For example, one gallon of biodiesel has 1.5 times the energy of a gallon of ethanol, so each gallon of biodiesel generates 1.5 RINs. RINs are generated at production or import of a biofuel, and are sold along with the physical gallons until the biofuel is blended with petroleum fuel. At this point, the RINs are separated from the gallons of biofuels. Separated RINs may be turned in to EPA to satisfy an RVO, retained for future compliance, or sold to other parties. RINs are traded on the EPA Moderated Transaction System (EMTS), an electronic platform built by EPA specifically for this purpose. The Oil Price Information Service (OPIS) and other commercial data providers track and report RIN price averages for every business day.
The RFS2 is designed to be 'technology forcing', governing both the pace and the intensity of the shift to more environmentally friendly fuels using a nested mandate structure. For this reason, four nested categories were established under the RFS2: both cellulosic biofuels and biomass-based diesel (BBD) are nested under the advanced biofuels category, which requires a greenhouse gas emissions (GHG) reduction of at least 50% compared to the fossil fuel being replaced; the advanced biofuels mandate in turn is part of the total renewable fuels category (TR) which requires GHG savings of at least 20%. The portion of the RFS that requires a 20% reduction in GHG is filled mainly by ethanol produced from corn starch. Each category also has a specific RIN type: D3 for cellulosic biofuels, D4 for biomass-based diesel, D5 for other advanced biofuels, and D6 for renewable fuel, which is also known as conventional biofuel. There is also a D7 RIN type for cellulosic diesel, which can be used to meet either the cellulosic biofuels obligation or the biomass-based diesel obligation (but not both simultaneously).

Figure 1 provides a graphical representation of this nested structure while Table 1 highlights the proposed evolution of RFS2 mandates by category.

FIGURE 1: NESTED MANDATE STRUCTURE UNDER THE RFS2



This structure allows for strategic overage from nested categories, if desirable, based on the relative cost of compliance. For example, additional units of biomass-based biodiesel (BBD) can be used to meet the advanced and total renewable mandate requirement.[3] Nesting thus enables the use of more efficient biofuels in GHG terms towards compliance with the larger mandate.

Note that the RFS2 does not impose a specific ethanol mandate: in an extreme scenario, D3 and D4 RINs could be used to meet the entire total renewable mandate. As a result, both increased ethanol blending and increased biodiesel blending can help to overcome the ethanol blend wall.

[3] Biodiesel not meeting the D4 GHG reduction threshold, but providing sufficient savings compared to the total renewable level to earn D6 RINs instead can also be used to comply with the total renewable mandate, but are omitted from our analysis for simplicity. According to the EPA Moderated Transaction System (EMTS), 252mn D6 RINs were generated from biodiesel or renewable diesel in 2013 (https://www.epa.gov/fuels-registration-reporting-and-compliance-help/2013-renewable-fuel-standard-data)

TABLE 1: RFS2 MANDATES BY CATEGORY

Mandate Category	RIN Label	2015 Volumetric Mandate (bn GAL)	2015 Percentage Mandate	2022 Volumetric Mandate (bn GAL)
Cellulosic biofuel	D3	0.123	0.069%	16
Biomass-based diesel	D4	1.73	1.49%	TBD
Advanced biofuel	D5	2.88	1.62%	21
Renewable fuel	D6	16.93	9.52%	36

Note: Volumetric mandates are shown in billion gallons of ethanol-equivalent except BBD which was originally introduced as a diesel standard and is therefore represented on a biodiesel-equivalent energy basis under the RFS. All percentage blend mandates, including D4, are shown in ethanol-equivalent terms.
Source: EPA (2010) and EPA (2015b)

This report is concerned with the market and welfare outcomes of increasing blend mandate requirements under the current structure of the RFS2, as well as with the structural implications of the chosen policy approach.

Empirical Assessment of the Ethanol Blend Wall Constraint

This section explores the severity of the blend wall in practice and discusses recent revisions to proposed mandate requirements. We propose a new measure called the ***ethanol RIN gap*** to capture the extent of the potential shortfall of D6 ethanol RINs as a result of the blend wall. We also highlight the many channels commonly employed in practice in order to meet the ethanol RIN gap.

Table 2 shows the evolution of the percentage standards over time.

Table 2: Evolution of EPA RFS2 Percentage Standards over Time

	Cellulosic	BBD	Total Advanced	Total RFS
2010	0.004%	1.1%	0.61%	8.25%
2011	0.003%	0.69%	0.78%	8.01%
2012	0.006%	0.91%	1.21%	9.23%
2013	0.004%	1.13%	1.62%	9.74%
2014	0.019%	1.41%	1.51%	9.19%
2015	0.069%	1.49%	1.62%	9.52%
2016	0.128%	1.59%	2.01%	10.1%
2017	0.173%	1.67%	2.22%	10.44%

Several structural aspects of the RFS2 make it challenging to assess at which total RFS percentage mandate requirement the ethanol blend wall becomes binding:

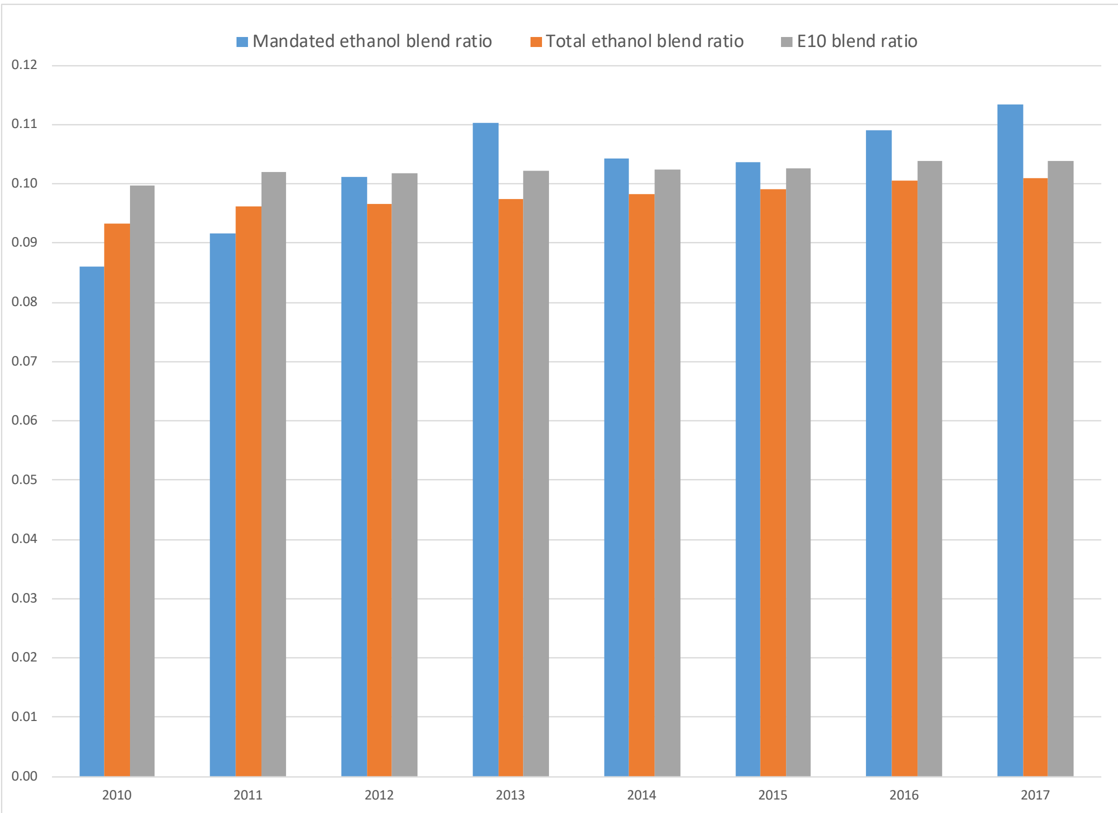
- As mentioned previously, the RFS2 does not impose any explicit ethanol mandates. Instead, ethanol from cellulosic sources (including corn fiber) can be used to generate D3 RINs; most sugarcane ethanol qualifies under the advanced mandate requirement; and corn starch ethanol falls under the residual requirement for total renewable fuels in excess of the advanced mandate, often referred to as conventional biofuels.
- The ethanol blend wall relates to the relative ethanol content in motor gasoline, measured as $\frac{E}{E+G}$. The percentage mandates on the other hand represent biofuel requirements as a fraction of the joint compliance base, e.g. $\frac{RVO}{G+D}$. Since the quantities of fossil-based fuels and biofuels are all endogenous due to their simultaneous determination in equilibrium, this difference in denominator makes a comparison between percentage blend mandate levels and the effective ethanol blend in motor gasoline challenging.

In order to make mandate requirements comparable to the ethanol blend wall, we define the ***implied ethanol blend mandate ratio*** α as the ratio of the implied mandated quantity of ethanol in the total forecast fuel blend, that is, $\alpha = E^M/(E^* + G^*)$ where E^M is defined as the total mandated volume less the BBD volume requirement in ethanol-equivalent terms (i.e. multiplied by its equivalence value, EV) and E^* and G^* are forecast ethanol and gasoline consumption, respectively.[4] These latter data are presented in the

[4] Note that this definition assumes no BBD overage in excess of the mandate level, i.e. all of the residual advanced and total renewable mandate are met with ethanol. This is not the case in practice as shown in Table 4. However, the per gallon cost of BBD relative to diesel is much higher than the ethanol price

EPA's annual rule setting. It should be noted that the implied ethanol mandate E^M does not necessarily equal forecast ethanol consumption E^* presented in the EPA's annual rulemaking standards. Furthermore, forecast ethanol and gasoline consumption $E^* + G^*$ are in volume terms, not adjusted for differential miles per gallon achieved per fuel. It also means that actual ethanol consumption E in a given year is not necessarily equal to E^M because (a) actual motor gasoline fuel consumption $E + G$ can be greater or less than the forecast value $E^* + G^*$; and (b) blenders have incentives (for various reasons) to over- or under-blend ethanol relative to the overall (implied) mandated ethanol blend ratio α. Annual data on the implied ethanol blend ratio mandated versus the actual ethanol blend ratio is shown in Figure 2 (the exact numbers are given in the first two rows of Table 4 discussed later).

FIGURE 2: ETHANOL BLEND RATIOS



Source: Calculated based on EPA EISA RFS Mandates, EIA consumption forecasts and realized consumption figures from the Short Term Energy Outlook (STEO)

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relative to the gasoline price indicating that the volumes shown in Table 4 are used to overcome the ethanol blend wall.

As Figure 2 shows, through 2011, the implied mandated ethanol blend ratio α (blue column in the graph) is lower than the realized ethanol blend ratio $E/(E+G)$ (orange column in the graph) where E is the realized ethanol consumption and G is the realized gasoline consumption. There can be several reasons for this, including the possibility of storing RINs for future use. But the more important event is that beginning in 2012, the mandated ratio exceeded the realized ratio. The realized blend ratio, however, was approximately 0.96 in both 2011 and 2012. This indicates that the blend wall is actually 9.6% rather than 10% as commonly assumed. Ethanol blending up to this point does not requireextra incentives to induce lower E0 or higher E85 But D6 RIN prices did not react until January 2013 which was a watershed year for several reasons. While not the first year where the mandated blend ratio exceeded the realized ratio, the market reacted very quickly and strongly in 2013 as the RIN deficit was over 1.7 billion (see Table 3). The large gap in the (implied) mandated versus realized ethanol blend ratio in 2013 dropped significantly in 2014 and 2015 as the EPA reduced the implied ethanol mandates in these years from those specified in the 2007 EISA. In fact, the 2014 realized ratio was less than the mandated ratio again while the rations were roughly equal in 2015, the year for which no formal mandate was proposed. Instead, the December 14, 2015 final ruling used projected realized values to set the mandate.

As mentioned previously, in addition to the nested structure of the RFS, the EPA "generalized" the RFS beginning in 2010 by introducing a joint compliance base: the BBD and implied ethanol standards are now set relative to the total forecast gasoline and diesel consumption jointly. Beginning in 2010, the percentage mandate ratio κ is thus calculated as the mandated volume for each biofuel mandate as specified in the 2007 EISA divided by the sum of forecast gasoline G^* and diesel D^* consumption. The BBD mandate is specified in actual gallons of BBD consumed but has an *equivalence value* (EV) towards the advanced mandate and total renewable component of the RFS of 1.5 times BBD consumption.[5] Table 2 presents the mandated ratios since 2010.

Recall that the RFS2 does not impose explicit ethanol mandates, although a cap exists at 15 billion gallons for conventional biofuel, which is predominantly supplied by corn starch ethanol. To gauge the severity of the ethanol blend wall constraint for a given set of mandate requirements, we calculate the ethanol RIN gap; the larger the RIN gap, the more "severe" the mandate. The ethanol RIN gap is the difference between how much ethanol can be used to meet the conventional biofuel portion of the RFS and how much ethanol can be blended if all gasoline is E10; it is defined in Equation 1:

EQUATION 1: ETHANOL RIN GAP

$$\begin{gathered}\boldsymbol{Ethanol\ RIN\ Gap\ (bn\ GAL)} \equiv \\ \boldsymbol{Implied\ Ethanol\ Requirement\ (assuming\ no\ overage)} \\ \boldsymbol{-\ Realized\ Ethanol\ Consumption}\end{gathered}$$

[5] The EPA uses an EV of 1.5 when setting the standards, which corresponds to the EV of biodiesel. At RIN retirement, each unit of biofuel obtains an equivalence value calculated based on its relative renewable content and its energy content as specified in paragraph 40 CFR 80.1415. Blenders or refiners can therefore obtain EVs of 1.6 and 1.7 (e.g., renewable diesel) in practice. The actual weighted average EV for compliance currently is 1.554.

Here, the required ethanol consumption can be calculated (pre-2010) with the nonjoint compliance base as:

EQUATION 2: IMPLIED ETHANOL REQUIREMENT (NONJOINT COMPLIANCE BASE)

$$\boldsymbol{Implied\ Ethanol\ Requirement\ (Nonjoint\ Compliance\ Base)}$$

$$\equiv \frac{\boldsymbol{RVO_{TR} - 1.5\ RVO_{BBD}}}{\boldsymbol{Forecast\ MG\ Consumption}} * \boldsymbol{Realized\ MG\ Consumption}$$

Since 2010, we need to rely on volumetric rather than percentage mandate requirements, since percentage standards provided by the EPA are calculated using the joint compliance base.

EQUATION 3: IMPLIED ETHANOL REQUIREMENT (JOINT COMPLIANCE BASE)

$$\boldsymbol{Implied\ Ethanol\ Requirement\ (Joint\ Compliance\ Base)}$$

$$\equiv (\boldsymbol{\kappa_{TR}} - \boldsymbol{\kappa_{BBD}}) * (\boldsymbol{Realized\ G} + \boldsymbol{Realized\ D})$$

The calculation of the implied ethanol requirement under the joint compliance base relies directly on the percentage blend mandates provided.

The calculations for the BBD RIN gap follow a similar logic, but are somewhat complicated by the existence of biodiesel and renewable diesel not qualifying under the D4 RIN category, and earning D5 or D6 RINs instead. The BBD requirement is simply given by[6]

EQUATION 4: BBD REQUIREMENT (JOINT COMPLIANCE BASE)

$$\boldsymbol{BBD\ Requirement\ (Joint\ Compliance\ Base)}$$

$$\equiv \boldsymbol{\kappa_{BBD}} * (\boldsymbol{Realized\ G} + \boldsymbol{Realized\ D})$$

However, the BBD RIN gap is given by

EQUATION 5: BBD RIN GAP

$$\boldsymbol{BBD\ RIN\ Gap\ (bn\ GAL)} \equiv$$

$$\boldsymbol{BBD\ Requirement - Realized\ Biodiesel\ and\ Renewable\ Diesel\ Consumption\ qualifying\ under\ the\ BBD\ Mandate\ Category}$$

[6] Note that the RFS2 imposes an actual requirement for BBD, while the ethanol requirement was implied based on the difference between total renewable and BBD mandates.

i.e., we need to adjust realized consumption numbers to back out D5 and D6 biodiesel and renewable diesel and only capture the volumes generating D4 RINs that count towards the BBD mandate requirement.

The EPA's decision in 2010 to have a joint compliance base changed the economics of the RFS because although the mandated *volume* of BBD and the implied volume of ethanol did not change, the *percentage standards* are now calculated relative to a different base. This implies that the number of required RINs since 2010 is different as it now depends on realized gasoline <u>plus</u> diesel consumption. From year to year, the trends in and shocks to realized diesel and gasoline consumption differ, thereby affecting the number of required RINs to fill each mandate.

To illustrate this, consider the data presented in Table 3. Rows 1 and 2 highlight that realized ethanol volumes do not need to exactly equal implied mandated volumes for two reasons: (i) BBDin excess of the mandate and biodiesel or renewable diesel that receive D5 or D6 RINs instead of D4 can be counted towards the total advanced or total renewable mandate category (we will show later there are non-transportation biofuels that also are counted towards the non-BBD mandate); and (ii) the EPA converts mandated volumes into percentage standards based on *forecast* fuel consumption. Ethanol consumption that meets the percentage mandate requirements on the other hand is based on realized gasoline plus diesel consumption which can differ from forecast gasoline plus diesel consumption.

Row 3 in Table 3 provides information on the (implied) *required* amount of ethanol to be consumed, given the percentage standard and realized consumption of gasoline (under the single compliance regime up to 2010 where required ethanol consumption was based on realized gasoline consumption in that year only) and the joint compliance base (where required ethanol consumption also depends on realized diesel consumption since 2010).

From this, we derive the ethanol RIN gap shown in row 4 and defined as the required amount of ethanol to be consumed (Row 3) minus the realized consumption of ethanol consumed (Row 1). A positive ethanol RIN gap implies that other sources of RINs are needed to meet the implied ethanol mandate. How obligated parties fulfilled their obligations in practice is presented in greater detail in Table 4 below.

Table 3 shows that there is a significant ethanol RIN gap for 2015 and 2016 and projected RIN gap for 2017, but these gaps are not nearly as high as the one seen in 2013. Note also that under the joint compliance base for ethanol, the RIN gap is significantly lower after 2013.

The impacts of the reversal in EPA policy in increasing mandates after initially reducing it for 2014 can be alleviated to some extent by the increase in forecast motor gasoline and diesel consumption for 2016 and 2017 (in mid-2015, forecast motor gasoline was 5 billion gallons lower than the 143 billion gallons forecast for 2016 in the September 2016 EIA forecast).[7] Likewise, forecast diesel consumption was 45.74, 55.01 and 53.21 billion gallons for 2014, 2015 and 2016, respectively while realized diesel consumption was 10 billion gallons lower than realized diesel consumption in 2014. This gives the EPA some wiggle room to reduce the ethanol RIN gap and not reduce the overall RFS as much. Nevertheless, annual outcomes depend critically on whether realized fuel consumption is lower or higher relative to the forecast prior to EPA finalizing the annual percentage standards.

Rows 6-9 in Table 3 provide analogous data for BBD.

The options to fill the ethanol RIN gap include using banked RINs generated in the previous year, borrowing RINs from the following year, increasing E85 sales, reducing E0 sales, buying D4 RINs from the over-blending of biodiesel, or using D6 RINs from new BBD production that did not meet the 50 percent GHG reduction threshold. In addition, Table 4 shows that the ethanol RIN gap was also filled using non-transportation RINs. The increase in E85 sales had a small but indirect effect on the ethanol RIN gap and its impact shows little growth so far. This will likely have to change in the future. D6 and D5 BBD consumption that does not count towards BBD mandate but still apply EV factor towards conventional (total RFS residual) and residual Advanced biofuel mandates.

Table 4 summarizes the basic ways to reduce the ethanol RIN Gap: RINs from BBD overage, D5 and D6 BBD RINs, and RINs from non-fossil and non-transportation fuel consumption (natural gas and home heating oil).[8] Data for these variables are presented in rows 3-5 of Table 4.

Rows 6-8 provide data on RINs generated form reduced E0 consumption, increased E85 consumption and RINs form a higher E10 blend.

The last four rows in Table 5 describe the implications of EPA reforms of the 2007 EISA on implied ethanol volumes mandated. Row 9 shows the increase in the BBD mandate, which with the EV, displaces ethanol, *ceteris paribus*. Row 10 shows the reduction in the advanced mandate level which, *ceteris paribus*, also results in less implied ethanol mandated. Row 11 gives the total 'squeeze" on ethanol while the final row gives the squeeze on the implied corn-ethanol mandate. Clearly, the issue of the ethanol blend wall would have been quite different if the EPA did not squeeze corn-ethanol mandate, and an even greater issue if cellulosic ethanol production took off as originally envisioned by policy makers in the 2007 EISA.

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[7] Consumption depends on consumer preferences, improved fuel mileage, crude oil prices, growth in GDP and any adjustments the EPA makes on mandated volumes of biofuels.

[8] Jet fuel is part of BBD D4 RINs.

Table 3: Empirical Ethanol and BBD RIN Gap (bn gal)

		2010	2011	2012	2013	2014	2015	2016	2017[f]
1	**Actual ethanol consumption**		12.89	12.85	13.21	13.44	13.94	14.18	14.26
2	**Mandated ethanol consumption**[2]		12.75	13.70	14.63	13.29	13.75	15.26	15.80
3	**Required ethanol consumption**[3]								
	(a) Single compliance base	11.96	12.30	13.46	14.93	13.70	13.98	15.59	15.91
	(b) Joint compliance base				15.0	13.83	14.52	15.39	15.5
4	**Ethanol RIN Gap**								
	(a) Single compliance base	-1.01	-0.59	0.62	1.71	0.82	0.63	1.23	1.79
	(b) Joint compliance base				1.78	0.38	0.57	1.02	1.58
6	**Actual BBD consumption**		0.87	0.92	1.61	1.55	1.67	2.13	2.27
7	**Mandated BBD consumption**		0.80	1	1.28	1.28	1.70	1.90	2.00
8	**Required BBD consumption**[3]								
	(a) Single compliance base	0.73	0.88	1.04	1.32	1.52	1.67	1.87	2.06
	(b) Joint compliance base		1.21	1.56	1.92	2.33	2.68	2.85	3.05
9	**BBD RIN Gap**								
	(a) Single compliance base	0.404	0.008	0.116	-0.277	0.076	0.115	-0.404	-0.275
	(b) Joint compliance base		-0.081	0.194	-0.196	0.452	0.563	-0.183	-0.221

[2] Implied ethanol mandate assuming BBD mandate just exactly filled.

[3] Given the mandated percentage standard and actual gasoline/diesel consumption in that year.

[f] Forecast

Table 4: How the Ethanol Blend Wall is Being Breached in Practice (bn gal)

		2011	2012	2013	2014	2015	2016	2017
1	Implied mandated ethanol blend ratio	0.0917	0.1012	0.1102	0.1043	0.1036	0.1090	0.1134
2	Actual ethanol blend ratio	0.0961	0.0966	0.09751	0.0983	0.0994	0.1004	0.1009
	Potential sources of RINs to fill Ethanol RIN Gap:							
3	RINs from BBD mandate overage[1]	0.1223	-0.2935	0.3022	-0.7020	-0.8750	0.2842	0.3440
4	D5 and D6 BBD RINs	0.0335	0.0217	0.3217	0.3518	0.461	0.459	0.36
5	Non-transportation biofuel[2]	0.0062	0.0002	0	0.0376	0.1409	0.19010	0.128
	RINs from change in mix of gasoline consumed:							
6	RINs from reduction in E0[3]				0.072	0.051		
7	RINs from year to year increase in E85 consumption	0.0212	0.0031	0.0143	0.0128	0.0095	0.0171	0.0707
8	RINs from increased ethanol blending in E10 (excl. Δ E0)[4]		(0.0099)	0.0378	0.0251	0.0570	0.060	
	RINs from EPA reforms of 2007 EISA							
9	Increase in BBD mandate (displaces ethanol)	0	0	0.4324	0.435	1.1335	1.395	
10	Decrease in Advanced mandate (less ethanol)	0	0	0	1.550	2.600	3.640	
11	Total squeeze on ethanol	0	0	0.43	1.99	3.73	5.04	
12	Squeeze on non-cellulosic ethanol	0	(0.49)	(0.55)	0.25	0.86	0.99	

[1] We assume that these D4 and D7 RINs (in 2013 and 2016) were not used in place of D5 and D6 RINs to overcome the ethanol blend wall – they are likely banked for future use instead as D4 RIN prices exceeded D6 RIN prices.

[2] These do not include D4 or D7 BBD RINs so non-transportation biofuel RINs (natural gas and home heating oil) help overcome the ethanol blend wall.

[3] Obtained from special EIA study https://www.eia.gov/todayinenergy/detail.php?id=26092

[4] The E10 blend ratio as defined here will continue to increase beyond 0.10 because of higher E15 sales and some blenders blending up to 10.40 percent ethanol in the motor gasoline fuel mix. Fuel ethanol is denatured with a small volume of gasoline-like material, so a blend of slightly more than 10 percent denatured ethanol may contain only 10 percent pure ethanol.

The sharp rise in D6 RIN prices in 2013 was followed by domestic biofuel policy flux from 2014 onwards. The EPA proposed a 2.94 billion gallons reduction in the total volume of mandated renewable fuels as stated in the 2007 Energy Independence and Security Act (EISA) for 2014. This proposal was made in response to two developments: (i) the cellulosic mandate was reduced because growth in supply at "reasonable" prices was deemed lower than anticipated; and (ii) the implied mandated ethanol volumes in excess of the blend wall were deemed too high in 2013 (see the extraordinarily high ethanol RIN gap in Table 3). These two factors were assumed to have caused D6 RIN prices to soar in early 2013.[9]

After an 18-month delay, on June 10, 2015, the EPA re-proposed RVO levels for 2014 and added proposed volumes for 2015 and 2016, as well as the BBD volume for 2017 (EPA, 2015b). This announcement implied mandated volumes for 2015 and 2016 above 2014 levels, but still limited the implied corn ethanol mandate. The multi-year rule that EPA proposed in June 2015 generated over 35,000 comments and continuing lawsuits against the EPA on both sides of the argument. The EPA finalized the rule for 2014, 2015 and 2016 on December 14 2015, with an increase in mandated volumes (see Table 5 below).

TABLE 5: PROPOSED VERSUS FINAL VOLUMES OF MANDATED BIOFUELS IN 2015 BY THE EPA

	Proposed June 10, 2015			**Final December 14, 2015**		
	2014	2015	2016	2014	2015	2016
Cellulosic biofuels (mn gal)	33	106	206	33	123	230
Biomass-based diesel (bn gal)	1.63	1.70	1.80	1.63	1.70	1.90
Advanced biofuel (bn gal)	2.68	2.90	3.40	2.67	2.88	3.61
Renewable fuel (bn gal)	15.93	16.30	17.4	16.28	16.93	18.11

Three numbers are highlighted for the 2016 proposed and final rulings in Table 5: the final BBD mandate increased by 100 million gallons compared to the June proposal, the advanced mandate increased by 210 million gallons, and the total renewable mandate category increased 710 million gallons (a 4 percent increase from that proposed six months earlier). In response to these changes, D6 RIN prices doubled in December 2015 (see Figure 3).

Why would an unexpected change in the proposed standards of such seemingly modest magnitudes have such a big impact on RIN prices? This report seeks to shed light on the fuel market dynamics given the ethanol blend wall by providing detailed simulation results for a partial equilibrium model capturing the most importance policy nuances of the RFS. There has been much controversy since the EPA's initial rule proposed in November 2013 for the year 2014 deviated from the volumes of mandated renewable fuels

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[9] This begs the question what would have happened if cellulosic ethanol production had taken off as policymakers expected in crafting the 2007 EISA. The EPA has reduced the cellulosic mandate each year, with a cut of almost 5.5 billion gallons for 2017. Clearly, this additional volume would have exacerbated the effect of the ethanol blend wall.

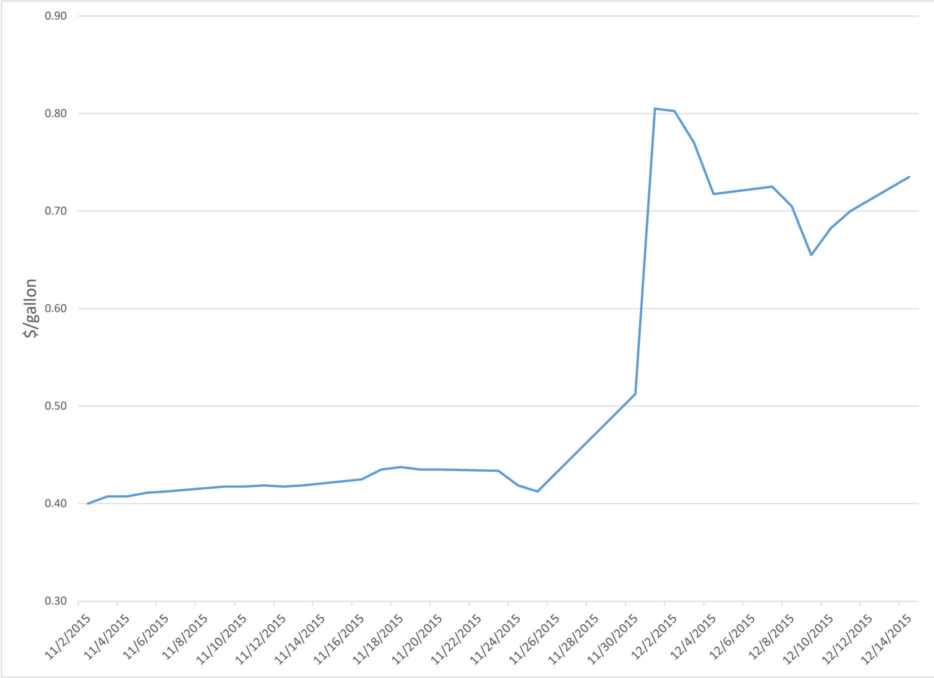
as stated in the 2007 Energy Independence and Security Act (EISA).[10] This was the first time the EPA deviated from the 2007 EISA statutes, due to concerns about the ability of the gasoline market to absorb the required volumes of ethanol (see Figure 4). As we show above, it is not straightforward to show when the ethanol blend wall becomes binding and how to measure the severity of the blend wall constraint. We therefore propose the notion of the ethanol RIN gap in order to empirically assess the difficulty in complying with implied ethanol mandates.

The analysis above highlights the significant challenges posed by the ethanol blend wall, which has become more severe over time. The next sections study the effects of the RFS on welfare and market outcomes in the simplified context of a static, one-period partial equilibrium model of U.S. fuel markets. Due to the complexity introduced by the variety of compliance options and the small numbers of D3, D5, and D7 RINs, we focus only on the interplay between D4 and D6 RINs. This set-up contains sufficient richness to evaluate the role of RIN prices and the economics of basic channels to overcome the blend wall, but is also tractable enough to provide a meaningful analytical formula for the price of RINs.

We find that diesel fuel consumers carry most of the economic burden caused by the ethanol blend wall, and provide a detailed explanation for this effect.

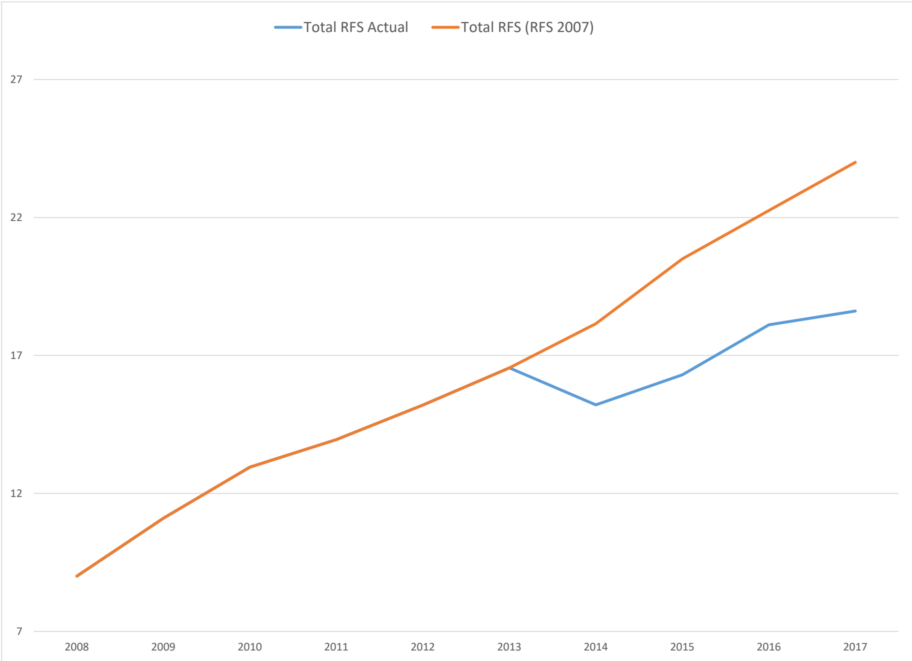
[10] The November 2013 proposed standards for 2014 were not officially adopted until June 10, 2015.

FIGURE 3: DAILY D6 RIN PRICES, NOV 2, 2015 - DEC 15, 2015 (USD)



Source: OPIS

FIGURE 4: HOW THE EPA DEVIATED FROM THE 2007 EISA BEGINNING IN 2014 (BN GAL)



Source: EPA Renewable Fuel Standards

STRUCTURAL FINDINGS REGARDING IMPACTS OF THE RFS DESIGN

We propose a short-term model of U.S. biofuels markets which explicitly captures the rigidities imposed by demand side infrastructure constraints. However, unlike most existing research, we model the creation of RIN prices more directly by allowing blenders and refiners to choose the quantity of RINs endogenously, and to then trade RINs between each other subject to a market clearing constraint. We also capture the nested structure of the U.S. biofuels mandate by explicitly modeling the biodiesel space and allowing for strategic overage of biodiesel RINs to meet the total renewable mandate.

Generally, existing models of RIN prices and the RFS2 can be differentiated along four dimensions: (i) short vs. long term approaches (e.g. considering the blend wall or abstracting away from current infrastructure constraints) (ii) link to agricultural markets and trade vs. closed economy, fuel-only models (iii) nesting vs. ethanol only and (iv) static vs dynamic settings. To obtain a parsimonious yet meaningful representation of the core value of RIN prices, and to study all available channels of mandate compliance, we have chosen a static, closed economy model considering only fuels and focusing exclusively on D4 and D6 RINs, but taking the nested mandate structure and short term infrastructure constraints into account. Our model is described in detail in Appendix A.

RESULT 1: THE FOUR COMPLIANCE CHANNELS AVAILABLE UNDER THE RFS2

Using a sequence of simulation results at changing mandate levels, we establish the existence of four distinct channels for mandate compliance under our simplified representation of the RFS2:

1. Increasing the blend ratio of ethanol in E10 (up to the legal limit of 10%)
2. Increasing E85 sales
3. Increasing the biodiesel share in diesel fuel
4. Decreasing the overall compliance base by selling less diesel fuel and/or motor gasoline

The first two compliance channels rely on increased ethanol blend ratios in motor gasoline (which could also be viewed as a decrease in E0 sales). The third channel makes use of the nested mandate structure, calling on RINs generated through biodiesel overage to comply with the total renewable mandate. To illustrate how the fourth compliance channel operates, consider an economy in which only motor gasoline is sold (i.e. there is no diesel fuel market), and the maximum E85 demand by FFV drivers is fixed at 1 bn gal. A mandate level of $\kappa_{TR} = 11.\bar{1}\%$ in this economy implies an ethanol blend ratio of 10%.[11] i.e. a blend ratio just at the blend wall. In this case, any amount of motor gasoline sales would be feasible under the mandate. If the mandate was raised to to $\kappa_{TR} = 12\%$ instead, the mandate would effectively impose a cap on total motor gasoline sales. To see this, consider the requirement

[11] Recall that percentage blend mandates are expressed as the amount of biofuel divided by the amount of fossil fuel (which in this simplified ethanol-only case corresponds to $\kappa = \frac{\mathrm{E}}{\mathrm{G}}$), while the blend wall relates to the relative share of ethanol in motor gasoline, $\frac{\mathrm{E}}{\mathrm{E+G}}$.

$$\frac{q_E}{q_G} = \frac{0.1\mathrm{q}_{E10} + 0.74 * 1}{0.9\mathrm{q}_{E10} + 0.26 * 1} \geq 12\%$$

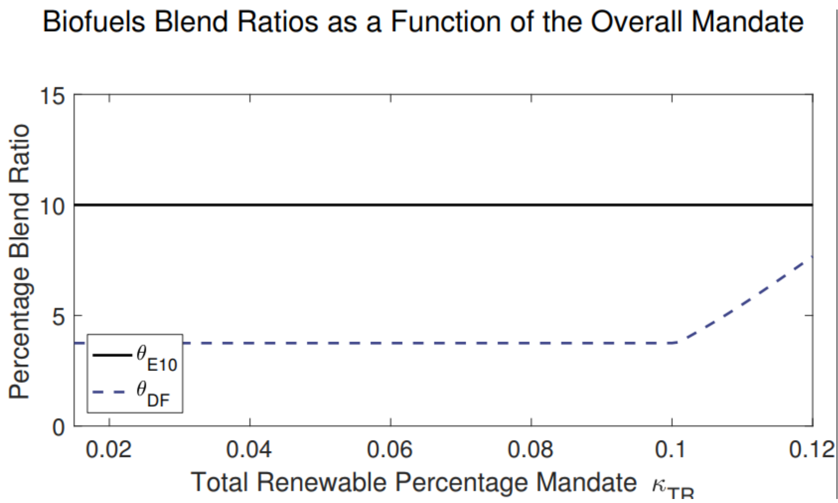
Assuming the maximum 1 billion gallons of E85 and solving for q_{E10}, we find a maximum of 89.6 bn gal of E10 sales in order to ensure mandate compliance. This fourth channel, which is rarely mentioned in the existing literature, plays a key role in practice since other channels grow costlier as mandates tighten.[12] In a model without nesting in which surplus biodiesel RINs cannot be used to overcome the blend wall, this channel becomes the only option for compliance once the blend wall has been hit and E85 demand has been exhausted.

The important role which biodiesel plays in overcoming the blend wall is evident in the choice of blend ratios. Our calibrated ethanol supply curve leads to ethanol prices cheap enough to encourage full use in E10. The E10 blend ratio is therefore stable at 10% regardless of the percentage blend mandate. The diesel fuel blend on the other hand changes significantly beyond the blend wall, increasing from around 3.7% to 7.8% as shown in Figure 5.[13] This change is purely driven by ethanol demand constraints as the BBD mandate level itself remains fixed at 1.5% throughout our simulations.

[12] Note that the EPA Final Standards for 2017 do allude to this effect: "Refiners and marketers typically viewed the constraints associated with the blendwall as representing a firm barrier that could not or should not be crossed, with costs for necessary infrastructure changes being prohibitively high and the associated opportunities for greater profits at retail being inconsequentially low. In their views, higher level ethanol blends such as E15 and E85 would be negligible in 2017 and standards that required higher ethanol blends to increase dramatically would compel refiners to reduce domestic supply of gasoline and diesel or risk noncompliance." (p. 89775)

[13] Note that this figure does not have a time component. Our model is calibrated to the 2015 market environment and the only thing we vary is the total renewable mandate, κ_{TR}.

FIGURE 5: CHANGES IN FUEL BLEND RATIOS



To emphasize this point, Figure 6 highlights the order in which the four compliance channels are activated. Figure 7 shows the relative reliance on each of the channels. While E85 quantities jump up once the price discount incentivizes switching by FFV drivers and exhibit a slow rate of growth beyond this point, biodiesel overage ramps up slightly later but increases at an almost constant rate to accommodate the increasing mandates. The fourth compliance channel is used as a measure of last resort and only becomes active at significantly higher mandate levels. Once initiated however, the reduction in the total compliance base also proceeds at a near constant rate.

FIGURE 6: ORDER OF ACTIVATION OF THE FOUR COMPLIANCE CHANNELS

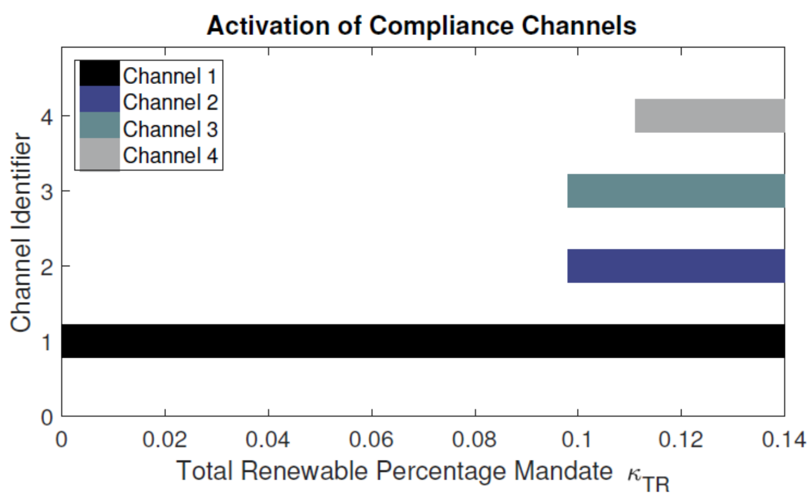
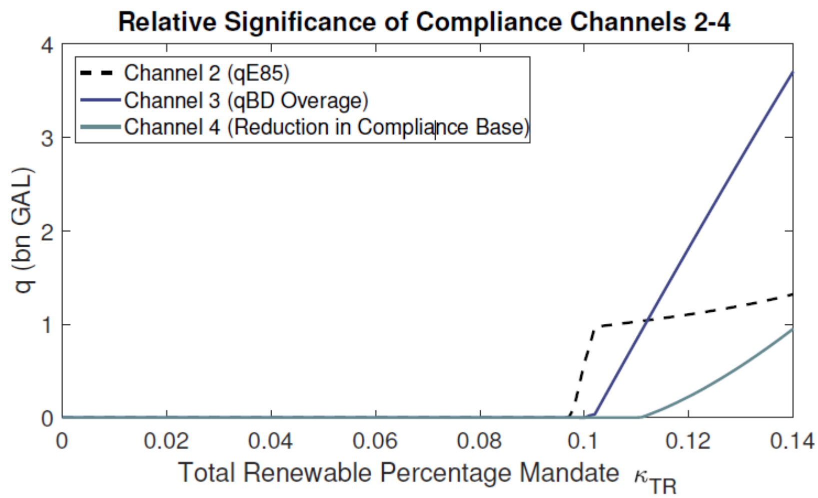


FIGURE 7: RELATIVE SIGNIFICANCE OF COMPLIANCE CHANNELS (BN GAL)



Result 2: The Core Value of RINs

Based on the behavioral equations outlined in Appendix A, we derive the following pricing formula for D4 and D6 RINs:

$$p_{D4} = \underbrace{\frac{1}{1.5\theta_{DF}}}_{\substack{Scaling\ Factor: \\ Diesel\ Fuel\ to\ D4\ RINs}} \left[\underbrace{(1-\theta_{DF})p_D + \theta_{DF}p_{BD} + \frac{\partial C_{DF}^B}{\partial q_{DF}}}_{\substack{Marginal\ Cost\ of\ Blending\ one \\ Additional\ Unit\ of\ Diesel\ Fuel}} - \underbrace{(p_{DF} - t_D)}_{\substack{Marginal\ Revenue\ from\ Selling\ one \\ Additional\ Unit\ of\ Diesel\ Fuel}} \right]$$

$$p_{D6} = \underbrace{\frac{1}{\theta_{E10}}}_{\substack{Scaling\ Factor: \\ E10\ to\ D6\ RINs}} \left[\underbrace{(1-\theta_{E10})p_G + \theta_{E10}p_E + \frac{\partial C_{MG}^B}{\partial q_{E10}}}_{\substack{Marginal\ Cost\ of\ Blending\ one \\ Additional\ Unit\ of\ E10}} - \underbrace{(p_{E10} - t_G)}_{\substack{Marginal\ Revenue\ from\ Selling\ one \\ Additional\ Unit\ of\ E10}} \right]$$

The *core value* of a D4 RIN thus represents the marginal cost of compensating the blender for employing one additional ethanol-equivalent unit of biodiesel. The blender faces the input costs for the two blending components, incurs a marginal cost of blending, and sells the final product at the diesel fuel price minus tax. If the costs of generating an additional unit of diesel fuel are higher than the price which can be achieved in the market, the blender demands a positive RIN price as compensation for blending since he is not himself obligated under the RFS.

By establishing these concise pricing formulas, we provide an alternative to the widely established simplification equating the price of RINs to the gap between ethanol supply and demand at the mandated level. Besides the obvious abstraction away from the nested mandate structure, we point out two key problems with the previous definition of RIN prices:

1. *Implied ethanol demand is not well defined:*
   The ethanol demand schedule is usually defined as the implied demand for ethanol through E10 and E85 as ethanol prices vary. However, due to the existence of the four different compliance channels, and the potential reduction of low-ethanol blends at high mandate levels in particular, the notion of implied ethanol demand is highly sensitive to the prevailing percentage mandate levels. Figure 8 illustrates this effect by showing simulated demand schedules for different total renewable blend mandates (κ_{TR}=0%, 9% and 11%). Clearly, for any given ethanol volume, the free-market supply demand gap is substantially different from the supply-demand gap given a binding mandate[14].

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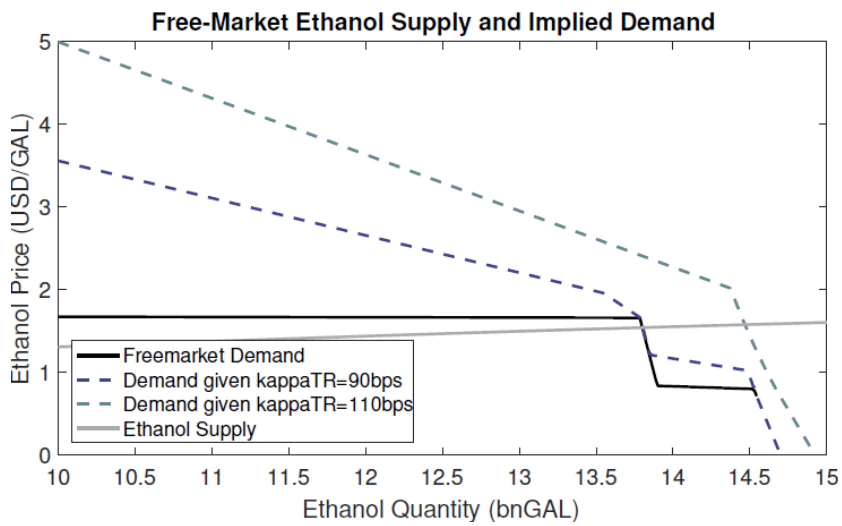
[14] At 0% and 9% mandate levels, we first see increased demand thanks to higher ethanol blend ratios in E10, and finally a jump in demand as ethanol becomes inexpensive enough to induce E85 sales. The 11% demand schedule only features one kink when channel four starts to dominate and the market contracts.

2. *Equilibrium ethanol quantities do not equal volumetric mandates:*
   Even assuming a well-defined implied ethanol demand schedule and ignoring the fact that the RFS2 does not impose any direct mandates for ethanol, the implied volumetric ethanol mandate is not a meaningful quantity to consider in order to assess the price of RINs. Percentage mandate requirements are calculated using forecast motor gasoline consumption which will not usually be fulfilled exactly as predicted.

FIGURE 8: IMPLIED ETHANOL DEMAND SCHEDULES AT DIFFERENT MANDATE LEVELS (BN GAL)



This description of RIN prices therefore represents an inaccurate and highly impractical representation of the core value of RINs. However, the notion of the supply-demand gap is highly correlated to the more accurate pricing formula we provide: both are a function of the elasticity of ethanol supply as well as the potential ethanol demand given the blend wall. For example, the D6 equilibrium RIN price depends negatively on p_{E85}. This means that if the price of E85 has to adjust downwards faster due to demand side bottlenecks, the RIN price will increase faster as mandates rise.

RESULT 3: THE INDEPENDENT EFFECTS OF THE NESTED MANDATE STRUCTURE AND THE JOINT COMPLIANCE BASE UNDER THE RFS: A DUAL LINK BETWEEN MOTOR GASOLINE AND DIESEL FUEL MARKETS

As mentioned previously, when assessing consumer welfare outcomes at varying mandate levels we find that diesel fuel consumers bear the bulk of the economic burden under the RFS2. The next section provides a detailed analysis of this result. A relevant structural question in this context is whether the shift of the ethanol blend wall effects from motor gasoline to diesel fuel consumer is purely an artifact of the nested mandate structure of the RFS2. Our simulation results for a model without nesting show that this is not the case. Rather, the independent effects of nesting and the joint compliance base create a **dual link** between the two consumer groups. Due to this dual link, the added flexibility provided by the nested mandate structure actually acts as a net welfare enhancement for diesel fuel consumers.

As discussed previously, the EPA's reasons for imposing a joint compliance base were distinct from the nested mandate structure choice. When designing our market framework without nesting, we therefore maintain the assumption of a joint gasoline and diesel compliance base. In this case, consumer surplus losses for diesel fuel consumers are about USD -8bn higher than in the reference case.

To understand why, note that blenders do generate much higher E85 sales for compliance under the non-nested mandate structure by driving E85 prices close to zero. As expected, they also maintain a lower diesel fuel blend ratio. However, by comparing the results in the 'No Nesting' column of Table 8 to the 'Reference' column in Table 6, it becomes evident that blenders charge higher relative diesel fuel prices given the price of diesel and biodiesel inputs. The blender's first order condition with respect to the quantity of diesel fuel is given by the following equation:

$$p_{DF} - t_D = \underbrace{\frac{\partial C_{DF}^B}{\partial q_{DF}}}_{\substack{Marginal\ Cost \\ of\ Blending}} + \underbrace{(1-\theta_{DF})p_D + \theta_{DF}(p_{BD} - tc_{BD})}_{Input\ Costs} - \underbrace{1.5\theta_{DF}p_{D4}}_{\substack{Value\ of\ RINs \\ Detached}}$$

D4 RINs no longer increase in value without nesting as the free-market diesel fuel blend ratio of 3.6% exceeds the BBD mandate requirement of 1.5% and the additional D4 RINs can no longer be used to meet the total renewable mandate. This means that D4 RIN prices no longer represent a cap for D6 RIN prices. Accordingly, the blender now must charge a higher diesel fuel price to maintain equality of marginal benefits (LHS) and marginal costs (RHS), *ceteris paribus*. Note in Table 8 that the price of D6 RINs is more than five times as high as the price of D4 RINs .

The higher diesel fuel price in this scenario with a joint compliance base but no nesting explains the consumer surplus losses which diesel fuel drivers experience.

WELFARE IMPACTS OF THE RFS ON FUEL CONSUMERS

Simulation results in this section rely on demand estimates from Pouliot and Babcock (2016), which allow for heterogeneous preferences for E10 and E85. Throughout this section, we will refer to Table 6 - Table 8 which provide a comparison of simulated market outcomes under the reference model to the different market and policy frameworks we explore. Tables Table 9 - Table 11 summarize the corresponding welfare results. We find that diesel fuel consumers bear the burden of increasing mandate requirements given a binding ethanol blend wall and argue that the constraint on E85 demand as shown in Figure 9 drives this result.

FIGURE 9: E85 DEMAND ESTIMATES FROM POULIOT AND BABCOCK (2016) FOR THE 2015 E10 PRICE OF 2.43 USD/GAL

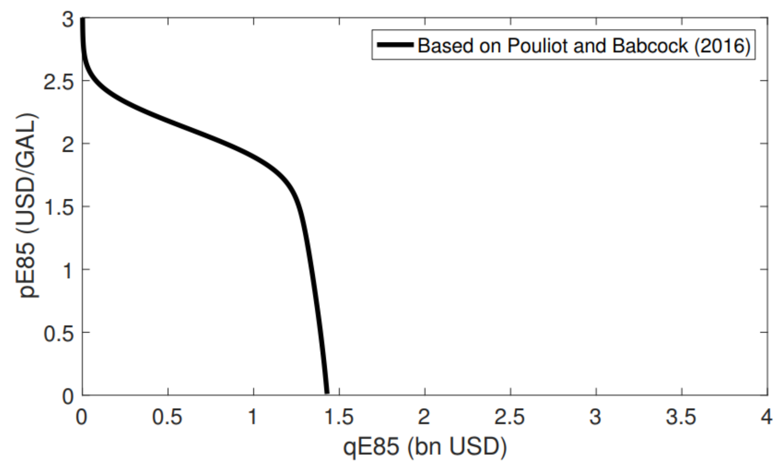
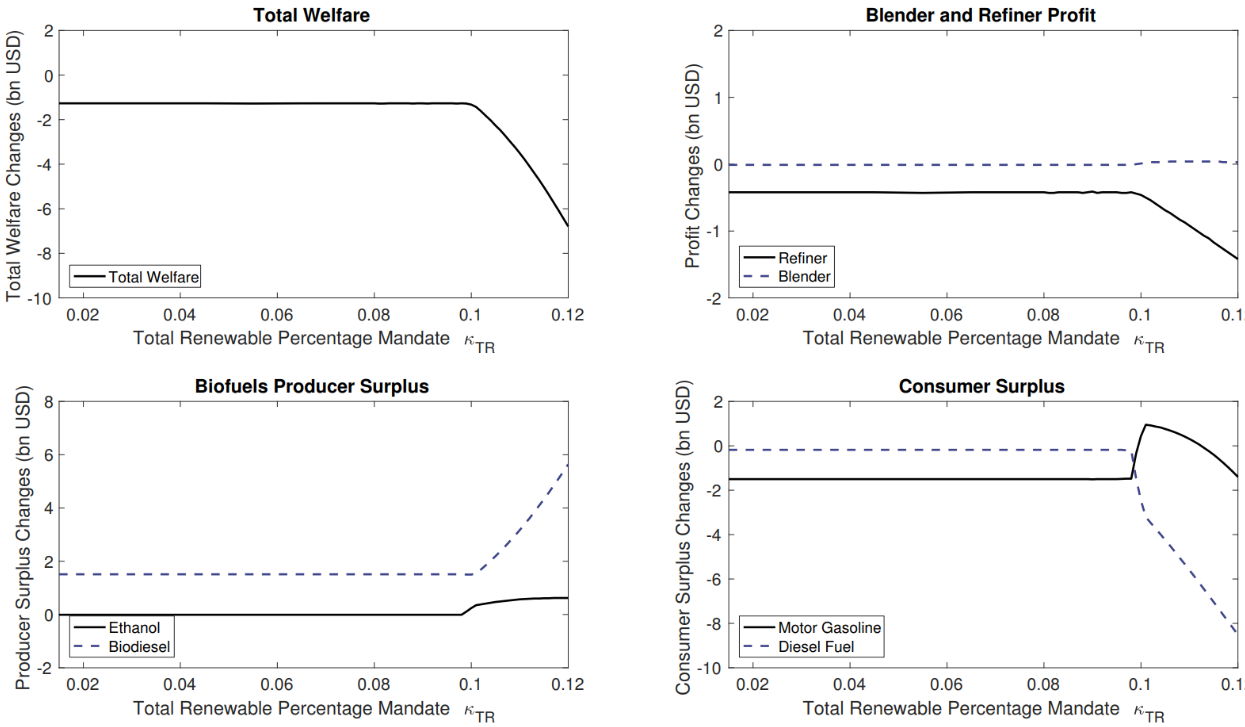


Figure 10 presents the evolution of welfare outcomes under our reference model as a function of varying mandate levels.[15] Taking only fuel markets into account, the RFS2 is net welfare reducing at increased mandate levels, mainly due to losses by refiners and diesel fuel consumers offset by profit gains for biodiesel producers. For models relating the welfare effects of the RFS2 to agricultural input markets and terms of trade see Meiselman (2016) and Moschini et al. (2016).

The fourth panel of this figure highlights the unequal effect of rising mandate levels on diesel fuel and motor gasoline consumers. In particular, the blend wall leads to sharp losses in diesel fuel consumer surplus as the biodiesel blend ratio increases, leading to a higher price at the pump and discouraging demand. Motor gasoline consumers on the other hand benefit from discounted E85 prices incentivizing them to switch to the high-ethanol blend.

[15] As mentioned in the previous section, the figures do not have a time component. Instead, for each level of κ_{TR}, the graph reflects the expected results given the U.S. market environment in 2015.

FIGURE 10: WELFARE RESULTS UNDER THE REFERENCE MODEL FOR TOTAL RENEWABLE MANDATE LEVELS UP TO 12% (BN USD)

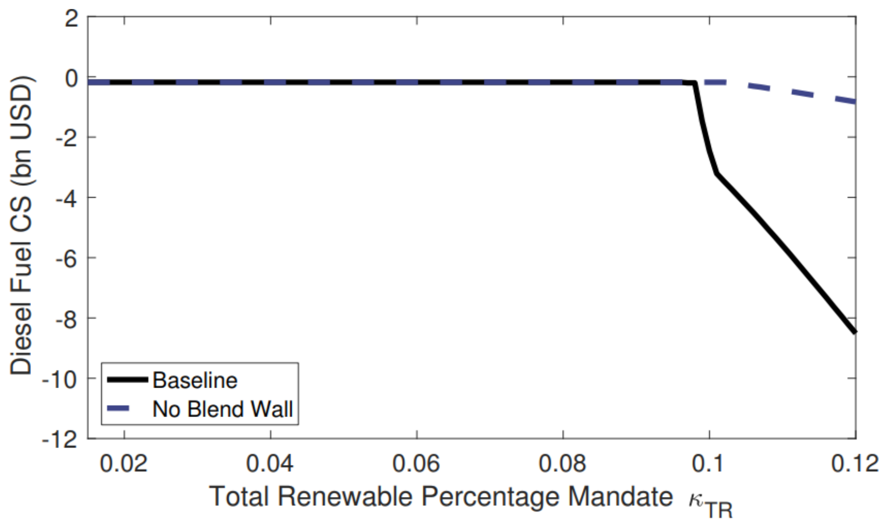


As mentioned previously, we argue that the welfare loss of diesel fuel consumers is largely attributable to the effects of the ethanol blend wall. We show that (i) in a model without a blend wall, the effect of rising total renewable mandates is largely borne by motor gasoline consumers and (ii) neither the more inelastic diesel fuel demand nor the effect of the biodiesel tax credit can explain the extent of the burden placed on diesel fuel consumers.

It is important to note that the ethanol blend wall does not become binding at a particular total renewable mandate level. As emphasized in the empirical section of this report, the RFS2 does not mandate specific amounts of ethanol use. Rather, corn and sugarcane ethanol are used to fill the gap between the BBD and total renewable mandate not met through BBD overage. In addition, the joint compliance base implies that the amount of ethanol blended is measured against the sum of petroleum gasoline and diesel, rather than gasoline alone. The blend wall on the other hand is a function of the amount of ethanol relative to gasoline. This means that the total renewable mandate level at which the blend wall starts binding is endogenous.

To prove that the welfare losses that diesel fuel consumers experience are indeed a consequence of the ethanol blend wall, we compare welfare results from our reference model to a model without blend wall. In this scenario, we model only a single type of motor gasoline with freely varying ethanol content, i.e. we drop the blend wall constraint on the blender. The 'No Blend Wall' column of Table 9 - Table 11 highlights the corresponding simulated welfare results at total renewable mandate levels of 9.5% - 11.5% respectively. Without the blend wall constraint and assuming zero total renewable mandates, blenders choose an optimal ethanol blend ratio of 10.6% while the biodiesel share in diesel fuel remains at the reference level of 3.6%. Figure 11 shows the difference in diesel fuel consumer surplus changes with and without the blend wall. This figure highlights that the blend wall represents the bulk of diesel fuel surplus losses.

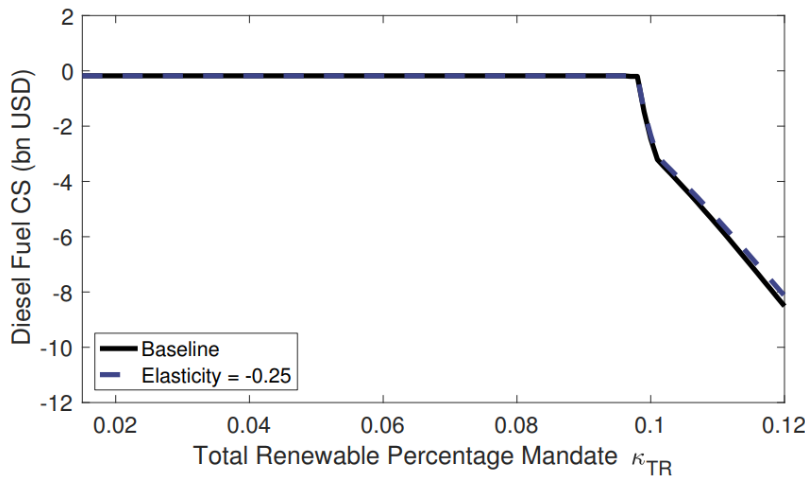
FIGURE 11: DIESEL FUEL CONSUMER SURPLUS CHANGES WITH AND WITHOUT THE ETHANOL BLEND WALL (BN USD)



There are two possible alternative explanations for why diesel fuel consumers shoulder most of the effect of the ethanol blend wall. First, the more inelastic demand for diesel fuel could make blenders more prone to target these consumers for price increases. Second, the biodiesel tax credit could add to the relative attractiveness of biodiesel blending compared to larger E85 price discounts. However, we show that neither of these two factors can explain the disproportional incidence on diesel fuel consumers.

First, we consider a model in which diesel fuel demand elasticity is increased to be on par with the elasticity of motor gasoline demand. In this case, we choose $\epsilon_{D_{DF}} = -0.25$ as in Pouliot and Babcock (2014) and obtain a corresponding cost function multiplier of $A_{D_{DF}}$ =57.27 based on calibrations to 2015 data. We find almost no welfare changes at the 9.5 and 10.5% total renewable mandate level relative to the baseline results (see Figure 12). At 11.5%, we see a slight increase in the diesel fuel consumer surplus of USD 0.2bn, largely offset by reductions in blender and refiner profits. This suggests that increased diesel fuel demand elasticity changes the burden share between blenders/refiners and diesel fuel consumers, but does not significantly alter the trade-off between ethanol and biodiesel use. As Table 8 suggests, most quantities and prices are unchanged with the exception of a net reduction in diesel fuel. The composition of diesel fuel remains unchanged at 6.6% biodiesel as in the reference case.

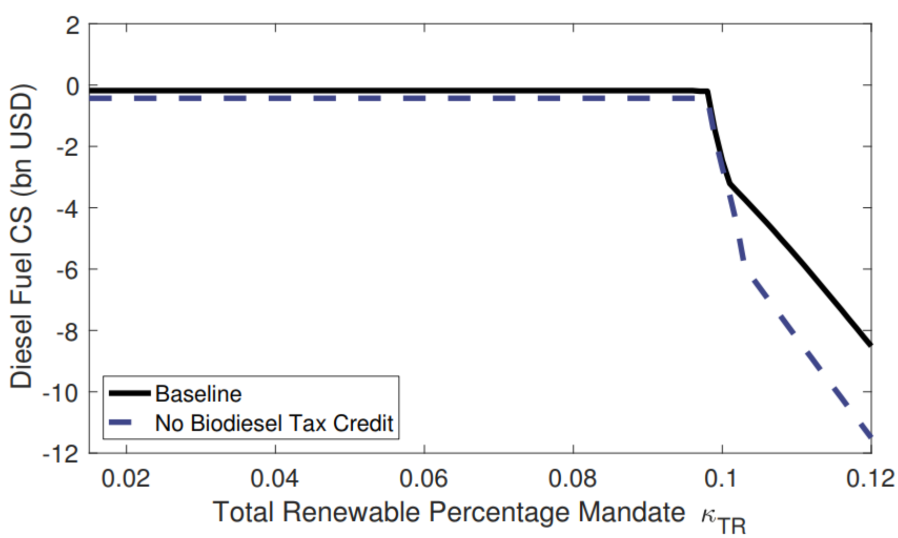
Figure 12: Diesel Fuel Consumer Surplus Changes under Different Demand Elasticities (bn USD)



As Figure 13 shows, the biodiesel tax credit also does not add to the imbalance of welfare effects for diesel fuel consumers. Instead, it insulates diesel fuel consumers from even greater losses by subsidizing the relatively more expensive biodiesel being blended. In a world without the tax credit, E85 sales are slightly higher than in the reference case as the biodiesel / ethanol trade-off shifts marginally towards ethanol. However, this effect is dominated by the increased price of diesel fuel as the biodiesel subsidy disappears. At the 11.5% mandate level, diesel fuel prices are almost 7 cents higher than in the reference case despite a similar fuel composition (see Table 8). The net welfare effect of eliminating the tax credit is roughly unchanged across mandate levels, ranging from -0.04 to -0.14bn USD. However, this net effect hides additional consumer surplus losses of USD -2.8bn for diesel fuel consumers, partly offset by a positive change in government tax revenues.

Interestingly, the tax credit has very little effect on refiner and blender profits, suggesting that the subsidy is largely being passed through to consumers in order to encourage higher diesel fuel sales.

Figure 13: Diesel Fuel Consumer Surplus Changes with and without the Biodiesel Tax Credit (bn USD)

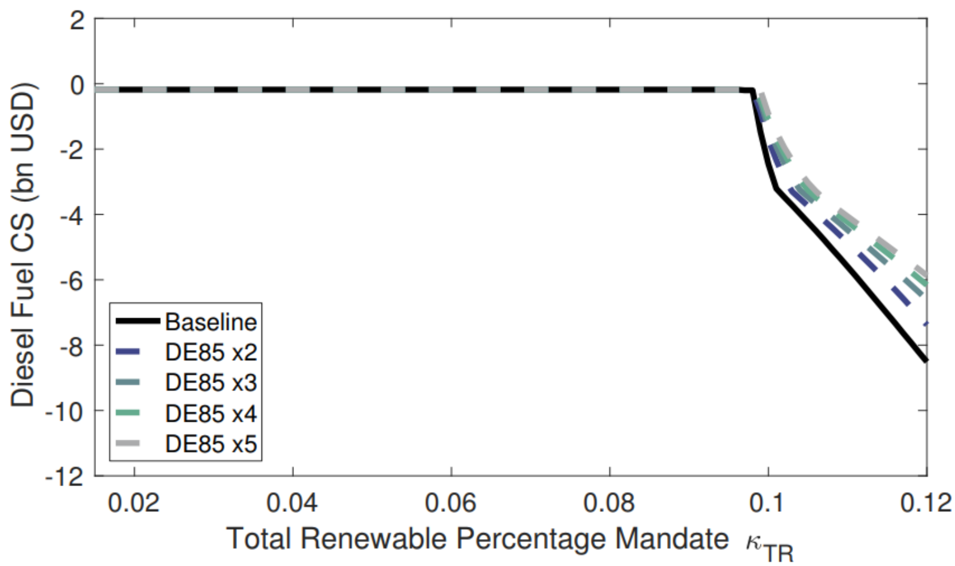


Having ruled out the relative elasticity of diesel fuel demand as well as the effect of the biodiesel tax credit as dominant factors determining the diesel fuel consumer surplus loss, we now show that an increase in

E85 demand can mitigate the welfare impacts of rising mandates. Note that such an increase effectively makes the ethanol blend wall less binding. We consider the effect of scaling up the level of E85 demand by fixed multipliers while adjusting down the demand for E10 to maintain the net motor gasoline demand levels observed in 2015.

Figure 14 depicts the change in diesel fuel consumer surplus losses as a function of increasing levels of E85 demand. If E85 demand increases fivefold, the diesel fuel consumer surplus loss at the 11.5% mandate level drops sharply to USD -5bn. This highlights the importance of reducing the demand-side bottleneck for high-ethanol blends in order to insulate diesel fuel consumers from the effects of the ethanol blend wall.

FIGURE 14: DIESEL FUEL CONSUMER SURPLUS CHANGES AT DIFFERENT E85 DEMAND LEVELS (BN USD)



CONCLUSION

This report summarizes our findings with respect to (i) data driven market insights; (ii) structural findings relating to the mechanism of the RFS2 such as the determination of RIN prices and an analysis of available compliance channels and their relative importance at varying mandate levels; and (iii) simulation results concerning the impact of the RFS2 on fuel market participants. The partial equilibrium model of U.S. biofuels markets we propose allows us to address the question of how the RFS2 operates, what the core value of RIN prices represents, and how consumers and producers are affected by the mandate.

This paper explores the severity of the blend wall in practice and discusses recent revisions to proposed mandate requirements. We propose a new measure called the ethanol RIN gap defined as required ethanol consumption (based on actual gasoline consumption and mandated ethanol percentage) minus the realized ethanol consumption. This captures the extent of the potential shortfall of D6 ethanol RINs as a result of the ethanol blend wall. We highlight the many channels commonly employed in practice in order to meet the ethanol RIN gap. Data for 2016 shows that the ethanol RIN gap was 1.02 billion gallons, 90 percent of which was filled with BBD overage, D5 and D6 BBD RINs, and non-transportation non-D4 RINs. Only 10 percent was covered by a reduction in E0, and by increases in E85 consumption and the E10 blend percentage.

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APPENDIX A: MODEL SPECIFICATION

We propose a model in which a representative, non-integrated refiner and blender choose equilibrium quantities to maximize profits. Since we are considering a short term model, we do not impose a zero profit constraint in this case. The model has an annual time horizon and does not allow for uncertainty or inter-temporal considerations such as the banking and borrowing of RINs. For the sake of parsimony, the cellulosic and advanced mandate categories are not explicitly modeled.

Throughout this paper, quantities, prices and blend ratios are represented by the letters q, p and θ respectively. The subscripts S, D and C distinguish between supply, demand and cost parameters. Product types are shown in (double) subscripts, while superscripts denote the refiner and blender (R, B). *Motor gasoline* (MG) refers to finished gasoline including ethanol blending components, while *diesel fuel* (DF) represents finished diesel including biodiesel for transportation. G and D symbolize gasoline and diesel derived from crude oil. RFS2 percentage blend mandates are denoted by κ, which represents the ratio of required renewable to fossil fuels.

Note that we are interested in the evolution of market outcomes and the associated welfare impacts holding everything except mandate levels constant.

The representative refiner solves the problem of maximizing revenue from refined product sales minus the cost of refining (C^R), subject to meeting the BBD mandate requirement as well as the residual total renewable requirement not met by BBD overage. By letting the mandates enter as inequality constraints, our model allows for strategic overage from nested mandate categories rather than imposing RIN bundles of fixed proportion. In addition, our treatment of the compliance obligation as a direct constraint on the refiner's profit maximization problem differs from Meiselman (2016) and Moschini, et al. (2016), who instead introduce the blend mandates as a market clearing constraint. Our model therefore most closely follows the actual incentive structure under the RFS.

EQUATION 6: REFINER PROBLEM

$$\max_{\{q_G,\, q_D,\, q_{D4}^R,\, q_{D6}^R\}} \Pi^R = p_G q_G + p_D q_D - C^R(q_G, q_D) - p_{D4} q_{D4}^R - p_{D6} q_{D6}^R$$

$$s.t. \quad q_{D4}^R \geq \kappa_{BBD}(q_G + q_D)$$

$$and \quad q_{D4}^R + q_{D6}^R \geq \kappa_{TR}(q_G + q_D)$$

The blender purchases petroleum gasoline and diesel as well as ethanol and biodiesel as inputs to the blending of motor gasoline and diesel fuel. For simplicity, we only consider two distinct types of motor gasoline: E10, with a blend ratio of up to 10%, and E85, which we assume to have a constant blend ratio of 74% ethanol in line with the average blend assumed by the EPA and frequently used in the literature. In practice, some gas stations also offer ethanol-free motor gasoline (E0), as well as E15 which contains up to 15% ethanol, is approved for use in models newer than 2001, but does not meet some car manufacturer warranties. Note that an increase in the E10 blend ratio could also be viewed as a reduction in E0 sales.

The blender can endogenously determine the blend ratios in E10 and diesel fuel ($\theta_{E10}, \theta_{DF}$), but θ_{E10} is capped at 10% by the blend wall. The blender incurs separate blending costs for motor gasoline and diesel fuel.

EQUATION 7: BLENDER PROBLEM

$$\max_{\substack{\{q_{E10},\, q_{E85},\, \theta_{E10} \\ q_{DF},\, q_{D4}^B,\, q_{D6}^B,\, \theta_{DF}\}}} \quad \Pi^B = q_{E10}(p_{E10} - t_{MG}) + q_{E85}(p_{E85} - t_{MG}) + q_{DF}(p_{DF} - t_{DF})$$

$$+ p_{D6}q_{D6}^B + p_{D4}q_{D4}^B + \theta_{DF}q_{DF}tc_{BD}$$

$$- ((1 - \theta_{E10})q_{E10} + 0.26q_{E85})p_G - (\theta_{E10}q_{E10} + 0.74q_{E85})p_E$$

$$- (1 - \theta_{DF})q_{DF}p_D - \theta_{DF}q_{DF}p_{BD}$$

$$- C_{MG}^B(q_{E10}, q_{E85}) - C_{DF}^B(q_{DF})$$

$$s.t. \qquad q_{D4}^B = 1.5\theta_{DF}q_{DF}$$

$$and \qquad q_{D6}^B = \theta_{E10}q_{E10} + 0.74q_{E85}$$

$$and \qquad \theta_{E10} \leq 0.1$$

The blender's revenue is based on his fuel sales net of taxes (t_G, t_D), his sale of RINs to the refiner as well as the biodiesel tax credit which he earns on the amount of biodiesel blended (tc_{BD}). This tax credit was recently extended through December 2016[16]. The two equality constraints of the blender reflect the process of RIN generation by detaching them from the biofuels used for blending. Recall that biodiesel has a higher energy value than ethanol and that RINs are measured in ethanol equivalent terms. We therefore apply an equivalence value of 1.5 to transform the amount of biodiesel blended into the available amount of D4 RINs.

All supply and demand functions are assumed to be of the constant elasticity form $q = Ap^{\epsilon}$ with an elasticity of ϵ and a scaling factor of A.

To model the consumer choice between E10 and E85, in Korting and Just (2017) we adopt a neo-classical approach: first, consumers are split into flexible-fuel vehicle (FFV) owners and conventional vehicle (C) owners. Rather than allowing for heterogeneous preferences for environmental quality and hence gradual switching behavior, we assume that all FFV drivers will switch from E10 to E85 whenever E85 prices become equally or more attractive on an energy-equivalent basis. We denote the demand functions for E10 and E85 by $(D_{E10}(p_{E10}, p_{E85}), D_{E85}(p_{E10}, p_{E85}))$, but will drop the price arguments going forward for notational convenience. Denoting by λ the energy-equivalence factor between E10 and E85, we therefore obtain the following piecewise demand functions:

[16] House of Representatives Bill 2029, Section 185

- Case 1: $p_{E85} > \lambda p_{E10}$: No p_{E85} will be consumed and all FFV drivers choose to consume E10 instead

$$D_{E85} = 0$$
$$D_{E10} = A_{D_{FFV}} p_{E10}^{\epsilon_{D_{MG}}} + A_{D_C} p_{E10}^{\epsilon_{D_{MG}}}$$

- Case 2: $p_{E85} = \lambda p_{E10}$: FFV drivers are indifferent between E10 and E85 and will therefore consume any quantity of E85 between zero and their total fuel demand. Any residual demand will be consumed in the form of E10:

$$q_{E85} \in [0, A_{D_{FFV}} p_{E10}^{\epsilon_{D_{MG}}}]$$

$$D_{E10} = A_{D_{FFV}} p_{E10}^{\epsilon_{D_{MG}}} + A_{D_C} p_{E10}^{\epsilon_{D_{MG}}} - q_{E85}$$

- Case 3: $p_{E85} < \lambda p_{E10}$: FFV drivers exclusively use E85

$$D_{E85} = A_{D_{FFV}} (\frac{1}{\lambda} p_{E85})^{\epsilon_{D_{MG}}}$$
$$D_{E10} = A_{D_C} p_{E10}^{\epsilon_{D_{MG}}}$$

In Korting, de Gorter and Just (2017) on the other hand we rely on demand estimates from Pouliot and Babcock (2016) which account for heterogeneous preferences for E10 and E85. We show that these demand estimates effectively operate as a smooth version of the neoclassical demand functions imposed in Korting and Just (2017). We find very similar simulation results using these two different demand specifications since our results are mainly driven by the stringent constraint on E85 demand which both specifications impose.

The equilibrium in our model is governed by the interplay of first order and complementary slackness conditions for blender and refiner as well as market clearing equations. The full list of equations is shown below.

Equation 8: Full Set of Equations

First Order Conditions

FOC Refiner	$p_g - \frac{\partial C^R}{\partial q_G} - \gamma^R_{D4}\kappa_{BBD} - \gamma^R_{D6}\kappa_{TR} = 0$
FOC Refiner	$p_D - \frac{\partial C^R}{\partial q_D} - \gamma^R_{D4}\kappa_{BBD} - \gamma^R_{D6}\kappa_{TR} = 0$
FOC Refiner	$p_{D4} - \gamma^R_{D4} - \gamma^R_{D6} = 0$
FOC Refiner	$p_{D6} - \gamma^R_{D6} = 0$
FOC Blender	$p_{E10} - t_{MG} - \frac{\partial C^{MG}_B}{\partial q_{E10}} - (1-\theta_{E10})p_g - \theta_{E10}(p_E - \gamma^B_{D6}) = 0$
FOC Blender	$p_{E85} - t_{MG} - \frac{\partial C^{MG}_B}{\partial q_{E85}} - 0.26p_g - 0.74(p_E - \gamma^B_{D6}) = 0$
FOC Blender	$p_{DF} - t_{DF} - \frac{\partial C^{DF}_B}{\partial q_{DF}} - (1-\theta_{DF})p_D - \theta_{DF}(p_{BD} - 1.5\gamma^B_{D4} - tc_{BD}) = 0$
FOC Blender	$p_{D4} - \gamma^B_{D4} = 0$
FOC Blender	$p_{D6} - \gamma^B_{D6} = 0$
FOC Blender	$q_{E10}(p_G + \gamma^B_{D6} - p_E) - \gamma^B_{E10} = 0$
FOC Blender	$q_{DF}(p_D + 1.5\gamma^B_{D4} - p_{BD} + tc_{BD}) = 0$

Market Clearing

MC Motor Gasoline	$q_{E10} - A_{D_C} p_{E10}^{\epsilon_{D_{MG}}} = 0$
MC Motor Gasoline	$q_{E85} - A_{D_{FFV}} \left(\frac{1}{\lambda} p_{E85}\right)^{\epsilon_{D_{MG}}} = 0$
MC Diesel Fuel	$q_{DF} - A_{D_{DF}} p_{DF}^{\epsilon_{D_{DF}}} = 0$
MC Gasoline	$q_G - (1-\theta_{E10})q_{E10} - 0.26q_{E85} = 0$
MC Ethanol	$S_E(p_E) - \theta_{E10}q_{E10} - 0.74q_{E85} = 0$
MC Diesel	$q_D - (1-\theta_{DF})q_{DF} = 0$
MC Biodiesel	$S_{BD}(p_{BD}) - \theta_{DF}q_{DF} = 0$
MC D4 RINs	$q^B_{D4} - q^R_{D4} = 0$
MC D6 RINs	$q^B_{D6} - q^R_{D6} = 0$

Complementary Slackness

CS Refiner	$\gamma^R_{D4}(q^R_{D4} - \kappa_{BBD}(q_G + q_D)) = 0$
CS Refiner	$\gamma^R_{D6}(q^R_{D4} + q^R_{D6} - \kappa_{TR}(q_G + q_D)) = 0$
CS Blender	$\gamma^B_{D4}(1.5\theta_{DF}q_{DF} - q^B_{D4}) = 0$
CS Blender	$\gamma^B_{D6}(\theta_{E10}q_{E10} + 0.74q_{E85} - q^B_{D6}) = 0$
CS Blender	$\gamma^B_{E10}(0.1 - \theta_{E10}) = 0$

Appendix B: Detailed Simulation Results

This section provides detailed simulation results as summarized in Korting, de Gorter and Just (2017). The first three tables, tables 2-4, show market outcomes at three different total renewable mandate levels. The second set of tables, tables 5-7, show the corresponding welfare results.

Table 6: Simulation Results at a Total Renewable Mandate Level of 9.5%

	Reference	No Tax Credit		Equal Elasticities		No Blend Wall		No Nesting	
	Result	Result	Change	Result	Change	Result	Change	Result	Change
	Blend Ratios (%)								
θ_{E10}	10.0%	10.0%	0.0%	10.0%	0.0%	10.6%	0.6%	10.0%	0.0%
θ_{DF}	3.7%	3.7%	0.0%	3.7%	0.0%	3.7%	0.0%	3.7%	0.0%
	Quantities (bGAL)								
q_{E10}	137.9	137.8	-0.1	137.9	0.0	-	-	137.9	0.0
q_{E85}	0.0	0.0	0.0	0.0	0.0	-	-	0.0	0.0
q_{MG}	137.9	137.8	-0.1	137.9	0.0	137.8	0.0	137.9	0.0
q_{DF}	44.7	44.7	0.0	44.8	0.1	44.7	0.0	44.7	0.0
q_G	124.1	124.0	-0.1	124.1	0.0	123.3	-0.8	124.1	0.0
q_D	43.0	43.0	0.0	43.1	0.1	43.0	0.0	43.0	0.0
q_E	13.8	13.8	0.0	13.8	0.0	14.6	0.8	13.8	0.0
q_{BD}	1.7	1.7	0.0	1.7	0.0	1.7	0.0	1.7	0.0
q_{D4}	2.5	2.5	0.0	2.5	0.0	2.5	0.0	2.5	0.0
q_{D6}	13.4	13.6	0.1	13.8	0.4	14.5	1.1	13.4	0.0
	Prices (USD/GAL)								
p_{E10}	2.44	2.45	0.01	2.44	0.00	-	-	2.44	0.00
p_{E85}	2.38	2.38	0.00	2.38	0.00	-	-	2.38	0.00
p_{MG}	-	-	-	-	-	2.45	-	-	-
p_{DF}	2.67	2.68	0.01	2.67	0.00	2.67	0.00	2.67	0.00
p_G	1.68	1.69	0.01	1.68	0.00	1.68	0.00	1.68	0.00
p_D	1.62	1.63	0.01	1.62	0.00	1.62	0.00	1.62	0.00
p_E	1.63	1.63	0.00	1.63	0.00	1.68	0.04	1.63	0.00
p_{BD}	3.88	3.88	0.00	3.88	0.00	3.87	-0.01	3.88	0.00
p_{D4}	0.84	1.50	0.66	0.84	0.00	0.83	0.00	0.84	0.00
p_{D6}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note: All values assume a constant biodiesel mandate level of $\kappa_{BBD} = 1.5\%$

TABLE 7: SIMULATION RESULTS AT A TOTAL RENEWABLE MANDATE LEVEL OF 10.5%

	Reference	No Tax Credit		Equal Elasticities		No Blend Wall		No Nesting	
	Result	Result	Change	Result	Change	Result	Change	Result	Change
				Blend Ratios (%)					
θ_{E10}	10.0%	10.0%	0.0%	10.0%	0.0%	10.8%	0.8%	10.0%	0.0%
θ_{DF}	4.5%	4.4%	-0.1%	4.5%	0.0%	3.7%	-0.8%	3.8%	-0.7%
				Quantities (bGAL)					
q_{E10}	137.1	137.2	0.0	137.1	0.0	-	-	137.7	0.6
q_{E85}	1.0	1.1	0.1	1.0	0.0	-	-	1.7	0.7
q_{MG}	138.1	138.2	0.1	138.1	0.0	137.8	-0.3	139.4	1.3
q_{DF}	44.6	44.5	-0.1	44.4	-0.1	44.7	0.1	44.4	-0.2
q_G	123.7	123.7	0.1	123.7	0.0	122.9	-0.8	124.4	0.7
q_D	42.6	42.5	0.0	42.4	-0.1	43.0	0.5	42.7	0.1
q_E	14.4	14.5	0.1	14.4	0.0	14.9	0.5	15.0	0.6
q_{BD}	2.0	2.0	0.0	2.0	0.0	1.7	-0.3	1.7	-0.3
q_{D4}	3.0	3.0	-0.1	3.0	0.0	2.5	-0.5	2.5	-0.5
q_{D6}	14.4	14.5	0.1	14.4	0.0	14.9	0.5	15.0	0.6
				Prices (USD/GAL)					
p_{E10}	2.43	2.43	0.00	2.43	0.00	-	-	2.39	-0.04
p_{E85}	1.67	1.25	-0.42	1.68	0.00	-	-	0.19	-1.49
p_{MG}	-	-	-	-	-	2.45	-	-	-
p_{DF}	2.76	2.82	0.06	2.76	0.00	2.67	-0.09	2.95	0.19
p_G	1.77	1.84	0.06	1.77	0.00	1.68	-0.09	1.96	0.19
p_D	1.72	1.78	0.06	1.71	0.00	1.62	-0.09	1.90	0.19
p_E	1.67	1.68	0.00	1.67	0.00	1.70	0.03	1.71	0.03
p_{BD}	4.25	4.21	-0.04	4.24	-0.01	3.86	-0.39	3.88	-0.37
p_{D4}	1.02	1.62	0.60	1.02	-0.01	0.83	-0.19	0.65	-0.37
p_{D6}	1.02	1.62	0.60	1.02	-0.01	0.02	-1.00	3.13	2.11

Note: All values assume a constant biodiesel mandate level of $\kappa_{BBD} = 1.5\%$

TABLE 8: SIMULATION RESULTS AT A TOTAL RENEWABLE MANDATE LEVEL OF 11.5%

	Reference	No Tax Credit		Equal Elasticities		No Blend Wall		No Nesting	
	Result	Result	Change	Result	Change	Result	Change	Result	Change
				Blend Ratios (%)					
θ_{E10}	10.0%	10.0%	0.0%	10.0%	0.0%	11.9%	1.9%	10.0%	0.0%
θ_{DF}	6.7%	6.6%	-0.1%	6.7%	0.0%	3.7%	-3.1%	3.8%	-3.0%
				Quantities (bGAL)					
q_{E10}	137.0	137.0	0.0	137.0	0.0	-	-	137.2	0.2
q_{E85}	1.1	1.2	0.1	1.1	0.0	-	-	4.1	3.0
q_{MG}	138.1	138.2	0.1	138.1	0.0	137.8	-0.3	141.3	3.2
q_{DF}	44.5	44.4	-0.1	44.2	-0.4	44.7	0.2	44.3	-0.2
q_G	123.6	123.6	0.0	123.6	0.0	121.3	-2.2	124.5	0.9
q_D	41.5	41.5	0.0	41.2	-0.3	43.0	1.5	42.6	1.1
q_E	14.5	14.6	0.1	14.5	0.0	16.4	2.0	16.7	2.2
q_{BD}	3.0	2.9	-0.1	3.0	0.0	1.6	-1.4	1.7	-1.3
q_{D4}	4.5	4.4	-0.1	4.5	0.0	2.5	-2.0	2.5	-2.0
q_{D6}	14.5	14.6	0.1	14.5	0.0	16.4	2.0	16.7	2.2
				Prices (USD/GAL)					
p_{E10}	2.44	2.44	0.00	2.44	0.00	-	-	2.42	-0.01
p_{E85}	1.27	0.85	-0.42	1.27	0.01	-	-	0.01	-1.26
p_{MG}	-	-	-	-	-	2.45	-	-	-
p_{DF}	2.83	2.90	0.07	2.83	0.00	2.67	-0.16	3.01	0.18
p_G	1.85	1.92	0.07	1.85	0.00	1.68	-0.16	2.03	0.18
p_D	1.79	1.86	0.07	1.79	0.00	1.63	-0.16	1.97	0.18
p_E	1.68	1.68	0.00	1.68	0.00	1.78	0.11	1.80	0.12
p_{BD}	5.20	5.15	-0.05	5.17	-0.02	3.85	-1.35	3.88	-1.32
p_{D4}	1.60	2.19	0.59	1.59	-0.01	0.81	-0.79	0.61	-1.00
p_{D6}	1.60	2.19	0.59	1.59	-0.01	0.10	-1.50	3.49	1.89

Note: All values assume a constant biodiesel mandate level of $\kappa_{BBD} = 1.5\%$

TABLE 9: WELFARE CHANGES COMPARED TO FREE-MARKET REFERENCE SCENARIO AT A TOTAL RENEWABLE MANDATE LEVEL OF 9.5% (BN USD)

	Reference	No Tax Credit		Equal Elasticities		No Blend Wall		No Nesting	
	Result	Result	Change	Result	Change	Result	Change	Result	Change
Producer Surplus									
Refiner	-0.42	-0.47	-0.05	-0.37	0.05	-0.75	-0.33	-0.42	0
Blender	-0.01	-0.02	-0.01	0.00	0.01	-0.01	0.00	-0.01	0.00
Ethanol	-0.01	-0.02	-0.01	-0.01	0.00	0.62	0.63	-0.01	0.00
Biodiesel	1.50	1.50	0.00	1.50	0.00	1.48	-0.02	1.50	0.00
Consumer Surplus									
Conventional	-1.21	-2.37	-1.16	-1.25	-0.04	-1.61	-0.40	-1.22	-0.01
FFV	-0.01	-0.02	-0.01	-0.01	0.00	-0.01	0.00	-0.01	0.00
Diesel Fuel	-0.45	-0.89	-0.44	-0.48	-0.03	-0.36	0.09	-0.45	0.00
Government Revenue and Value of Carbon Savings									
Tax Revenue	-0.98	-0.12	0.85	-0.92	0.06	-0.98	-0.01	-0.98	0.00
Value of CO2 Savings	0.32	0.37	0.05	0.26	-0.05	0.48	0.16	0.32	0.00
Total	-1.27	-2.04	-0.77	-1.27	-0.01	-1.14	0.13	-1.28	-0.01

Note: 'Results' are calculated as welfare changes compared to the free-market case ($\kappa_{TR} = \kappa_{BBD} = 0$) under the reference model. 'Changes' reflect the difference in welfare changes between the reference model and the alternate model a total renewable mandate level of $\kappa_{TR} = 9.5\%$. All values assume a constant biodiesel mandate level of $\kappa_{BBD} = 1.5\%$

TABLE 10: WELFARE CHANGES COMPARED TO FREE-MARKET REFERENCE SCENARIO AT A TOTAL RENEWABLE MANDATE LEVEL OF 10.5% (BN USD)

	Reference	No Tax Credit		Equal Elasticities		No Blend Wall		No Nesting	
	Result	Result	Change	Result	Change	Result	Change	Result	Change
				Producer Surplus					
Refiner	-0.77	-0.76	0.01	-0.83	-0.06	-0.91	-0.14	-0.43	0.34
Blender	-0.02	-0.02	0.00	-0.03	-0.01	-0.01	0.01	0.05	0.07
Ethanol	0.53	0.58	0.05	0.53	0.00	0.95	0.42	1.03	0.50
Biodiesel	2.18	2.10	-0.08	2.16	-0.02	1.48	-0.70	1.50	-0.68
				Consumer Surplus					
Conventional	0.83	1.21	0.38	0.86	0.03	-1.73	-2.56	6.21	5.38
FFV	0.28	0.84	0.56	0.28	0.00	-0.01	-0.29	2.57	2.29
Diesel Fuel	-4.58	-7.37	-2.79	-4.52	0.06	-0.40	4.18	-12.84	-8.26
				Government Revenue and Value of Carbon Savings					
Tax Revenue	-1.26	0.01	1.26	-1.32	-0.07	-0.99	0.27	-0.45	0.81
Value of CO2 Savings	0.49	0.47	-0.01	0.56	0.07	0.55	0.07	0.06	-0.43
Total	-2.32	-2.94	-0.62	-2.32	0.00	-1.05	1.27	-2.31	0.01

Note: 'Results' are calculated as welfare changes compared to the free-market case ($\kappa_{TR} = \kappa_{BBD} = 0$) under the reference model. 'Changes' reflect the difference in welfare changes between the reference model and the alternate model a total renewable mandate level of $\kappa_{TR} = 10.5\%$. All values assume a constant biodiesel mandate level of $\kappa_{BBD} = 1.5\%$

TABLE 11: WELFARE CHANGES COMPARED TO FREE-MARKET REFERENCE SCENARIO AT A TOTAL RENEWABLE MANDATE LEVEL OF 1.5% (BN USD)

	Reference	No Tax Credit		Equal Elasticities		No Blend Wall		No Nesting	
	Result	Result	Change	Result	Change	Result	Change	Result	Change
Producer Surplus									
Refiner	-1.24	-1.25	-0.01	-1.37	-0.13	-1.56	-0.32	-0.39	0.85
Blender	-0.03	-0.04	-0.01	-0.08	-0.05	-0.01	0.02	0.17	0.20
Ethanol	0.57	0.63	0.06	0.57	0.00	2.26	1.69	2.51	1.94
Biodiesel	4.53	4.39	-0.14	4.47	-0.06	1.45	-3.08	1.50	-3.03
Consumer Surplus									
Conventional	-0.39	-0.73	-0.34	-0.29	0.10	-2.27	-1.88	1.48	1.87
FFV	0.82	1.41	0.59	0.81	-0.01	-0.02	-0.84	3.08	2.26
Diesel Fuel	-7.88	-10.88	-3.00	-7.71	0.17	-0.59	7.29	-15.81	-7.93
Government Revenue and Value of Carbon Savings									
Tax Revenue	-2.32	-0.08	2.24	-2.47	-0.15	-1.00	1.32	0.34	2.66
Value of CO2 Savings	0.84	0.84	0.00	1.00	0.16	0.86	0.02	-0.38	-1.22
Total	-5.09	-5.71	-0.61	-5.07	0.02	-0.86	4.24	-7.50	-2.40

Note: 'Results' are calculated as welfare changes compared to the free-market case ($\kappa_{TR} = \kappa_{BBD} = 0$) under the reference model. 'Changes' reflect the difference in welfare changes between the reference model and the alternate model a total renewable mandate level of $\kappa_{TR} = 11.5\%$. All values assume a constant biodiesel mandate level of $\kappa_{BBD} = 1.5\%$

Appendix C: Data Sources and Elasticity Parameters from the Literature

Table 12: Data Sources

Variable	Description	2015	Units	Source
q_G	Gasoline in Transport. excl. Ethanol	124.72	bGAL	EIA
q_E	Ethanol in Transport	13.38	bGAL	EIA
q_{E10}	E10 Consumption	138.02	bGAL	Calculated
q_{E85}	E85 Consumption	0.07	bGAL	EIA
θ_{E10}	Implied E10 Ethanol Content	9.65%	Percent	Calculated
q_D	Diesel Fuel in Transport. excl. Biodiesel	43.17	bGAL	EIA
q_{BD}	Biodiesel in Transport.	1.48	bGAL	EIA
q_{DF}	Distillate Fuel Oil in Transport.	44.65	bGAL	EIA
θ_{DF}	Implied Biodiesel Content	3.31%	Percent	Calculated
p_G	Refiner Price of Motor Gasoline for Resale	1.72	USD/GAL	EIA
p_E	Ethanol Nebraska Rack, FOB Omaha	1.61	USD/GAL	NEO
p_{E10}	Regular Motor Gasoline, All Areas	2.43	USD/GAL	EIA
p_{E85}	E85 Prices	1.96	USD/GAL	e85prices.com
p_D	Refiner Price of No. 2 Diesel Fuel for Resale	1.66	USD/GAL	EIA
p_{BD}	U.S. Retail Fuel Prices B99/B100	3.65	USD/GAL	DOE AFDC
p_{DF}	On-Highway Diesel Fuel Price	2.71	USD/GAL	EIA
κ_{TR}	Final Percentage Standards: Renewable Fuel	9.52%	Percent	EPA
κ_{BBD}	Final Percentage Standards: BBD	1.49%	Percent	EPA
p_{D6}	Ethanol RINs (D6)	0.55	USD/RIN	OPIS
p_{D4}	Biodiesel RINs (D4)	0.72	USD/RIN	OPIS

Table 13: Elasticity Estimates form the Literature

Variable	Description	Value	Source
	Supply Elasticities		
ε_{S_E}	Ethanol	2	Lee and Sumner (2010)
$\varepsilon_{S_{BD}}$	Biodiesel	2	(at 1.2b GAL) Babcock et al. (2013)
	Demand Elasticities		
$\varepsilon_{D_{MG}}$	Motor Gasoline	-0.25	Pouliot and Babcock (2014)
$\varepsilon_{D_{DF}}$	Diesel Fuel	-0.07	Dahl (2012)