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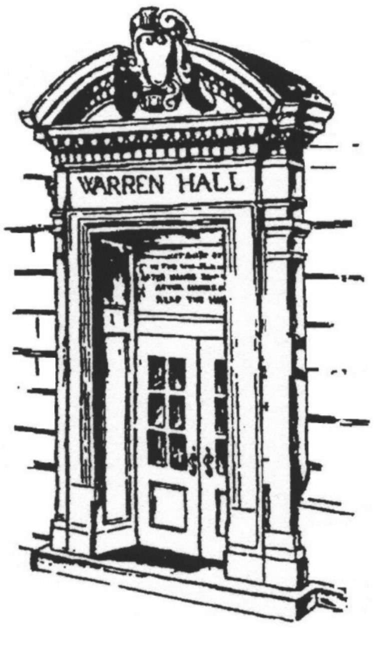

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The Charles H. Dyson School of Applied Economics and Management
Cornell University, Ithaca, New York 14853-7801 USA

Demystifying RINs: A Partial Equilibrium Model of U.S. Biofuels Markets

Christina Korting, David R. Just

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Demystifying RINs: A Partial Equilibrium Model of U.S. Biofuels Markets

Christina Korting[a,b,*], David R. Just[a]

[a] *Dyson School of Applied Economics and Management, Cornell University, USA*
[b] *Warren Hall, 137 Reservoir Avenue, Ithaca, NY 14850*

Abstract

We explore four fundamental channels of mandate compliance available under current U.S. biofuels policy: increased ethanol blending through E10 or E85, increased biodiesel blending, and a reduction in the overall compliance base. Simulation results highlight the interplay and varying importance of these channels at increasing blend mandate levels. In addition, we establish how RIN prices are formed: 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 free-market ethanol supply and demand at the mandate level. We demonstrate the importance of this distinction in case of binding demand side infrastructure constraints such as the ethanol blend wall: as percentage blend mandates increase, the market for low-ethanol blends may contract in order to reduce the overall compliance base. This has important implications for implied ethanol demand in the economy.

Keywords: Biofuels, Renewable Fuels Standards, blend mandate
JEL: H23, Q21, Q42

1. Introduction

U.S. biofuels policy has reached a critical junction. By lowering the final 2014-2016 blend mandate requirements in December 2015, the EPA has acknowledged the difficulty of complying with the original 2010 renewable fuel targets due to important demand side bottlenecks. To gauge the intensity of the feasibility debate currently raging in the biofuels space, it suffices to look at the number of comments received on proposed rulemakings by the EPA: 23 in 2011, 488 in 2012, 94 in 2013, and 344,947 in 2014 [1].

Given the current state of the market, it is more important than ever to understand the available compliance mechanisms, their impacts and limitations. Important groundwork in this context was laid by De Gorter and Just (2009) and Lapan and Moschini (2012) who analyze the general market effects and incidence of a blend mandate. Pouliot and Babcock (2014) provide estimates of potential demand for high-ethanol blends given current infrastructure constraints, which Pouliot and Babcock (2015) integrate into a short term partial equilibrium model accounting for existing market rigidities. Forthcoming work by Lade et al. (2015) explores the dynamic nature of the mandate.

*Corresponding author
Email addresses: `cmk272@cornell.edu` (Christina Korting), `drj3@cornell.edu` (David R. Just)

[1] see www.regulations.gov, dockets EPA-HQ-OAR-2010-0133-0001 for 2011, EPA-HQ-OAR-2010-0133-0102 for 2012, EPA-HQ-OAR-2012-0546-0001 for 2013, EPA-HQ-OAR-2013-0479-0037 for 2014

We contribute to this discussion by extending the existing literature in two important ways: First, we make explicit which compliance channels are available under the current biofuels policy and when they are employed. To do so, we propose a partial equilibrium model which takes into account the nested mandate structure of the RFS2. As market pressures increase due to higher total renewable mandates in the presence of ethanol infrastructure constraints, our simulation results provide evidence for two important compliance channels not usually emphasized in the literature: overage from nested mandate categories and a contraction of the market for low-ethanol blend fuels such as E10 in order to reduce the overall compliance base.

Second, we let the exchange of RINs enter the model endogenously as an additional decision variable for non-integrated blenders and refiners. This allows us to conclusively establish how RIN prices are formed and what they represent. Contrary to most of the existing literature, we find that the *core value* of a RIN in equilibrium reflects the marginal cost of compensating the blender for employing one additional ethanol-equivalent unit of biofuel[2]. Previously, this core value was usually equated to the gap between free-market ethanol supply and demand at the mandate level (e.g. McPhail et al. (2011), Whistance and Thompson (2014) and Markel et al. (2016)). Figure 1 illustrates this idea. While the two definitions of RIN prices are conceptually very similar, we emphasize the importance of this distinction by

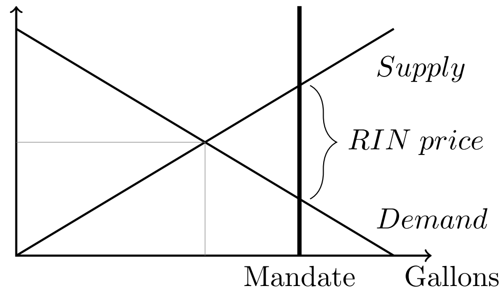

Figure 1: Proposed RIN Price Formation in Existing Literature; Market for Ethanol

showing the strong dependence of the notion of implied ethanol demand on prevailing percentage mandate levels. Our RIN price formula therefore provides a more concise and reliable way to explain the price of RINs.

2. Renewable Fuel Standards

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 reasons for promoting the use of biofuels are manifold: (a) protecting against rising fossil fuel prices; (b) reducing emissions from the transportation sector; (c) promoting energy security by reducing the dependency on fossil fuel imports; and (d) increasing farm income (Rajagopal and Zilberman (2007); McCarl and Boadu (2009)). The Renewable Fuel Standards share many of their environmental goals with other existing energy policies such as fuel taxes and fuel efficiency standards[3].

The RFS2 imposes a series of annual volumetric targets which are subsequently converted into blend mandates for the year ahead using forecast gasoline and diesel consumption

[2]RIN prices are usually broken down into three components: (i) the core value, or cost of complying with the mandate, (ii) the marginal value of transferring physical blending opportunities from high-cost to low-cost blenders, and (iii) the real option value of meeting binding mandates in the future thanks to the (limited) bankability of RINs. Our model focuses on the first component since it tends to dominate RIN prices when mandates are binding. However, our model could be extended to a dynamic setting including heterogeneous cost structures for blenders in order to capture the remaining RIN price components.

[3]For more details about the RFS, please see Appendix A

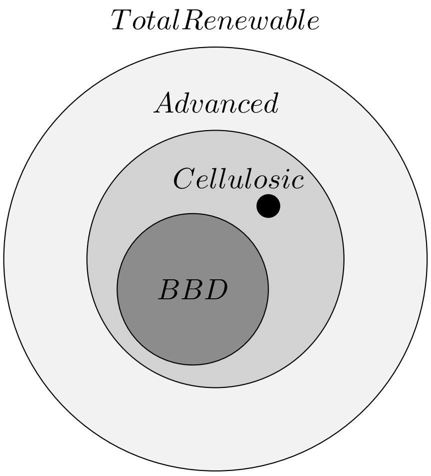

Figure 2: Nested Mandate Structure under the RFS2

levels. The obligated parties are refiners and importers of fossil fuels who often do not directly control the final blend of consumer motor fuels. Compliance is therefore monitored through financial instruments called Renewable Identification Numbers (RINs) which represent one ethanol-equivalent unit of biofuel blended. RINs are generated at production or import of a biofuel, and become detached and separately tradable at blending.

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%. Figure 2 provides a graphical representation of this nested structure.

The residual part of the total renewable fuels mandate not met through advanced biofuels is often referred to as conventional biofuels. It is usually filled using U.S. corn-based ethanol or biodiesel which did not meet the advanced biofuel GHG savings requirements[4]. However, overage from the advanced biofuels category could equally be used for compliance towards the overall mandate. It is therefore important to note that the RFS2 does not impose explicit ethanol volume requirements.

At the end of each year, every obligated party has to comply with all four sub-categories of the RFS2. For instance, a pure gasoline importer would still have to provide BBD RINs to the EPA in order to meet his renewable volume obligation (RVO). Table 1 highlights some volumetric and percentage blend targets by category and introduces the labeling convention for RINs. For example, cellulosic biofuels generate D3 RINs. The nested mandate structure leads to an implicit pricing relationship between the categories since any D3 or D4 RIN can also be used to comply with the advanced or total biofuels mandate: the prices must always satisfy $p_{D3}, p_{D4} \geq p_{D5} \geq p_{D6}$. These pricing relationships will hold with equality if the wider mandates become binding and there is a need to attract overage from some of the nested subcategories.

2013 was the first year when BBD and conventional RIN prices approached parity. The fundamental driver behind this convergence was the attainment of the so called *ethanol blend wall*: ethanol is corrosive and therefore risks damaging engines and fuel tanks at concentrations of more than 10% in cars that are not specifically equipped to use it. In 2013, most motor gasoline was already sold with a 10% ethanol share. There are currently

[4]Based on data from 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). We maintain a single biodiesel supply curve for simplicity in this model. It may be interesting to analyze the dichotomy between D4 and D6 biodiesel inputs and the resulting market dynamics in future work.

Table 1: RFS2 Mandates by Category

		2015		2022
Mandate Category	Label	Volumetric Mandate (bn GAL)	Percentage Mandate	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

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 (2015)

four distinct ethanol-gasoline blends sold in the U.S.: (i) E0 which contains no ethanol, (ii) E10 which contains up to 10% ethanol and can be used in all cars, (iii) E15 which contains up to 15% ethanol, is approved for use in models newer than 2001, but does not meet some car manufacturer warranties and is not currently widely available, and (iv) E85 which contains between 51-83% ethanol. E85 is designated for use in so called flexible-fuel vehicles (FFVs) that can run on higher blends but currently represent a small percentage of the U.S. fleet. We focus on E10 and E85 as the two dominant blends in the U.S. market[5].

3. Methodology

3.1. Model

Like Pouliot and Babcock (2015), we propose a short term model of the U.S. biofuels market which explicitly captures the rigidities imposed by demand side infrastructure constraints. However, our framework extends their setting in two important ways: First, 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. Second, we capture the nested structure of the U.S. biofuels mandate by explicitly modeling the biodiesel space and allowing for strategic overage of biodiesel RINs in order 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. In order 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, but taking the nested mandate structure and short term infrastructure constraints into account. An explicit distinction between conventional and flex-fuel vehicle drivers differen-

[5] The most recent EPA final rule document for 2014-2016 predicts E15 consumption of about 320mn GAL in 2016 assuming an optimistic rate of growth in retail availability. However, the relatively higher ethanol content in E15 is expected to be roughly offset by small amounts of E0 sales. Their most favorable infrastructure scenario for E85 would lead to an estimated 400mn GAL consumed in 2016. As a reference point, 2014 consumption is estimated at 150mn GAL (EPA (2015), pp. 77460-4)

tiates our approach from Christensen and Siddiqui (2015) who largely abstract away from the ethanol consumption bottleneck by assuming a perfectly inelastic motor gasoline demand which can be arbitrarily split between E10 and E85.

Based on our model choice, the refiner (R) 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. Throughout this paper, *motor gasoline* (MG) denotes finished gasoline including ethanol blending components, while *diesel fuel* (DF) refers to finished diesel including biodiesel for transportation. G and D on the other hand 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[6]. All quantities and prices are denoted as $q_\circ$ and $p_\circ$ respectively, where $\circ$ stands for a generic subscript. An exhaustive list of variable descriptions is provided in Appendix C.

$$\begin{aligned}
&\max_{\{q_G,\, q_D,\, q^R_{D4},\, q^R_{D6}\}} \Pi^R = \\
&\qquad p_G q_G + p_D q_D - C^R(q_G, q_D) \\
&\qquad - p_{D4} q^R_{D4} - p_{D6} q^R_{D6} \\
&s.t. \quad q^R_{D4} \geq \kappa_{BBD}(q_G + q_D) \\
&and \quad q^R_{D4} + q^R_{D6} \geq \kappa_{TR}(q_G + q_D)
\end{aligned} \tag{1}$$

The first constraint specifies that the quantity of D4 RINs retired has to be at least commensurate with the BBD percentage mandate requirement (κ_{BBD}) multiplied by the total amount of fossil fuels consumed in the economy. Given the nested mandate structure, D4 RINs also count towards the total renewable mandate. The second constraint therefore imposes that the sum of D4 and D6 retirements has to exceed the TR percentage mandate applied to the total compliance base.

In stating the blender's problem (B), we will assume that E85 always has an ethanol content of 74%. This assumption is in line with the average E85 specifications reported by the EPA and used in the literature (e.g. Knittel et al. (2015)). The E10 ethanol content on the other hand, represented by θ_{E10}, is allowed to vary between zero and 10% . This permits blenders to use less than 10% ethanol at low mandate levels and thereby implicitly captures the physical reality of E0 sales. The biodiesel blend ratio in diesel fuel (θ_{DF}) is allowed to vary freely since there are no blend wall constraints in the biodiesel market. Biodiesel blends up to 5% require no separate labelling at the pump, and blends up to 20% do not require engine modifications and are commonly used in the U.S.

$$\begin{aligned}
&\max_{\substack{\{q_{E10},\, q_{E85},\, \theta_{E10} \\ q_{DF},\, q^B_{D4},\, q^B_{D6},\, \theta_{DF}\}}} \Pi^B = \\
&\qquad q_{E10}(p_{E10} - t_{MG}) + q_{E85}(p_{E85} - t_{MG}) \\
&\qquad + q_{DF}(p_{DF} - t_{DF}) \\
&\qquad + p_{D6} q^B_{D6} + p_{D4} q^B_{D4} + \theta_{DF} q_{DF} tc_{BD} \\
&\qquad - ((1 - \theta_{E10}) q_{E10} + 0.26 q_{E85}) p_G \\
&\qquad - (\theta_{E10} q_{E10} + 0.74 q_{E85}) p_E \\
&\qquad - (1 - \theta_{DF}) q_{DF} p_D - \theta_{DF} q_{DF} p_{BD} \\
&\qquad - C^B_{MG}(q_{E10}, q_{E85}) - C^B_{DF}(q_{DF}) \\
&s.t. \qquad q^B_{D4} \leq 1.5 \theta_{DF} q_{DF} \\
&and \qquad q^B_{D6} \leq \theta_{E10} q_{E10} + 0.74 q_{E85} \\
&and \qquad \theta_{E10} \leq 0.1
\end{aligned} \tag{2}$$

The blender generates revenue by selling E10, E85 and diesel fuel and incurs a cost of blending denoted by C^B. The ethanol content in E10 as well as the biodiesel content in diesel fuel are endogenous to his decision. The blender's constraints represent the process of

[6] Note that the blend wall is a physical limitation which relates to the amount of ethanol relative to the overall fuel quantity instead. We will therefore sometimes convert mandate amounts into these terms for illustration

RIN generation: the number of units generated has to be proportional to the amount of biofuels blended.

All percentage blend mandates, and therefore all RIN quantities, are set in ethanol-equivalent terms by the RFS. The first constraint for the blender, which represents $D4$ RIN generation, therefore applies an equivalence value of 1.5 in order to account for the higher energy content of biodiesel compared to ethanol. The second constraints reflects the generation of D6 RINs through motor gasoline sales. The last constraint effectively imposes the blend wall, constraining the maximum ethanol content in E10 to 10%.

The blender has to deduct gasoline and diesel fuel taxes, t_{MG} and t_{DF}, on every gallon sold, but receives a 1 USD/GAL biodiesel blender tax credit, tc_{BD}, on the amount of biodiesel he blends[7]. C_B^{MG} and C_B^{DF} represent the blending costs for motor gasoline and diesel fuel respectively.

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. Throughout this paper, subscripts are used to differentiate between cost, supply and demand functions (C, S, D), and then indicate the relevant product. To model the consumer choice between E10 and E85, 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 $D_{\circ}(p_{E10}, p_{E85})$, 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:

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

$$D_{E85} \in [0, A_{D_{FFV}} p_{E10}^{\epsilon_{D_{MG}}}]$$
$$D_{E10} = A_{D_{FFV}} p_{E10}^{\epsilon_{D_{MG}}} + A_{DC} p_{E10}^{\epsilon_{D_{MG}}} - D_{E85}$$

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

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

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 provided in Appendix B. Before presenting the simulation results for this model in section 4.3, we will first discuss the data we use in calibrating the model to market.

3.2. Data and Calibration

The scale parameters $A_{\circ}$ for the fuel demand functions are calibrated to annual price and quantity data from 2015. Table 2 below highlights the elasticity estimates from the literature that were chosen for our calibrations:

[7] This tax credit has recently been extended to December 2016 through House of Representatives Bill 2029, Section 185

Table 2: Elasticity Estimates from the Literature

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

In order to calibrate the motor gasoline demand functions, we use E85 demand estimates from Figure 7 of Pouliot and Babcock (2014). Based on current infrastructure limitations, the E85 demand at a price of 1 USD/GAL in this figure is at around 1.2 bGAL. While Pouliot and Babcock (2014) allow for gradual switching behavior from E10 to E85, the 1 USD/GAL price level is far enough below the assumed energy-equivalent E10 price to suppose that virtually all switching would have occurred. Any further consumption increases beyond this point can therefore be attributed to increased driving demand at low fuel prices. The motor gasoline demand of conventional drivers in our model is calibrated to the residual of total motor gasoline demand minus FFV demand.

In order to calibrate the cost functions, we rely on the perfect competition assumption and choose the scale parameter A which equalizes marginal cost and marginal revenue (price) in 2015. In this case, this is equivalent to imposing a zero profit condition. Table C.3 highlights key data sources as well as the corresponding realizations for 2015.

4. Results

4.1. Compliance Channels

Using a sequence of simulation results at changing mandate levels, we are able to establish the existence of four distinct channels for mandate compliance in our model:

1. Increasing the blend ratio of ethanol in E10 (up to 10%)
2. Increasing E85 sales
3. Increasing the biodiesel share in diesel fuel beyond the BBD mandate
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 $\kappa_{TR} = 11.\overline{11}\%$ in this economy implies an ethanol blend ratio of 10%, 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

$$\frac{q_E}{q_G} = \frac{0.1q_{E10} + 0.74 * 1}{0.9q_{E10} + 0.26 * 1} \geq 12\% \tag{3}$$

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 more costly as mandates tighten.

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.

Our simulation results in section 4.3 provide evidence for the existence of all four channels. They also highlight the interplay of the different compliance channels as blend mandates increase given the 2015 market environment.

4.2. The Price of RINs

Based on the behavioral equations outlined in Appendix B, we derive the pricing formula for D4 RINs given in equation 5. The term

$$\frac{\partial C_B^{DF}}{\partial q_{DF}} = A^B_{C_{DF}} \epsilon^B_{C_{DF}} q_{DF}^{(\epsilon^B_{C_{DF}}-1)} \tag{4}$$

represents the marginal cost of blending diesel fuel. 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 is able to sell 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.

Similarly, for D6 RINs we find the pricing relationship outlined in equation 6 assuming both fuel blends are sold in equilibrium. The interpretation of terms in these equations is equivalent to the diesel fuel case.

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. Beside the obvious abstraction away from the nested mandate structure, there are two key problems with this notion:

- *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 3 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[8].
- *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 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.

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

[8] 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 cheap enough to induce E85 sales. The 11% demand schedule only features one kink when channel four starts to dominate and the market contracts

$$p_{D4} = \underbrace{\frac{1}{1.5\theta_{DF}}}_{\substack{\text{Scaling Factor:} \\ \text{Diesel Fuel to D4 RINs}}} \left[\underbrace{(1-\theta_{DF})p_D + \theta_{DF}p_{BD} + \frac{\partial C_B^{DF}}{\partial q_{DF}}}_{\substack{\text{Marginal Cost of Blending one} \\ \text{Additional Unit of Diesel Fuel}}} - \underbrace{(p_{DF} - t_D)}_{\substack{\text{Marginal Revenue from Selling one} \\ \text{Additional Unit of Diesel Fuel}}} \right] \tag{5}$$

$$\begin{aligned} p_{D6} &= \underbrace{\frac{1}{\theta_{E10}}}_{\substack{\text{Scaling Factor:} \\ \text{E10 to D6 RINs}}} \left[\underbrace{(1-\theta_{E10})p_G + \theta_{E10}p_E + \frac{\partial C_B^{MG}}{\partial q_{E10}}}_{\substack{\text{Marginal Cost of Blending one} \\ \text{Additional Unit of E10}}} - \underbrace{(p_{E10} - t_{MG})}_{\substack{\text{Marginal Revenue from Selling one} \\ \text{Additional Unit of E10}}} \right] \\ &= \underbrace{\frac{1}{0.74}}_{\substack{\text{Scaling Factor:} \\ \text{E85 to D6 RINs}}} \left[\underbrace{0.26p_G + 0.74p_E + \frac{\partial C_B^{MG}}{\partial q_{E85}}}_{\substack{\text{Marginal Cost of Blending one} \\ \text{Additional Unit of E85}}} - \underbrace{(p_{E85} - t_{MG})}_{\substack{\text{Marginal Revenue from Selling one} \\ \text{Additional Unit of E85}}} \right] \end{aligned} \tag{6}$$

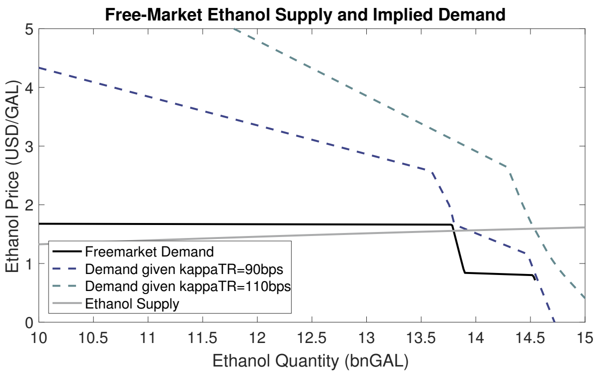

Figure 3: Implied Ethanol Demand Schedules at Different Mandate Levels

example, the D6 equilibrium RIN price in equation 6 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.

In order to reinforce this idea and to study the evolution of equilibrium pricing relationships at varying mandate levels, we provide comparative static results for a simplified motor-gasoline-only model (see Appendix D for a detailed model description). By calculating the comparative statics results based on this reduced framework, we can solve for upper bounds on κ_{TR} which guarantee that p_{E85} declines with mandate levels as would be expected. The corresponding bounds are provided in equation 7.

The bound on p_{E85} is a function of the scaled distance to the blend wall ($\frac{0.1}{0.9}$ in an ethanol-only world) plus an additional term which depends on the quantity of low-ethanol blend sales (q_{E10}). The resulting expression will be-

$$\frac{dp_{E85}}{d\kappa_{TR}} \leq 0 \quad \Leftrightarrow \quad \kappa_{TR} \leq \frac{0.1}{0.9}\left(\frac{p_E}{\epsilon_{S_E} p_{D6}} + 1\right) + \frac{q_{E10}}{0.9 p_{D6} B_{D_C}} \tag{7}$$

come small if the imposed blend mandate requires a heavy reliance on channel four with q_{E10} sales declining in order to lower the compliance base and p_{D6} exploding. In a very extreme scenario in which motor gasoline markets effectively shut down, we could thus encounter E85 prices that rise with the mandate level. Otherwise, p_{E85} is guaranteed to depend negatively on the prevailing mandate level.

Appendix D provides a similar formula for an upper bound on mandate levels which guarantees increasing RIN prices as a function of percentage standards. Our comparative statics results therefore show that under 'normal' market environments, RIN prices will increase with blend mandate levels while E85 prices decrease. This implies the negative correlation between RIN prices and the price of high-ethanol blends pointed out above. However, under very extreme circumstances, the fourth compliance channel may become so dominant that these natural relationships are no longer guaranteed to hold.

4.3. Simulation Results

Figure 4 shows the impact of an increasing κ_{TR} mandate in the market for consumer fuels. Throughout these simulations, we hold the biomass-based diesel mandate fixed at its 2015 level of around 1.5%. The first row of graphs represents quantity changes, while the second row highlights changes in equilibrium prices. It is important to note that these graphs do not have a time component, but rather represent the market outcomes if a given mandate level was imposed in a market environment similar to the U.S. in 2015.

The quantity of E85 jumps up sharply in response to the blend wall[9]. This change of consumption is induced by a drastic reduction in E85 prices which incentivizes FFV drivers to switch to the cheaper fuel. As some consumers abandon E10 for E85, the E10 price drops, thereby enabling an increase in E10 consumption by conventional vehicle owners. This phenomenon explains the small uptick in E10 consumption in the first panel of Figure 4.

The E10/E85 switching corresponds to compliance channel two in action: more ethanol is blended into motor gasoline in order to meet the mandate. Overall motor gasoline use increases as low prices induce more E85 consumption by FFV drivers. We also find clear evidence for the fourth compliance mechanism: as the mandate tightens and the inducement of additional E85 consumption becomes more costly, total motor gasoline consumption begins to decline again as shown in Figure 5. Because we are modelling E85 demand using a constant-elasticity function, the expansion in E85 here dominates the curtailment of E10. However, if we were to impose a cap on E85 consumption, we would expect overall motor gasoline use to decline as channel four would begin to dominate once channel two has been exhausted.

Looking at the diesel fuel market as shown in the right hand side panels of Figure 4, it becomes evident that the dominant compliance channel in our model is an increase in the biodiesel blend ratio, accompanied by increasing diesel fuel prices. The decrease in diesel fuel sales is thus driven by a supply shock in the form of increased marginal costs due to higher

[9]As noted previously, the blend wall occurs in the ethanol-only model whenever $\frac{E}{G}$ becomes larger than 10%, which corresponds to an ethanol-only mandate of $11.\overline{11}\%$. However, in a market with both motor gasoline and diesel, $\kappa_{TR} = \frac{E+BD}{D+G}$ which is why the blend wall now occurs before the salient level of $11.\overline{11}\%$

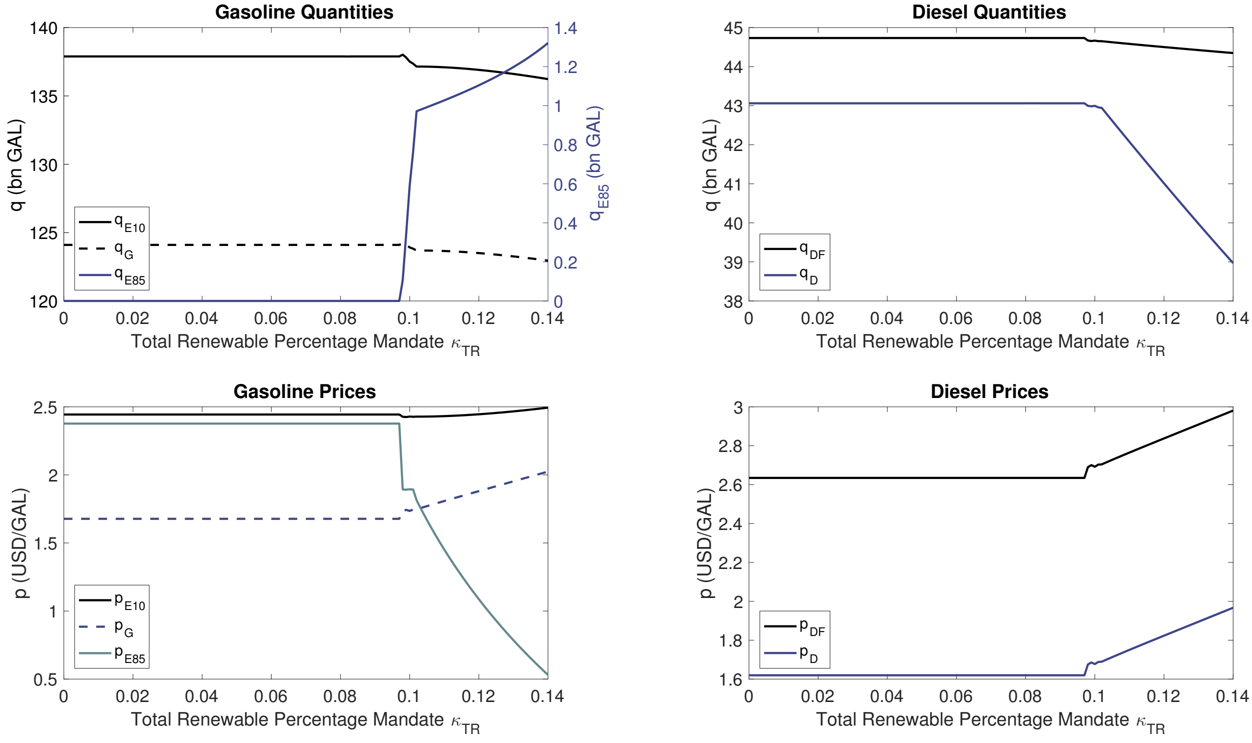

Figure 4: Price and Quantity Changes for Consumer Fuels. All Prices are Shown in USD/GAL. All Quantities are Shown in bn GAL.

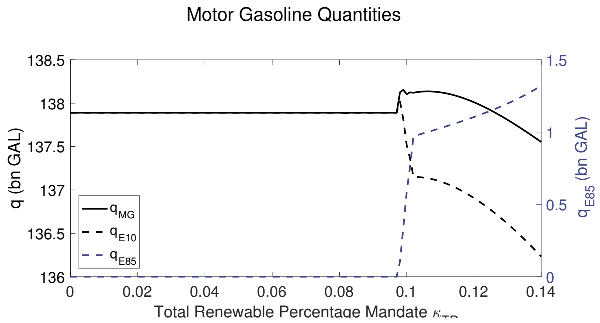

Figure 5: Quantity Changes in Motor Gasoline (bn GAL)

biodiesel use.

The important role which biodiesel plays in overcoming the blend wall is also evident in the choice of blend ratios. Our calibrated ethanol supply curve leads to ethanol prices cheap enough to encourage full use in E10, but not cheap enough to also encourage the production of E85 at low mandate levels. The E10 blend ratio is therefore stable at 10% regardless of the percentage blend mandate[10]. 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 6. This change is purely driven by ethanol demand constraints as the BBD mandate level itself remains fixed at 1.5% throughout our simulations.

Finally, Figure 7 depicts the changing equi-

[10]The free-market blend ratio which refiners would choose in the absence of a blend wall in our model is 12.5%

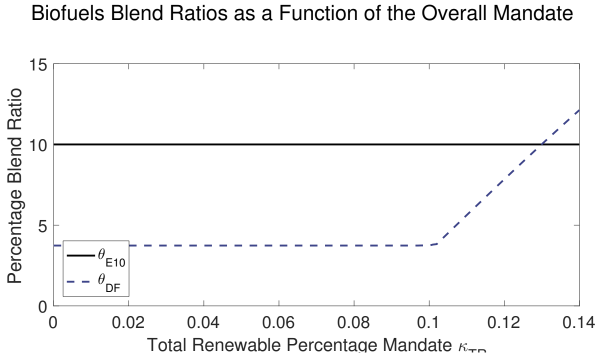

Figure 6: Changes in Fuel Blend Ratios (Percent)

libria in the biofuels market[11]. The increase in ethanol and D6 RIN quantities is effectively capped due to the blend wall. The increase in biodiesel and D4 RIN quantities on the other hand is unconstrained and progresses in line with the increasing biodiesel blend ratio we observed in the previous figure. The difference between biodiesel and D4 quantities is due to the 1.5 equivalence value applied in biodiesel RIN generation.

As noted in section 2, the nested mandate structure leads to an implicit pricing relationship between D4 and D6 RINs: the prices must always satisfy $p_{D4} \geq p_{D6}$. This relationship holds with equality when the wider mandate becomes binding and needs to attract overage from the nested sub-category. This effect becomes evident in the second panel of Figure 7.

We also observe a sharp increase in biodiesel prices compared to ethanol prices due to the demand constraints in E85. This suggests that the diesel market, and hence the transportation sector, carries a large part of the economic burden imposed by the ethanol consumption bottleneck.

5. Conclusion

We propose a parsimonious partial equilibrium framework which demonstrates the available compliance channels under current U.S. biofuels policy. Our simulation results provide evidence for a strong reliance on both biodiesel overage and a reduction in low-ethanol motor gasoline blends in order to meet the total renewable mandate given a binding blend wall. Since heavy trucks and trains account for most of the diesel consumption in the U.S., this suggests important general equilibrium ramifications as the higher cost of transportation will likely be passed on in the form of higher consumer prices. In addition, assuming limited biodiesel production capacity in the short term, we expect the fourth compliance channel to play an increasingly important role going forward. This implies significant welfare losses for drivers of cars without flexible-fuel capacity.

We also present a concise 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. Previous research had often represented RIN prices as the gap between free-market ethanol supply and demand at the mandate level. Our simulation results highlight the important approximation error induced by this notion of RIN rices by showing the strong dependence of implied ethanol demand on the prevailing blend mandate requirements.

Future work will focus on establishing the feasibility of the proposed RFS mandate progression under different infrastructure scenarios. If the technology forcing potential of the RFS2 cannot be realized as expected, it is important to understand which additional policy tools could be employed in order to overcome the current bottleneck in ethanol consumption. Our model provides a convenient starting point to explore the effect of additional

[11]The erratic behavior of D6 RIN quantities below the blend wall is due to over-blending of ethanol at low mandate levels. Given a zero RIN price and no bankability, the chosen quantity in our model oscillates freely as neither blender nor refiner have an incentive to exchange the superfluous RINs. Once the mandate starts binding and RIN prices become positive, the quantities of ethanol and generated D6 RINs in our model converge as expected

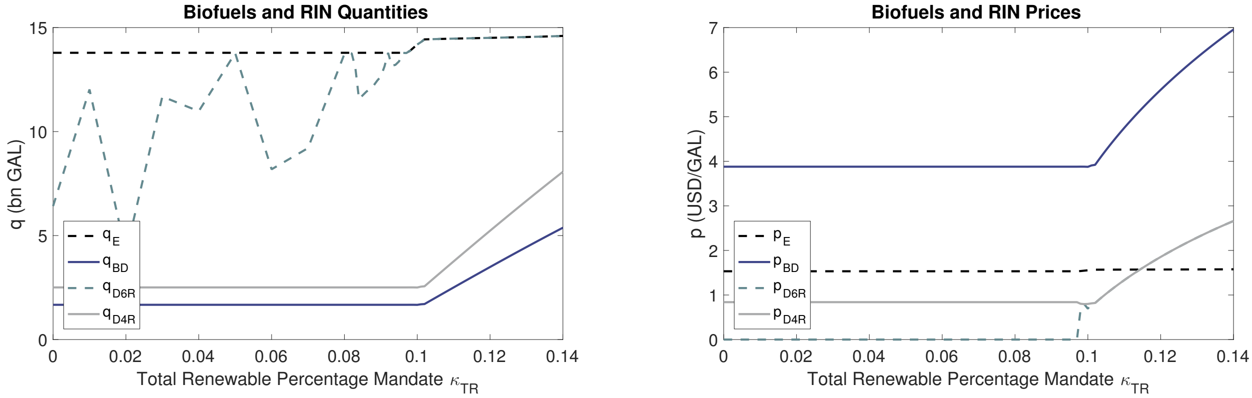

Figure 7: Price and Quantity Changes for Biofuels. All Prices are Shown in USD/GAL. All Quantities are Shown in bn GAL.

incentive structures such as increased biodiesel tax credits.

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Appendix A. Additional Information on the RFS

The RFS2 is implemented as a set of annual volumetric mandates for the 48 contiguous states and Hawaii that are subject to final review by the EPA[12]. In order to apportion these requirements to the obligated parties, the mandates are transformed into percentage blend obligations by dividing the required amount of renewable fuel for the year ahead by the total forecast amount of gasoline and diesel consumption. The forecasts are obtained from the November issue of the Short-Term Energy Outlook[13] preceding the mandate year. The RFS2 thus effectively operates as a blend mandate for biofuels.

Compliance is monitored through so called renewable identification numbers (RINs). RINs represent an accounting mechanism in which a unique 38 digit tracking number is assigned to every gallon of biofuel produced domestically or imported into the U.S. Once the underlying gallon has been physically blended for final consumption in the transportation sector, the RIN becomes detached from the renewable fuel it accompanies and turns into an independently tradable financial instrument. The advantage of this mechanism is that the obligated party can be a step removed from the physical blending process: the necessary amount of RINs for compliance can be procured through the blending of biofuels, purchases in the RIN market or a combination thereof. Similar to a cap-and-trade scheme, RINs therefore allow for efficiency gains through strategic over- and under-blending by obligated parties with heterogeneous cost structures.

In fact, the RFS places the percentage blend obligations on refiners and importers of fossil fuels rather than blenders. This distinction is important since, as highlighted in NERA (2015), around 40% of US refiners in 2015 were neither integrated with blenders nor retailers[14]. The original justification for the choice of obligated party was to minimize regulated parties since the number of importers and refiners at the time was lower than the number of blenders using ethanol. However, due to the increased mandate levels under the RFS2, virtually all blenders now purchase some amount of ethanol and have therefore become regulated, though for the most part not obligated, parties.

The U.S. biofuels environment has been analyzed from a multitude of different angles. Introductions to the regulatory framework as well as the nature of RINs can be found in McCarl and Boadu (2009), McPhail et al. (2011) and Verleger (2013)[15].

A number of papers have challenged the net environmental benefits of the RFS2. Searchinger et al. (2008) were the first to raise the concern that the use of corn-based ethanol might actually increase global greenhouse gas levels due to indirect land use change. A general equilibrium study by Bento et al. (2015) cautions that the RFS in its current form increases emissions due to significant leakages in both land and fuel markets. This result is also underlined by Holland et al. (2015) who explore unintended consequences of the RFS and find that land-use costs from erosion and habitat loss under the RFS2 could be as high

[12] Alaska, Hawaii and non-contiguous U.S. territories are exempted from the program unless they opt in. Unlike Hawaii, Alaska has not yet chosen to exercise this option.

[13] *http://www.eia.gov/forecasts/steo/outlook.cfm*

[14] Percentage based on the number of active firms in the market rather than throughput

[15] The Department of Agricultural and Consumer Economics at the University of Illinois at Urbana-Champaign (*http://farmdocdaily.illinois.edu*) and the Center for Agricultural and Rural Development at Iowa State University (CARD) (*https://www.card.iastate.edu/policy_briefs*) provide regular market commentary and policy briefs to discuss changes to the regulation or market environment. Similarly, Congressional Research Service reports to congress such as Schnepf and Yacobucci (2010) and Yacobucci (2010) provide valuable insights into current discussions around the RFS2.

as \$693 million while a cap-and-trade system would add virtually zero costs of this type.

Another source of concern is the effect of biofuels policies on food prices. De Gorter et al. (2015) explore the nature of the link between crop and fuels markets which U.S. biofuels policy has shaped. They note that agricultural crops such as corn and soybeans can effectively lock on to oil prices through the fundamental pricing relationships implied by blending. These insights help to inform the debate on biofuels' potential to exacerbate famine during food price booms such as in 2007/2008 (Ford and Senauer (2007), Wright (2014)).

Appendix B. Nested Model

The blender and refiner cost functions are represented by constant elasticity functions. In this case, we require $\epsilon > 1$ in order to ensure convexity of the cost function, and hence concavity of the profit function. We allow for synergy effects such as benefits from shared storage infrastructure in the production of gasoline and diesel, as well as in the blending of E10 and E85 by letting both products feed into one joint cost function. Motor gasoline blending and diesel fuel blending on the other hand are treated as separate. The proposed cost functions are therefore of the form highlighted in equation B.1.

In total, the model consists of 25 equations in 25 unknowns:

- Nine quantities: q_{E10}, q_{E85}, q_G, q_{DF}, q_D, q^R_{D4}, q^B_{D4}, q^R_{D6}, q^B_{D6}
- Nine prices: p_{E10}, p_{E85}, p_G, p_{DF}, p_D, p_{BD}, p_{D4}, p_{D6}, p_E
- Five Lagrange multipliers: γ^R_{D4}, γ^R_{D6}, γ^B_{D4}, γ^B_{D6}, γ^B_{E10}
- Two Blend Ratios: θ_{E10}, θ_{DF}

The full set of behavioral equations is shown in the set of equations B.2.

Appendix C. Data and Calibration Results

Throughout this paper, the symbol $\circ$ stands for a generic subscript. The capital letters $D_\circ$, $C_\circ$ and $S_\circ$ represent demand, cost and supply functions respectively. Quantities are always denoted by $q_\circ$ while $p_\circ$ represents prices. The superscripts B and R designate variables pertaining to the blender or refiner respectively.

Table C.3 highlights key data sources as well as the corresponding realizations for 2015. Quantities are shown in billion gallons (bGAL) and prices in USD per gallon or USD per RIN.

Most of the data is collected from the EIA Monthly Energy Review Beta website[16], while the quantity of E85 is calculated as the sum of conventional gasoline blended with fuel ethanol for blends higher than 55%[17] and renewable fuel and oxygenate plant net production of finished motor gasoline[18]. Ethanol prices were obtained through Bloomberg while RIN prices were purchased from OPIS. We are using the B99/B100 biodiesel prices from the DOE Alternative Fuels Data Center as a proxy for wholesale biodiesel prices.

Relevant motor gasoline and diesel fuel tax rates were obtained from the EIA. Including federal and average state taxes, the tax rates for 2015 were at 44.89 USc/GAL and 51.64 USc/GAL respectively. Based on the outlined parametric assumptions and elasticity choices we obtain the calibration results shown in table C.4.

Using these calibrated inputs, we apply a sequential quadratic programming procedure to simulate market equilibria for different mandate levels. Additional notation is summarized in table C.5.

[16] http://www.eia.gov/beta/

[17] EIA Weekly Refiner and Blender Net Production update

[18] EIA Petroleum and Other Liquids report

$$\begin{aligned} \text{Refiner:} \quad & (A^R_{C_G} q_G + A^R_{C_D} q_D)^{\epsilon^R_C} \\ \text{Blender (MG):} \quad & (A^B_{C_{E10}} q_{E10} + A^B_{C_{E85}} q_{E85})^{\epsilon^B_{C_{MG}}} \\ \text{Blender (DF):} \quad & A^B_{C_{DF}} q_{DF}^{\epsilon^B_{C_{DF}}} \end{aligned} \tag{B.1}$$

Appendix D. Reduced Model: Motor Gasoline Only

Refiner's Problem (linear cost of blending, c^R):

$$\begin{aligned} & \max_{\{q_G,\, q^R_{D6}\}} \Pi^R = \\ & p_G q_G - c^R q_G - p_{D6} q^R_{D6} \\ s.t. \quad & q^R_{D6} \geq \kappa_{TR} q_G \end{aligned} \tag{D.2}$$

Blender's Problem (linear markups for blending, (m_{E10}, m_{E85})):

$$\begin{aligned} & \max_{\{q_{E10},\, q_{E85},\, q^B_{D6}\}} \Pi^B = \\ & q_{E10}(p_{E10} - m_{E10} - t_{MG}) \\ & + q_{E85}(p_{E85} - m_{E85} - t_{MG}) \\ & + p_{D6} q^B_{D6} \\ & - (0.9 q_{E10} + 0.26 q_{E85}) p_G \\ & - (0.1 q_{E10} + 0.74 q_{E85}) p_E \\ s.t. \quad & q^B_{D6} \leq \theta_{E10} q_{E10} + 0.74 q_{E85} \end{aligned} \tag{D.3}$$

Linear Demand Functions:

- Case 1: $p_{E85} > \lambda p_{E10}$

$$\begin{aligned} D_{E85} &= 0 \\ D_{E10} &= A_{D_{FFV}} + A_{D_C} \\ &\quad - (B_{D_{FFV}} + B_{D_C}) p_{E10} \end{aligned}$$

- Case 2: $p_{E85} = \lambda p_{E10}$

$$\begin{aligned} D_{E85} &\in [0, A_{D_{FFV}} - B_{D_{FFV}} p_{E10}] \\ D_{E10} &= A_{D_{FFV}} + A_{D_C} \\ &\quad - (B_{D_{FFV}} + B_{D_C}) p_{E10} - q_{E85} \end{aligned}$$

- Case 3: $p_{E85} < \lambda p_{E10}$

$$\begin{aligned} D_{E85} &= A_{D_{FFV}} - \frac{B_{D_{FFV}}}{\lambda} p_{E85} \\ D_{E10} &= A_{D_C} - B_{D_C} p_{E10} \end{aligned}$$

Upper bound on κ_{TR} to ensure that the price of D6 RINs rises with increasing mandate levels provided in equation D.1.

First Order Conditions

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

Market Clearing

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

Complementary Slackness

$$
\begin{aligned}
&\textit{CS Refiner} && \gamma^R_{D4}(q^R_{D4} - \kappa_{BBD}(q_G + q_D)) = 0 \\
&\textit{CS Refiner} && \gamma^R_{D6}(q^R_{D4} + q^R_{D6} - \kappa_{TR}(q_G + q_D)) = 0 \\
&\textit{CS Blender} && \gamma^B_{D4}(1.5\theta_{DF}q_{DF} - q^B_{D4}) = 0 \\
&\textit{CS Blender} && \gamma^B_{D6}(\theta_{E10}q_{E10} + 0.74q_{E85} - q^B_{D6}) = 0 \\
&\textit{CS Blender} && \gamma^B_{E10}(0.1 - \theta_{E10}) = 0
\end{aligned}
\tag{B.2}
$$

Table C.3: 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	Prompt Month Denatured Ethanol Futures	1.51	USD/GAL	Bloomberg
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 C.4: Calibration Results

Variable	Description	Value
$A^R_{C_G}$	Cost Refiner (Gasoline)	0.623
$A^R_{C_D}$	Cost Refiner (Diesel)	0.655
$A^B_{C_{E10}}$	Cost Blender (E10)	0.243
$A^B_{C_{E85}}$	Cost Blender (E85)	0.175
$A^B_{C_{DF}}$	Cost Blender (Diesel Fuel)	0.270
A_{S_E}	Supply Ethanol	2.541
$A_{S_{BD}}$	Supply Biodiesel	0.065
A_{D_C}	Demand Motor Gasoline, Conventional Cars	177.177
$A_{D_{FFV}}$	Demand Motor Gasoline, FFVs	1.200
$A_{D_{DF}}$	Demand Diesel Fuel	47.348

Table C.5: Additional Notation

Variable	Description
γ^R_{D4}	Refiner Lagrange Multiplier Refiner (D4 RINs)
γ^R_{D6}	Refiner Lagrange Multiplier Refiner (D4+D6 RINs)
γ^B_{D4}	Blender Lagrange Multiplier Refiner (D4 RINs)
γ^B_{D6}	Blender Lagrange Multiplier Refiner (D6 RINs)
γ^B_{E10}	Blender Lagrange Multiplier Refiner (E10 blend ratio)
t_{MG}	Motor Gasoline Taxes
t_{DF}	Diesel Fuel Taxes
tc_{BD}	Biodiesel Tax Credit
λ	Energy-equivalence Factor between E10 and E85
$C^R(\cdot)$	Refiner Cost Function
$C^B_{MG}(\cdot)$	Blender Motor Gasoline Cost Function
$C^B_{DF}(\cdot)$	Blender Diesel Fuel Cost Function

$$\kappa_{TR} \leq \frac{\epsilon_{S_E}(0.1 * 0.9\lambda B_{D_C} + 0.26 * 0.74 B_{D_{FFV}}) + \frac{p_E}{q_E}\frac{q_G}{p_{D6}}(0.1^2\lambda B_{D_C} + 0.74^2 B_{D_{FFV}}) + \lambda\epsilon_{S_E}\frac{q_G}{p_{D6}}}{\epsilon_{S_E}(0.9^2\lambda B_{D_C} + 0.26^2 B_{D_{FFV}}) + \frac{p_E}{q_E} B_{D_C} B_{D_{FFV}}(0.1 * 0.26 - 0.74 * 0.9)^2} \tag{D.1}$$

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