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# **Doomed by design: Structural Implications of the Renewable Fuel Standard for E85 Demand**

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**Abstract:** The current consumption of ethanol in the US has fallen short of the ambitious goals of the Renewable Fuel Standard (RFS) which sought to induce the consumption of high blend rates of ethanol and the production of ethanol from not only corn but also cellulosic feedstocks. Instead, a “blend wall” has emerged and limited the demand for ethanol to 10% of motor gasoline (E10) consumed, and there has been negligible production of cellulosic biofuels. Blenders have chosen to comply with the RFS by increasing the blending of biomass-based biodiesel beyond levels that were originally targeted instead of creating a demand for higher ethanol blends by pricing them at an energy-equivalent level with E10. This paper develops a conceptual framework and a simulation model to examine the extent to which the design of the RFS, specifically, its nested structure and the cellulosic biofuel waiver credit are creating disincentives for blenders to pass-through the price incentives (referred to as Renewable Identification Numbers (RINs)) needed to induce demand for E85 and for producing cellulosic biofuels. This analysis provides a conceptual rationale for the observed finding in the empirical literature of incomplete pass-through of RINs to higher ethanol blends and informs policymakers about the unintended consequences of the design of the RFS for its effectiveness.

**Keywords:** Renewable Fuel Standards, RIN Pass-through, Renewable Identification Number, Biodiesel overage, E85 demand

## 1 Introduction

The US Renewable Fuel Standard (RFS), a technology-forcing policy, was established in 2007 to accelerate the supply of various types of biofuels and to stimulate demand for high blends of ethanol in the transportation fuel. The broad categories of biofuels mandated by the RFS include conventional or renewable biofuel (corn ethanol), advanced biofuel (sugarcane ethanol), biomass-based diesel (from soybean oil<sup>1</sup>), and cellulosic biofuel (from biomass feedstocks); these biofuels differ in the savings in greenhouse gas (GHG) intensity relative to conventional fossil fuel. The RFS set an overall target of 36 billion gallons for total biofuels which includes a minimum target of 16 billion gallons for biofuel from cellulosic feedstocks, 1 billion gallons of biomass-based diesel, and 5 billion gallons for other advanced biofuels by 2022; the rest of the mandate could be met by producing conventional biofuel from corn starch to a maximum of 15 billion gallons. Although the RFS specified volumetric mandates for different types of biofuels, it was implemented by setting blend rates at the national level. The refineries or importers that supply gasoline or diesel for domestic use are required to apply the blend rates and blend biofuel proportional to the amount of total fossil fuel they process.

The RFS has failed to achieve its goals as originally intended. While the supply of conventional biofuels from corn has increased to about 15 billion gallons as mandated, production of cellulosic feedstocks has fallen far short of the targeted amount whereas biodiesel production has exceeded the amount originally mandated. Additionally, achieving the RFS statutory target in 2017 would have required a blend rate of 16% of ethanol and required a significant amount of ethanol be sold as higher blends with 85% ethanol (E85). However, the

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<sup>1</sup> The biomass-based oil diesel is from non-petroleum renewable resources such as soybean oil, cananol oil, and other vegetable-oil and animal fat. Soybean oil sources count for more than 80% of the total biodiesel feedstock. We use “biodiesel” as shorted form of biomass-based diesel in the following context.

RFS has failed to generate consumer demand for the higher-blend fuels and ethanol is primarily sold in a 10% blend as E10. Since 2012, a “blend wall” has emerged since sales of higher blends, principally E85, have not grown at the rate needed to produce the volumes mandated originally by the RFS. Consumption of E85 requires flex-fuel vehicles (FFV) to be able to combust higher blends of ethanol as well as pricing of E85 to be at least at parity with the energy-equivalent price of E10. However, the price of E85 has been 7-29% higher than the energy equivalent price of E10 since 2007 (as shown in Figure 1). The absence of demand for ethanol has led to a scaling down of the mandate since 2012, largely by waiving the cellulosic biofuel component of the RFS. A perfectly functioning RFS would ensure that the retail price of ethanol was at parity with gasoline and reflected its lower energy content and provide incentives for consumers to switch from low blend (E10) to higher blend (E85) ethanol.

The purpose of this paper is to analyze the factors that explain the divergence between the observed volumes of the different types of biofuels produced and those mandated by the RFS in 2017. Specifically, we seek to examine the extent to which the key elements of the design of the RFS explains its (in-)effectiveness in meeting its goals. We also examine the implications of the shortfall in meeting the goals of the RFS on the greenhouse gas (GHG) emissions intensity of transportation fuel.

The RFS sought to allow for expansion of advanced and cellulosic biofuels beyond the minimums specified for greater GHG reduction potential while limiting conventional biofuel to an upper bound. It was therefore, designed with a nested structure in which cellulosic ethanol qualifies for the cellulosic, other advanced, and conventional fuel components. Biomass-based diesel certifies for biomass-based diesel, other advanced, and conventional fuel components.

Advanced biofuels qualify for advanced and conventional biofuel components. Corn-based ethanol can only be applied towards the conventional biofuel component.

Compliance with the mandate is achieved by associating a Renewable Identification Number (RIN) with each unit of biofuel. When biofuel is blended with petroleum, RINs are detached from biofuel and can be traded in the RIN market and obligated parties are required to acquire enough RINs to meet their volume obligation every year. Theoretically, with a binding mandate, the price of RINs is the gap between the marginal cost of producing biofuel and the gasoline price at energy equivalent value. Therefore, this RIN price represents the cost of compliance with the mandate for obligated parties. A well-functioning RIN market ensures that the price of biofuel paid by blenders is equal to its marginal cost of production net the RIN value to biorefineries (Miao, Hennessy, and Babcock, 2012). The requirement on blenders to purchase RINs operates as an implicit tax on blending fossil fuels and an implicit subsidy to biofuels. As shown in Table 1, the nested structure of the RFS creates four separate types of Renewable Identification Numbers (RINs) – conventional fuel (D6), cellulosic (D3), biomass-based diesel (D4), and other advanced fuel (D5). Since any of the advanced component classifications could be used to fulfill the conventional biofuel component of the mandate, cellulosic, biodiesel, and advanced RINs should always be valued higher than conventional ethanol RINs.<sup>2</sup>

Additionally, since the supply of cellulosic biofuel is limited and uncertain, the RFS gave the EPA authority to reset the cellulosic biofuel mandate to a lower level and simultaneously offer cellulosic waiver credits to be used to meet the annual cellulosic mandate. The obligated parties

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<sup>2</sup> If this were not the case then an arbitrage opportunity would exist where an obligated party could sell conventional ethanol RINs and purchase an equal volume of advanced RINs for mandate compliance while profiting on the RIN trade. The reverse trade would not work since conventional ethanol RINs cannot be applied towards any of the advanced mandate classifications.

can purchase the waiver credits up to the level of their cellulosic biofuel obligation less the number of cellulosic biofuels RINs that they own to meet their annual cellulosic compliance requirements. The EPA calculates the price of the waiver as the higher of \$0.25 plus the difference between \$3.00 and the average wholesale gasoline price, both prices are inflation adjusted.

Early studies by de Gorter & Just (2009) and Lapan & Moschini (2012) analyze the implications of implementing the mandate by selling a pre-blended fuel with a given blend rate and showed that under perfect competition a blend rate mandate would implicitly tax gasoline and subsidize ethanol. These studies imply full pass-through of RIN value from blender to biofuel producer to the biofuel consumer when the blend rates are lower than 10%. Pouliot & Babcock (2015) studied the RFS compliance mechanism and concluded that a higher mandate would lower E85 price and increase E85 use. While higher blend fuel demand is modeled, they continued to assume complete RINs price pass through. However, recent studies by Knittel et al. (2017), Lade & Bushnell, (2018), and Li & Stock (2018) showed that there is incomplete RINs pass-through between wholesale and retail ethanol price that leads to higher retail E85 price at the energy equivalent basis. While the rationale behind such incomplete pass-through has yet to be discussed, Korting & Just (2017) show that refiners meet the total biofuels mandate by selling biodiesel beyond its statutory blending level bypassing ethanol blend wall. However, none of these studies discussed the consequences of the nested structure of the RFS that allows refiners to use D4 (biodiesel) RINs to comply with the overall renewable fuels mandate instead of creating demand for higher blend ethanol.

We construct a conceptual economic model of the US transportation sector with four representative agents: wholesale petroleum fuel producers (including gasoline and diesel),

wholesale biofuel producers (corn ethanol, cellulosic ethanol, and biodiesel), blenders, and retail fuel consumers. Instead of analyzing the profit-maximizing problem of the refiners and blenders separately (as in Korting & Just, 2017), we develop an integrated representation of the fuel distribution system from the wholesaler producers to the consumers, similar to a social planner's problem, to endogenously determine the induced effect of the design of the RFS on fuel pricing strategies. This representation allows us to endogenously determine optimal prices and quantities of different types of renewable and non-renewable fuels used in the US transportation fuel mix as well as RIN credit volumes and their market prices under the current and alternative designs of the RFS. In addition to analyzing the effects of the nested structure of the RFS we also examine the effects of the cellulosic waiver option in the RFS on the RINs and fuel markets. We study the implications of the design of the RFS by conducting comparative static analysis of stepwise changes in the design features of RFS by analyzing three different policy structures: (i) an integrated nested structure with the cellulosic waiver authority, (ii) nested structure of RFS without the cellulosic waiver; and (iii) a counterfactual non-nested structure design without the waiver. We then conduct a numerical simulation to determine the fuel prices under alternative RFS compliance mechanism.

In the next section, we provide the background of the RFS and the RINs market and describe 2017 compliance mechanism in terms of the nested structure of the RFS. We present the conceptual framework of the model in section 3. Following that, we show our analytical findings. Simulation results and the corresponding GHG estimations are presented in section 4. We conclude section 5 with the discussion of our results.

## **2 Background**



Under the Energy Independence Security Act (EISA) of 2007, the Environmental Protection Agency (EPA) is responsible for administering the RFS. The law requires EPA to announce the total annual renewable fuels mandate and the corresponding sub-mandates of cellulosic biofuel and biomass-based biodiesel by November 30<sup>th</sup> of the previous year. The EPA has the authority to waive the mandate and reduce the applicable volume of cellulosic ethanol if the inadequate domestic supply generates potentially severe economic harm (Coppess & Irwin, 2017).

Since 2011 they are waiving a significant portion of the cellulosic biofuel mandate and the corresponding overall renewable fuel volumes. In 2017, the EPA used its waiver authority and reduced the cellulosic biofuel mandate from 5.5 billion to 311 million gallons. In contrast, the EPA increased the advanced biomass-based diesel requirement to 2 billion gallons during the same period, keeping the conventional gap unchanged at 15 billion gallons. The actual volume of different types of biofuel produced by the obligated parties (refiners or oil importers) diverged from the mandated amounts<sup>3</sup>, 2.56 billion gallons of biodiesel were counted towards the mandate and only 261 million gallons of cellulosic biofuel was produced in 2017. The conventional ethanol production also fell short by 1.1 billion gallons in the conventional fuel gap, which is partly offset by the additional amount of biodiesel produced. Therefore, the overage of biodiesel with RFS compliance is hindering further growth of ethanol demand.

The EISA also requires EPA to issue cellulosic waiver credits corresponding to the waived volume of the cellulosic biofuel mandate. The obligated parties (oil refiners and importers) can use those waiver credits to comply with the cellulosic mandate obligations when they are not able to produce enough such biofuel. However, unlike RINs, the cellulosic waiver credits are

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<sup>3</sup> Source: <https://www.epa.gov/fuels-registration-reporting-and-compliance-help/annual-compliance-data-obligated-parties-and#nested-rvo>

neither tradable nor can be used to meet the total renewable fuels mandate. In other words, in case when the obligated parties are using cellulosic waiver credits they need to acquire an equivalent volume of non-cellulosic RINs to meet the overall mandate requirements. While there is no direct subsidy towards the conventional ethanol production, biodiesel producers enjoy \$1 per gallon of tax credit according to the Biodiesel Tax Credit Extension Act. The cellulosic biofuel producers tax credit expired in 2016.

The RFS mandate is enforced through the nested RIN compliance mechanism to enhance the GHG emission reduction potential. There are four different categories of RINs: D3, D4, D5, and D6 corresponding to cellulosic (60% less GHG emission compared to the replaced fossil fuels), biomass-based biodiesel (50% less GHG emission), advanced biofuels (50% less GHG emission), and conventional renewable fuel (20% less GHG emission). Due to the nested structure of the RFS, D3, D4, and D5 can be counted towards the total renewable fuel compliance; but the inverse is not allowed. If the mandates are binding then D3 (cellulosic) and D4 (biodiesel) RIN prices are higher than D6 (conventional) RIN prices. However, in recent years, D4 and D6 RIN prices converge as shown in Figure 2, because of the over-production of the biodiesel RINs, whereas the oil refineries inability to meet cellulosic obligation leads to soaring D3 RIN price. In this study, we analyze the role of the RFS design features (nested structure with and without cellulosic credit waiver, and non-tested structure) toward the RIN prices and pass-through.

### **3 Theoretical Model**

#### **3.1 Model Setup**

We now describe a stylized partial equilibrium, multi-market, closed economy analytical model to analyze the social welfare maximizing optimizing choices of fuel mix, equilibrium quantities

and prices in the U.S. transportation sector subject to the RFS mandate constraints. The stylized transportation sector model consists of fuel consumers, fuel blenders, biofuel producers, and refineries. The decision variables of fuel identity are defined as follows. We formulate one aggregated consumers demand for E10 and E85 that allows a normative fuel shift to E85 on the energy equivalent basis. Because FFV has a market share over 7%, the utmost ethanol demand could be as high as 15% of the total gasoline fuel. The aggregated demand of the total blended gasoline fuels ( $q_{gf}$ ) is defined as  $\gamma_{E10}q_{E10} + \gamma_{E85}q_{E85}$ , where  $q_{E10}$  and  $q_{E85}$  are E10 and E85 blend demand that are functionally equivalent on gasoline base for FFV drivers.  $\gamma_{E10}$ , and  $\gamma_{E85}$  are the corresponding gasoline energy equivalent coefficients, respectively. We model a separate demand for blended biodiesel ( $q_{df}$ ) for all the diesel-fueled vehicles.

The blender purchases gasoline ( $q_g$ ) and diesel ( $q_d$ ) from refineries; corn ethanol ( $q_e$ ), cellulosic ethanol ( $q_c$ ), and biodiesel ( $q_b$ ) from biofuel producers to produce two types of ethanol blended fuel of E10 and E85<sup>4</sup> and blended diesel. Total ethanol (including corn and cellulosic) produced is equal to the amount blended into E10 (10% of the volume of E10) and E85 (74% of the volume of E85). This is represented as  $q_e + q_c = 0.1q_{E10} + 0.74q_{E85}$ . Similarly, the total amount of gasoline blended is equal to the amount blended in E10 and E85 which contain 90% and 26% of gasoline respectively; thus  $q_g = 0.9q_{E10} + 0.26q_{E85}$ . The retail biodiesel is blended from petroleum diesel and biomass-based biodiesel, represented as  $q_{df} = q_b + q_d$ , where biodiesel has close energy content to diesel. Unlike ethanol blends, the recent level of biodiesel

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<sup>4</sup> Considering that there is very little demand for E15 (15% ethanol blend) and for simplicity of our analysis we only consider E10 and E85 throughout our study.

blended with petroleum diesel is less likely to pass the 5% blend (B5), which is allowed to be sold without label and is accepted for warranted diesel vehicle and engines (EPA, 2016).

Following the EPA guidelines, we further construct the RIN market by specifying the RINs' generation processes with every gallon of biofuels produced. The blended volume of cellulosic ethanol determines the D3 RINs ( $q_{D3}$ ); the amount of D4 RINs produced ( $q_{D4}$ ) is calculated by multiplying the total volume of biomass-based diesel with 1.5 to convert it to ethanol-equivalent volume. The total quantity of D6 RINs ( $q_{D6}$ ) is determined by the volume of corn ethanol blended with gasoline. We define the ethanol-equivalent volume of each of the three different categories of RINs as:  $q_{D3} = q_c$ ,  $q_{D4} = 1.5q_b$ , and,  $q_{D6} = q_e$ .

We represent the social planner's optimization problem to determine the optimal quantity and mix of alternative fuels and RINs as well as their prices, subject to the RFS policy mandate and alternative structure specified in the RFS as follows:

$$\begin{aligned} \max_{\{q_{gf}, q_{df}, q_e, q_c, q_g, q_d, q_b, q_{cw}\}} \text{Social Welfare} = & \int_0^{q_{gf}} D_{gf}(\cdot) dq_f + \int_0^{q_{df}} D_{df}(\cdot) dq_{df} - \\ & \int_0^{q_e} S_e(\cdot) dq_e - \int_0^{q_c} S_c(\cdot) dq_c - \int_0^{q_b} S_b(\cdot) dq_b - \int_0^{q_g} S_g(\cdot) dq_g - \int_0^{q_d} S_d(\cdot) dq_d - C(q_{gf}, q_{df}) - \\ & P_{cw}q_{cw} + t_Bq_b \end{aligned} \quad (1)$$

For simplicity, we denote the short-term inverse demand and supply functions as  $D(\cdot)$  and  $S(\cdot)$ , respectively. The first two integrals of the downward sloping consumer demand functions for blended gasoline and diesel  $D_{gf}(\cdot)$  and  $D_{df}(\cdot)$  in equation 1 display the total benefit consumer gains. The next five terms are the production costs integrating the upward sloping supply functions of corn ethanol, cellulosic ethanol, biodiesel, gasoline, and diesel are represented by  $S_e(\cdot)$ ,  $S_c(\cdot)$ ,  $S_b(\cdot)$ ,  $S_g(\cdot)$ , and  $S_d(\cdot)$ .  $C(q_{gf}, q_{df})$  is the blending cost incurred by the blenders in

producing the blended fuels represented as  $w_{gf}q_{gf} + w_{df}q_{df}$ , where  $w_{gf}$  and  $w_{df}$  are per unit cost of the blended gasoline mix product and blended biodiesel product, respectively.  $P_{cw}$  is the assigned price for each unit of cellulosic waiver credit ( $q_{cw}$ ) and  $t_B$  is the \$1 biodiesel tax credit per gallon of biodiesel blended.

Subject to

$$q_{D4} \geq \theta_b (q_g + q_d); \quad (2)$$

$$q_{D3} + q_{cw} \geq \theta_c (q_g + q_d); \quad (3)$$

$$q_{D3} + q_{D4} + q_{D6} \geq \theta_r (q_g + q_d) \quad (4)$$

Equations 2-4 represent the status-quo RFS blend mandate<sup>5</sup>. The RFS requires the renewable fuel volume mandates to be met annually through the RIN compliance mechanism. The volumetric RIN targets for each fuel type cellulosic ( $q_{D3}$ ), biodiesel ( $q_{D4}$ ), and conventional ethanol ( $q_{D6}$ ) are operated by multiplying blend rates corresponding to different categories of biofuels:  $\theta_b$  (biodiesel),  $\theta_c$  (cellulosic), and  $\theta_r$  (overall renewable fuel) with total petroleum fuel consumed ( $q_g + q_d$ ). The biodiesel RIN required should be at least biodiesel blend rate times the total petroleum fuel. The cellulosic waiver credits that can be explicitly used to meet cellulosic mandate is introduced in equation (3), while the nested feature of the RFS is represented by equation (4) which allows all types of biofuels to be counted towards the overall mandate.

We further introduce two alternative designs of RFS scenarios to address the normative behavior of the fuel supply, fuel blend, and RIN incentives. First, we assume that the obligated parties are not offered with the option to use cellulosic waiver credit by setting  $q_{cw} = 0$  in equation (2) and

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<sup>5</sup> As majority of the D5 RINs are generated from sugarcane ethanol imported from Brazil and since we assume a closed economy in this study, for simplicity of our analysis we only consider above mentioned three categories of RINs compliance mechanism.

label it as “Nested without waiver RFS” scenario. Second, we develop a counterfactual “Non-nested RFS scenario without waiver” by substituting equations (3) and (4) with  $q_{D3} \geq$

$\theta_c (q_g + q_d)$ , and  $q_{D6} \geq \theta_e (q_g + q_d)$ , respectively.

By using the Lagrangian method, we solve the model to determine the Karush-Kuhn-Tucker (K-K-T) optimality conditions for the key decision variables with interior solutions as summarized in Table 2. The detail description of the Lagrangian representation and mathematical derivation can be found in the appendix A1. Since we assume that conventional and cellulosic ethanol are perfectly substitutable, we find that wholesale corn ethanol price ( $p_E^{ws}$ ) is obtained either by subtracting D6 RIN credit price ( $P_{D6}$ ) from the marginal cost of corn ethanol ( $S_e(q_e)$ ) or by subtracting D3 RIN credit price ( $P_{D3}$ ) from the marginal cost of cellulosic ethanol ( $S_e(q_e)$ ). Biodiesel wholesale price ( $p_d^{ws}$ ) is determined by subtracting 1.5 times (ethanol energy equivalent) D4 RIN credit price ( $P_{D4}$ ) and the biodiesel tax credit ( $t_B$ ) from the marginal cost of biodiesel  $S_b(q_b)$ . Gasoline and diesel wholesale prices are obtained by adding per gallon fossil fuel tax which is implicitly derived from the summation of the shadow prices of three blend mandates times the respective blend rates ( $\lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r$ ) to the corresponding marginal gasoline  $S_g(q_g)$  and diesel  $S_d(q_d)$  costs. The per gallon E10 ( $p_{E10}^{rt}$ ) and E85 ( $p_{E85}^{rt}$ ) retail prices are determined by the different ethanol and gasoline blend combinations plus the blending cost. Lastly, the retail prices of the gasoline mix of E10 and E85 are the same and obtained by the demand function of gasoline mix fuels at the optimal level of the fuels consumption. This condition can be held only when E85 consumption is nonzero. This indicates the conditions for FFV owner to switch to E85 when retail price of E85 is at parity. Similarly, the retail price of blended diesel from the blended diesel demand curve is equal to the wholesale price of diesel plus the blending cost.

### 3.2 Analytical results

In this section, we analytically explore the underlying factors that determine the RIN price and find justification for the incomplete RIN pass-through. We trace the impact of alternative RFS structural design on the RIN prices and shadow price of cellulosic mandate waiver. Our results suggest that the over-production of biodiesel beyond the statutory blending mandate happens due to two factors: (i) the nested structure of the RFS, and (ii) the usage of cellulosic waiver credits by the obligated parties. We show that such overage results in incomplete RIN pass through from wholesale to retail price, creating a price gap between E10 and E85 at the energy equivalent basis. We further construct a comparative statics framework to study the blenders' marginal conditions for choosing additional biodiesel to comply with the overall renewable mandate instead of ethanol.

#### 3.2.1 Policy implication on the RIN pricing and cellulosic waiver credit

As already shown in the first order condition in Table 2, RIN prices subsidize the biofuel producers to reduce the production cost and serve as marginal compliance costs for the obligated party. Under the nested structure with or without cellulosic credit waivers, D3 RIN price ( $P_{D3}$ ) is equal to the sum of shadow prices of the cellulosic ( $\lambda_c$ ) and the total renewable fuel mandates ( $\lambda_r$ ). D4 RIN price ( $P_{D4}$ ) is the sum of shadow prices of the biodiesel ( $\lambda_b$ ) and the total renewable fuel mandates ( $\lambda_r$ ). D6 RIN price ( $P_{D6}$ ) is equal to the shadow price of only total renewable fuel mandate ( $\lambda_r$ ) as shown in table 2, which suggest D3 and D4 RIN prices are higher than D6 RINs. Our results are driven by the fact that due to the nested structure of the RFS, the advanced RINs (D3 and D4) can be used to comply with the overall renewable fuel mandate (D3).

However, in reality biodiesel is observed to be overproduced beyond its mandated level that which results in zero compliance cost to meet the ( $\lambda_b = 0$ ). Therefore, the price of D4 RIN converges to D6 price (as observed in Figure 2), and biodiesel becomes the marginal fuel to meet the total renewable fuel mandate. In contrast to the nested setting, the RIN prices under the non-nested structure are independent and are equal to the shadow prices of the fuel type-specific mandate as shown in Table 3.

As mentioned in the earlier, EPA offers the cellulosic credit waivers and the refiners and oil importers can either purchase D3 RINs or cellulosic waiver depending on their corresponding price to meet the cellulosic mandate requirement. The first order condition of the cellulosic waiver credit shows that the price of cellulosic credit waiver ( $P_{cw}$ ) is equal to the shadow price of the cellulosic mandate ( $\lambda_c$ ), which is the marginal compliance cost of using cellulosic waiver to meet the cellulosic mandate. The obligated party purchases the cellulosic waiver credit when the waiver cost is equal to the marginal compliance cost of cellulosic biofuel mandate. Our model provides a threshold to the cellulosic waiver credit price at the shadow price of cellulosic biofuel mandate, above which implemented by the EPA could incentivize the cellulosic ethanol production.

### 3.2.2 Pass-through of RINs to E85

We explore the cause of higher E85 price compared to E10, by taking the difference between the retail prices of E10 and E85 obtained from Table 2 and reorganize it in equation 5.

$$p_{E85}^{rt} - p_{E10}^{rt} = \left( \mu \frac{S_e(\cdot)q_e + S_c(\cdot)q_c}{q_e + q_c} - vS_g(\cdot) \right) - \left[ \mu \frac{P_{D6} \times q_e + P_{D3} \times q_c}{q_e + q_c} + v(\lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r) \right] \quad (5)$$



where  $\mu = \frac{0.74}{\gamma_{E85}} - \frac{0.1}{\gamma_{E10}}$  and  $v = \frac{0.9}{\gamma_{E10}} - \frac{0.26}{\gamma_{E85}}$ . The marginal cost difference of producing the two fuels is represented in the first bracket, and the RFS incentives through the D3 and D6 RIN credits mechanism corresponding to the volume of cellulosic ( $q_c$ ) and conventional ethanol ( $q_e$ ) along with the implicit taxes imposed on the gasoline is shown in the second bracket.

Similar to Knittel et al. (2017), we define the “pass-through” in equation (6) to the extent to which the additional RIN incentive covers the production cost gap between E85 and E10, and as the ratio of the RFS incentives difference to the production cost gap between E10 and E85.

$$\text{Pass-through} = \frac{\mu \frac{P_{D6} \times q_e + P_{D3} \times q_c}{q_e + q_c} + v(\lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r)}{\mu \frac{S_e(\cdot) q_e + S_c(\cdot) q_c}{q_e + q_c} - v S_g(\cdot)} \quad (6)$$

Using the above “pass-through” definition, we show how the alternative RFS structural design affects the pricing strategies of E85 versus E10 at the blend wall.

**PROPOSITION 1:** *Non-nested RFS mandate at the blend wall secures the complete RIN pass-through and price E10 and E85 at the energy parity by implicitly taxing E10 and subsidizing E85, regardless of biodiesel production*

The marginal increase of the ethanol blend rate at 10% blending level, demonstrated as  $\theta_c + \theta_e = 0.1 q_g / [0.9(q_g + q_d)]$ , results in positive E85 use as shown in appendix 2.1. The positive marginal E85 consumption supported by KKT theory leads to 100% RIN pass-through and the retail E85 price ( $p_{E85}^{rt}$ ) is equal to E10 price ( $p_{E10}^{rt}$ ) at the energy equivalent basis. Therefore, under the counterfactual non-nested structure, the RFS incentive is fully passed through to E85 even in the presence of the blend wall constraints, leading to E10 and E85 price parity at the gasoline energy equivalent basis which increases E85 consumption. Note that the biodiesel production does not affect the prices of E10 and E85.

PROPOSITION 2: *Existing biodiesel overage under nested RFS mandate and the blend wall prevents full RIN pass-through from wholesale ethanol to retail E85 resulting in higher E85 price compared to E10*

We re-write the blend percentage mandate at blend wall in terms of the nested structure of the RFS as  $\theta_r - \theta_b = 0.1q_g/[0.9(q_g + q_d)]$ . We find that at the 10% blending rate, E85 demand ( $q_{E85}$ ) is  $\frac{-[q_{D4} - \theta_b(q_g + q_d)]}{0.74 - 0.26(\theta_r - \theta_b)}$ . The biodiesel over production  $q_{D4} - \theta_b(q_g + q_d) > 0$  leads to zero E85 consumption. Unlike the non-nested structure, the marginal increase in ethanol blend is not able to create positive ethanol demand. This is mainly driven by the fact that the overage of biodiesel production hinders the complete RIN pass-through which lead to higher E85 price than E10.

However, if the policymaker is fully aware of the amount of the biodiesel over-compliance, E85 demand can be stimulated by raising the blend rate  $(\theta_r - \theta_b)$  greater than

$\frac{0.1q_{E10} + [q_{D4} - \theta_b(q_g + q_d)]}{0.9q_{E10} + q_d}$ . Given the blend wall limit condition discussed above, we derive a range

of the blend rates of  $\theta_r - \theta_b$  that not be able to overcome the blend wall with ethanol blend

stagnated at 10%:  $\frac{0.1q_g}{[0.9(q_g + q_d)]} < \theta_r - \theta_b < \frac{0.1q_{E10} + [q_{D4} - \theta_b(q_g + q_d)]}{0.9q_{E10} + q_d}$ . Details are shown in

appendix A2.2.

We obtain identical results when cellulosic waiver credits are introduced along with the nested structure of the RFS. However, with the issuance of the cellulosic waiver, the biodiesel D4 RINs can substitute either corn ethanol D6 RINs or cellulosic D3 RINs to comply with the total renewable fuel standard. This could increase D4 overages as  $q_{D4} - \theta_b(q_g + q_d)$  and further

hinders E85 consumption as D3 and D6 RINs prices fall widening the gap between E85 and E10 retail price.

Since 2000, average retail prices of E85 were higher than E10 price at the gasoline energy equivalent and at times the price gap raised up to \$1.6 per gge which suggests that either D3 and D6 RINs price were not enough to establish price parity or RIN incentives were not completely passed through from wholesale to retail prices. We analytically show that due to the nested structure of the RFS, over-production of biodiesel causes incomplete RIN pass-through. Thus in order to achieve ethanol consumption beyond blend wall, E85 and E10 price parity ( $p_{E85}^{rt} = p_{E10}^{rt}$ ) is required which can be accomplished through the RFS incentive mechanism.

### 3.2.3 Strategic biodiesel overage choice

To examine the economic drivers for the blenders to choose biodiesel over other biofuels, we use comparative statics and study the compliance cost with the marginal increase in the biodiesel production across the mandates. Unlike Korting and Just (2017), we consider blenders to earn zero profit under perfectly competitive market with a free-entry to the blending industry. We focus on the marginal change in the total blending cost with the structural change in RFS policy (i) from the non-nested structure to the nested with a marginal increase in D4 RIN compliance beyond the mandated level, and (ii) from the nested to the nested waiver with the addition of the cellulosic waiver option. The total differentiation analysis gives the following propositions. The detailed derivation and the proofs for the propositions are provided in Appendix A3.

PROPOSITION 3: *Blenders choose to comply with the mandate through the biodiesel pathway instead of the ethanol pathway if the elasticity-weighted marginal cost of using biodiesel is lower than that of conventional biofuel when*

$$\left(\frac{1}{\eta_b} + 1\right) S_b(q_b) < \left(\frac{1}{\eta_e} + 1\right) S_e(q_e),$$

where  $\eta_b$  and  $\eta_e$  are the elasticities of the supply for biodiesel and conventional corn ethanol and  $S_b$  and  $S_e$  are the marginal cost of producing biodiesel and corn ethanol, respectively. If the elasticity-weighted marginal cost of biodiesel is lower than the elasticity-weighted marginal cost of corn ethanol, the blenders will choose to blend more biodiesel beyond the mandated level of biodiesel required by the RFS.

This supplements the Korting & Just (2017) on the analytical rationale of using biodiesel and provides the explicit blending condition for the blenders to use biodiesel overage as an important channel to comply with the total renewable fuel mandate. We note that the observed wholesale price of ethanol (\$1.61 per gallon) is less than the biodiesel price (\$3.55 per gallon), the reorganized condition implies supply elasticities of biodiesel should be higher than the corn

ethanol as  $\frac{\frac{1}{\eta_b}+1}{\frac{1}{\eta_e}+1} < \frac{S_e(q_e)}{S_b(q_b)}$  that the biodiesel is favored over corn ethanol. The biodiesel production

can be scaled beyond the blend wall until the marginal cost ratio raise to  $\frac{S_e(q_e)}{S_b(q_b)} = \frac{\frac{1}{\eta_b}+1}{\frac{1}{\eta_e}+1}$ .

PROPOSITION 4: *The provision of a cellulosic biofuel waiver will lead blenders to further substitute biodiesel for cellulosic ethanol to meet the total renewable fuel mandate only when*

$$(\frac{1}{\eta_b} + 1)S_b(\cdot) < (\frac{1}{\eta_e} + 1)S_e(\cdot) < (\frac{1}{\eta_c} + 1)S_c(\cdot).$$

Added on the nested structure, the cellulosic waiver credits provide another option to meet the cellulosic mandate as well as a new pathway for the biodiesel over-compliance. The necessary condition for overusing the D4 RIN is when the elasticity-weighted marginal cost of using biodiesel is cheaper than those of corn ethanol and cellulosic ethanol. Note that the drop in the weighted marginal cost in using biodiesel to substitute the cellulosic waiver  $(\frac{1}{\eta_c} + 1)S_c(\cdot) - (\frac{1}{\eta_b} + 1)S_b(\cdot)$  is greater than that of being used for replacing the corn ethanol  $(\frac{1}{\eta_e} + 1)S_e(\cdot) - (\frac{1}{\eta_b} + 1)S_b(\cdot)$ . This indicates that the most efficient way to use excess biodiesel D4 RIN is to first replace the cellulosic waiver credit and then to meet the conventional fuel mandate gap.

The biodiesel overage for cellulosic mandate will stop when the marginal cost raise up until  $(\frac{1}{\eta_b} + 1)S_b(\cdot) > (\frac{1}{\eta_c} + 1)S_c(\cdot)$ , that is when the weighted marginal cost of producing biodiesel is higher than the weighted marginal cost of producing cellulosic ethanol. Moreover, when biodiesel is overproduced up to the point when  $(\frac{1}{\eta_b} + 1)S_b(\cdot) > (\frac{1}{\eta_e} + 1)S_e(\cdot)$ , that is the biodiesel is more costly compared to the conventional corn ethanol, beyond which biodiesel will no longer be used to meet the total renewable fuel mandate. The extent to which the strategic biodiesel overage applies depends on the relative marginal production cost and the supply elasticities of biodiesel, corn ethanol, and cellulosic ethanol at the equilibrium production level.

#### 4 Numerical model and data description

The above-mentioned analysis is further used to develop a numerical multi-market partial equilibrium simulation model of the US fuel sectors that integrates the fuel wholesalers, blenders, and fuel consumers. The model is used to investigate numerically the impact of the structural design of RFS towards the incomplete RIN pass-through for the year 2017. Market equilibrium is achieved by maximizing the sum of the US fuel consumers' and producers' surpluses in the transportation sector subject to the policy constraints. The model endogenously solves the market equilibrium prices and quantities for the different types of fuel and RIN markets.

The model input includes parameterized fuel demand and supply functions, and RFS percentage blend mandate. We formulate linear functions for the fuels demand and the wholesale fuel supply markets. Table 4 lists the elasticities applied in the model and the reference range from the literature. Pivoted at observed E10 price of \$2.26 per gasoline gallon equivalent (gge<sup>6</sup>) in 2017 (DOE, 2017), the aggregated demand is 143.01 billion gallons. We consider a short-term mixed gasoline fuel demand elasticity of -0.03 that is within the EIA estimated range. Similarly, the aggregated demand curve for diesel fuel is built on the 2017 observed total diesel fuel use level (60.28 billion gallon diesel and 2.61 billion gallons of biodiesel in 2017) and at a reported retail price at \$2.73 per gallon (DOE, 2017). The demand elasticity for diesel is assumed to be -0.37, which is within the range of the reported literature (Table 4).

The short-run upward sloping linear curves are set up for the supply of gasoline, diesel, corn ethanol, cellulosic ethanol, and biodiesel. The supplies of each type of fuels are calibrated to the actual 2017 volumes. For simplicity, we consider a closed economy and adjust the domestic

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<sup>6</sup> The volume of gasoline mixed fuels are displayed in gasoline gallon equivalence (gge). The RIN credits are measured by ethanol gallon equivalence (ege).

gasoline and diesel production by excluding the volume of the US net fuel exports. The 2017 fuels production data used to calibrate our model is as follows: the domestic net gasoline and diesel production are 128.58 billion gallons and 60.28 billion gallons, respectively, and the domestic ethanol production is 14.43 billion gallons (EIA, 2019c). We assume all cellulosic ethanol are domestically produced. Meanwhile, we observe that with a rising net import of biodiesel at 0.3 billion gallons from the rest of world in 2017 (EIA, 2019b), the total biodiesel used for RFS compliance reach 2.61 billion gallons. The calibrated elasticities of supply functions are provided in Table 4.

The next step is to simulate the 2017 RFS volume mandate obligations with the percentage standard. Our model endogenously determines the validated fossil fuel levels of gasoline and diesel of the nested structure of RFS with the cellulosic waiver, which may differ from the EPA reported percentage levels. Nonetheless, the validated volumes are within the 10% range to the 2017 actual volume of biofuel consumed, which we use to obtain close estimates of mandated blend rates of different biofuel types with the actual percentages. We also calibrate the blend rates for the other two counterfactual scenarios: nested without cellulosic waiver and the non-nested to reach a comparable 2017 biofuel production level.

The last step is to trace the GHG implication of alternative RFS policy design. Based on EPA's emission intensity (US EPA, 2016) and Oak Ridge National Laboratory's (2019) energy density, we calculate the total life cycle emission corresponding to the volume of different type of fuel use. The emission factors per gallon of the fuel are obtained by multiplying the emission intensity with the energy intensity, as shown in Table 6.

#### **4.1 Simulation results**

We first validate and calibrate the comprehensive nested RFS structural design and cellulosic waiver scenario with the 2017 historical data and find that the results are within the 10% deviation range, except the D6 price (as shown in Table 5). Even though the simulated D6 RIN price is 24% higher than the observed \$ 0.57 per ege, the absolute deviation is only \$ 0.14 per ege. Previous studies (Chen, Huang, Khanna, & Önal, 2014; Nuñez & Önal, 2016) use similar tolerance level to validate their models. Henceforth, we think our stylized model provides a reasonable approximation to the market conditions in the fuel market in the US.

#### 4.1.1 . Effects on RINs compliance

Figure 3 compares the volume of actual RIN retired to comply with the RFS mandate in 2017 against three simulative policy scenarios: non-nested RFS, nested without waiver RFS, and nested RFS with the waiver. The volumes of different types of biofuels required by the RFS are represented by the dashed line which in total is 18.311 ethanol-equivalent gallon (ege) with 15 billion conventional ethanol, 3 billion ethanol-equivalent gallon biodiesel, and 311 million cellulosic ethanol.

Our simulation results show that the non-nested structure of the RFS can produce the exact mandated amounts for each type of biofuel as required by the law. The distinct biofuel mandate leads to achieving the cellulosic biofuel target without using cellulosic waiver credits. However, when we simulated the nested structure of the RFS without waiver to achieve the overall biofuels mandate, our model predicts a over-production of 1.28 billion eges of D4 RINs replacing 8.5% of the D6 RINs (compared to the non-nested RFS as shown by the downward arrow in the second column) which hinders further ethanol blend growth beyond E10. However, when we introduce the cellulosic waiver along with the nested structure of the RFS, we find this displacement lowers to 7% (down arrow in the third bar) while that biodiesel overage increase



slightly. We find the rest of biodiesel RINs substitute 200 million egs of the cellulosic ethanol (up arrow on the top of the third bar) that are bundled with the cellulosic waiver credits.

The above results show the strategic D4 RINs overage is exercised under both nested with and without cellulosic waiver scenarios. Biodiesel embraced in the nested structure are counted towards the total renewable fuel mandate and substitutes D6 RINs. The additional cellulosic waiver credit prioritizes another pathway of D4 RINs overage to be used along with cellulosic waiver credit. The actual observation shows a consistent pattern of D4 overage: first refiners use it to fill the 0.012 billion gallons of cellulosic waiver credits gaps and then use the remaining 0.83 billion to offset the shortfalls in the conventional corn ethanol.

#### 4.1.2 Effects on RINs incentives and fuel pricing

Figure 4 compares observed 2017 RIN prices with the RINs prices obtained from solving our model under three scenarios. RIN prices quantify the per unit subsidy that the biofuels producers required to meet the corresponding biofuel mandate. In each scenario, the corresponding RIN prices are affected by the alternative RFS mechanism as well. In case of the RFS mandate with the assumption that they are not nested we find D3, D4, and D4 RIN prices as \$3.14, \$0.29, and \$1.16 per ege, respectively.

Our nested-RFS scenario without waiver finds that both D6 and D3 RIN price drop by 42% and 10% to \$0.71 and \$2.87 per ege, while D4 RIN price doubles to \$0.71 per ege compared to the non-nested RFS scenario. As shown, D4 and D6 prices converge, which happens due to the slack biodiesel mandate resultant from the over-production of biodiesel under the nested structure of the RFS as shown in Figure 4. We find similar outcomes in case of nested RFS with the waiver scenario. D4 and D6 prices are identical at \$0.71 per ege, but the D3 RIN price declines further to \$2.71 per ege. The additional 5% drop in the D3 price is justified by the availability of

cellulosic waiver credit option to meet the cellulosic mandate. We also plot the actual D3, D4, and D6 RIN prices in 2017, which are within the range of our simulated outcomes. The observed greater D4 RIN price verifies a stronger incentive for biodiesel overproduction while it undermines the support for the ethanol RINs (D3 and D6) and correspondingly diverts the incentive away from E85.

The retail fuels (E10 and E85) prices are shown in Figure 5. We find that the nested structure of the RFS results in the widening price gaps between E10 and E85. The E10 prices remain relatively constant at \$2.26 per gge across alternative RFS policy scenarios. However, E85 prices soar with less ethanol RINs passed through in the case of nested RFS scenarios. The E85 price is hence 12% higher than E10 under the nested structure without cellulosic waiver and 14.2% higher under nested with the waiver.

We further disentangle the retail price gaps between E10 and E85 into marginal production cost difference and the additional RIN incentives to E85 compared to E10 (as discussed in 3.2.2).

When the RIN pass-through is weak, it hardly covers the marginal cost difference of producing these two blended fuels. As shown in Figure 6, the marginal production cost gap drops from \$1.16 per gge to \$1.00 per gge from non-nested RFS to nested without waiver scenarios, while the corresponding RIN incentives difference falls at an even faster rate from \$1.16 per gge to \$0.71 per gge. We find that the RIN pass-through fall to 71% when we model RFS with nested structure, while our simulation model finds 100% RIN pass-through for non-nested RFS scenario as shown in Figure 6. Additionally, RIN incentives further drop to \$0.68 per gge in case of nested with waiver scenario that reduces pass-through to 68%. However, in reality in 2017 the RIN pass-through incentives is only 54%. The D4 RIN is adversely advanced, which is not passed through to E85, and sets a higher price floor for the E85 pricing with biodiesel being

overproduced. However, the actual observed pass-through is lower due to the slightly higher production cost difference and lower RIN incentives.

#### 4.1.3 GHG implications

The intention of the nested structure of the RFS is to achieve higher GHG emissions reduction through the use of advanced biofuels beyond the original mandate volume. If cellulosic waiver credits are used to meet the cellulosic mandate and equal amount of biodiesel D4 RINs are counted towards the overall mandate, it is expected that the RFS will achieve lower GHG mitigation as biodiesel has only at least 50% less GHG emission potential compared to cellulosic ethanol which can at least reduce 60% GHG emissions compared to fossil fuels. However, if biodiesel is used to meet the conventional mandate that only reduces GHG emission by at least 20%, then biodiesel overage is effective in terms of lower carbon intensity.

The GHG implication of each policy design and the breakdown of sources are displayed in Table 7. The total GHG emission under non-nested structure is 2,281 million metric ton (MMT), 62% and 33% of which are from gasoline and diesel, respectively, while the total biofuels mandate of achieving RFS only contributes to 5% of the total GHG emissions. We find that compared to the non-nested RFS scenario, the nested structure without cellulosic waiver only reduce GHG emission by 3.39 MMT. The gasoline emission increased by 9.58 MMT due to 0.85 billion gallons higher gasoline consumption driven by lower implicit taxes on fossil fuels compared to the non-nested structure. Contrarily, 0.85 billion gallon less petroleum diesel use decreases the emission by 10.8 MMT as the blenders overusing biodiesel to meet both the conventional and overall biofuels mandate. This overage also replaces 8.23 MMT of GHG emission which otherwise would have been derived from conventional corn ethanol.

The addition of the cellulosic waiver along with the nested structure of the RFS, the emissions and volumetric production in the gasoline and diesel are almost the same. But the conventional corn ethanol reduces the GHG emission to 7 MMT due to increased production ethanol as biodiesel overage for conventional fuel declines. The allowance of cellulosic waiver results in reduction in cellulosic biofuel usage by 200 million gallons lead to 0.42 MMT higher GHG emission. We note the nest structure RFS with cellulosic waiver scenario limits the total GHG emission reduction further by 1.74 MMT. In general, the overall impact of the existing design feature of the RFS on the total GHG emission is minimal compared to the non-nested structure.

## **4.2 Sensitivity analysis**

We now examine the robustness of our findings by altering the parametric assumptions in the model. We consider the alternative parametric assumptions to perform the sensitivity analysis (i) lower the supply elasticity of biodiesel to test the extent of D4 RIN overage (ii) decrease the biodiesel tax credit, and (iii) increase the cellulosic waiver price. These key parameters are the main drivers that create biodiesel overproduction. The outcome variables of interest discussed in this section are the D4 RIN overages and RIN pass-through.

As analytically derived in proposition 3 and 4, the low elasticity-weighted production cost and high supply elasticity of biodiesel support the blender's fuel choice towards biodiesel to the RFS overall mandate. The impact of supply elasticity of the biodiesel on the D4 RIN overage is shown in Figure 7. A slight decrease in the biodiesel supply elasticity from 2.09 (benchmark) to 1.86 leads to a drop in D4 RIN overage from 1.22 billion to 0.63 billion eges, whereas the RIN pass-through raises from 69% to 100%. Correspondingly, the end use of D4 RIN overage for backfilling the cellulosic waiver credit (grey bars in Figure 7) reduces by 40% and increases 92

million gallons of cellulosic ethanol, whereas the D4 RIN overage replacing the D6 RIN (blue bars in Figure 7) falls by 50% and increases the corn ethanol production by 493 million gallons. This is consistent with the analytical findings that a higher biodiesel supply elasticity induces blenders to use more biodiesel to meet the overall mandate, and thus a less elastic biodiesel production leads to complete RIN pass-through and may create higher demand for E85. We note that the lower biodiesel supply elasticities at 1.87 and 1.86 still incur 0.83 and 0.63 billion eges of D4 RIN overage, while in these cases the RIN pass-through are 100%. This happens because the upper-bound threshold ( $\frac{0.1q_{E10}+[q_{D4}-\theta_b \times (q_g+q_d)]}{0.9q_{E10}+q_d}$ ) derived in 3.2.2 is lowered due to reduced biodiesel overage, which induces E85 consumption beyond 10% blend wall.

We next analyze the effect of three levels of biodiesel tax credit: No credit, \$0.5 per gallon credit, and \$1 per gallon on the blender's choice of D4 RIN overage and corresponding RIN pass-through. The results in Figure 8 show that when lowering the tax credit from the benchmark scenario of \$1 to \$0.5 per gallon, the D4 RIN overages are relatively constant at 1.27 billion eges with 0.19 billion eges backfilling the cellulosic waiver and 1.08 billion eges for D6 RIN replacement. The D4 RIN then drops to 0.63 million eges when we assume that there is no biodiesel tax credit which inversely promotes the cellulosic ethanol production by 80 million eges and adds 561 million eges more corn ethanol produced for compliance. We find that the RIN pass-through significantly increases to 97% when the tax credit is reduced to \$0.5 per gallon, and 100% RIN pass-through can be achieved in the absence of biodiesel tax credit. We also observe that net RIN incentive passed to retail E85 and E10 price gaps increased from \$0.43 per gge to \$0.73 per gge when the tax credit is reduced from \$1 to \$0.5 per gallon, and further increases to \$1.09 per gallon in absence of the tax credit. The RIN incentive raises and supplements the missing biodiesel tax credit to support the refiners to meet the overall mandate.

Lastly, we compare the effect of cellulosic waiver credit price on the amount of cellulosic waiver purchased and its implication on the RIN pass-through. Four levels of the cellulosic waiver credit are tested: the formulated price at \$1.8 per unit following the EPA instruction, the announced EPA price in 2017 at \$2 per unit as benchmark, the shadow price of cellulosic waiver of the nested structure mandate at \$ 2.2 per unit, and an intermediate level of \$2.1 per unit. Our analysis finds that when the cellulosic waiver price is at \$1.8, the cellulosic waiver credit dominates the D3 RIN compliance and meet the 311 million cellulosic biofuel mandate. As the cellulosic waiver price increases from \$1.8 to \$2.2 as shown in Figure 9, the waiver purchased gradually decline to zero. The falling cellulosic waiver credits purchases require less biodiesel RINs to be counted toward the overall mandate, which leads to improving pass-through from 66% to 71%. Nonetheless, the role of cellulosic waiver in affecting the pass-through is limited. Even in the absence of cellulosic waiver credit, we find that there still is an incomplete RIN pass-through.

## **5 Discussion and conclusion**

This paper examines the disincentives created by the design features of the Renewable Fuel Standard, specifically the nested structure and cellulosic waiver, that hinder blenders to fully pass-through the RIN incentives to induce demand for E85 and for producing cellulosic biofuels. We construct an analytical partial equilibrium welfare economic model with explicit consideration of RINs market, cellulosic waiver credit, and nested structure of the RFS and provide an economic rationale for the biodiesel overage and its impact on the currently observing partial RIN pass-through. Our theoretical analysis shows that the economic incentives to completely pass-through RINs is hindered by biodiesel over-production, which not only is replacing the D6 RIN but also counted towards advanced mandate equivalent to the volume of

cellulosic waiver due to the nested structure. Such behavior limits RIN incentive and sets a price floor for the E85 price that should have been at parity with E10 if the RIN pass-through is complete which happen in case of non-nested RFS.

We analytically show that biodiesel overage is happening either due to lower elasticity-weighted marginal cost. Based on Irwin (2013) and Babcock, Agroicone, & Peng (2013) biodiesel elasticity estimates, we argue that our proposition 3 and 4 will hold when biodiesel supply elasticity is greater than 1.5 and greater than other biofuels. We also conclude that under the nested RFS structure there is an orderly sequence in biodiesel overage first use cellulosic waiver credit equivalent D4 RIN to meet the advanced mandate and then use the rest to fill the D6 RIN shortfall.

Our calibrated numerical simulation model quantifies the effects of the RFS structural designs on RIN compliance, RIN prices, fuel prices, and GHG emissions for the U.S. in 2017. Compared to the non-nested RFS structure, the nested RFS with the cellulosic waiver scenario reduces the production of corn ethanol by 61% and cellulosic ethanol by 7%, while overproducing biodiesel by 1.28 billion gallons weakens conventional D6 RIN price by 42% and cellulosic D3 RIN price by 15%. Our study shows that there are unintended consequences of this weak ethanol D6 and D3 RIN values which lead to a 14.2% higher retail price of E85 compared to E10 on the gasoline energy equivalent basis. The ethanol RIN incentives only compensate up to 68% of the marginal production costs gap between E85 and E10, resulting in incomplete RIN pass-through to the retail ethanol blended fuels prices. Indeed, we find that the biodiesel overage has higher GHG emission reduction potential which was one of the original intentions of the RFS even though the magnitude is small (as shown in Table 7). However, the broader question of discussion is whether this short-term benefit is enough to justify the unintended consequences of the nested

structure of the RFS, which is hindering the increase in overall ethanol demand and creating E85 and E10 price disparity.

The sensitivity analysis validates the analytical findings that the main driver of biodiesel overage is the more elastic biodiesel supply relative to other biofuels, while biodiesel tax credit can be responsible as well. We find that the inelastic supply curve of biodiesel can stimulate more corn and cellulosic ethanol production by improving the RIN pass-through. The absence of the biodiesel tax credit leads to recovering the pass-through while strengthening both the D3 and D6 RIN prices.

Finally, this paper shows the conceptual rationale for the blenders to overuse biodiesel to meet the mandate because of the structural design of the RFS. It enhances the D4 RIN value and weakens the D3 and D6 RIN pass-through incentives to increase high blend ethanol E85 demand. The nested RFS structure allows biomass-based diesel to compete with bioethanol to meet the overall renewable fuel mandate. Even though the motivation behind the nested structure of the RFS is a greater reduction in GHG emissions, we find that the over-production of biodiesel barely reduce the overall 2017 US transportation sector GHG emission. While the recent EPA's year-round E15 approval may ameliorate 10% blend wall problem in short time which could possibly generate a new 15% blend wall in the long run, it is still far below the estimated 2022 blend target of 26% originally envisioned by the original RFS. The unintended biodiesel overage advanced only narrowly in GHG reduction as a result of diesel-embedded nested structure stagnates the ethanol production and penetration into the gasoline market, which slows down the decarbonization of the gasoline fuels.

By proposing a counterfactual non-nested structure of the RFS, we disentangle three different types of biofuels and enforce a fuel type-specific mandate and shows complete RIN pass-through



both analytically and numerically in this study. We argue that the non-nested RFS structural design we propose and test in this study will serve as a separate mandate for ethanol which is used by the light-duty vehicle, and for biodiesel used with blended diesel to fuel medium- and heavy-duty vehicle fleets. The policy implications of the disjointed standard that clarifies each biofuel target would purposefully serve better for two vehicle fleets and achieve the biofuel targets.

We plan to include other factors that affect the RIN prices, for example, RINs banking provision, and small refinery exemptions in the future extension of this study where we plan to analysis the complexity of the RFS in the context of open economy by incorporating US fuels trade with the rest of the world.

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Figures and Tables

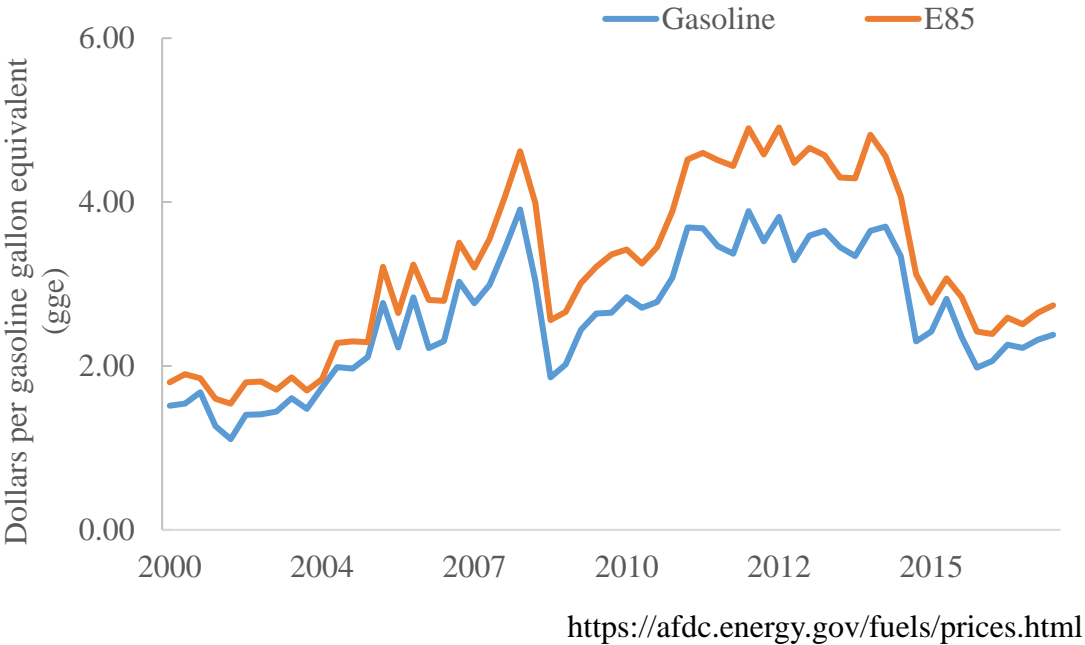


Figure 1. US gasoline and E85 retail fuel price trends

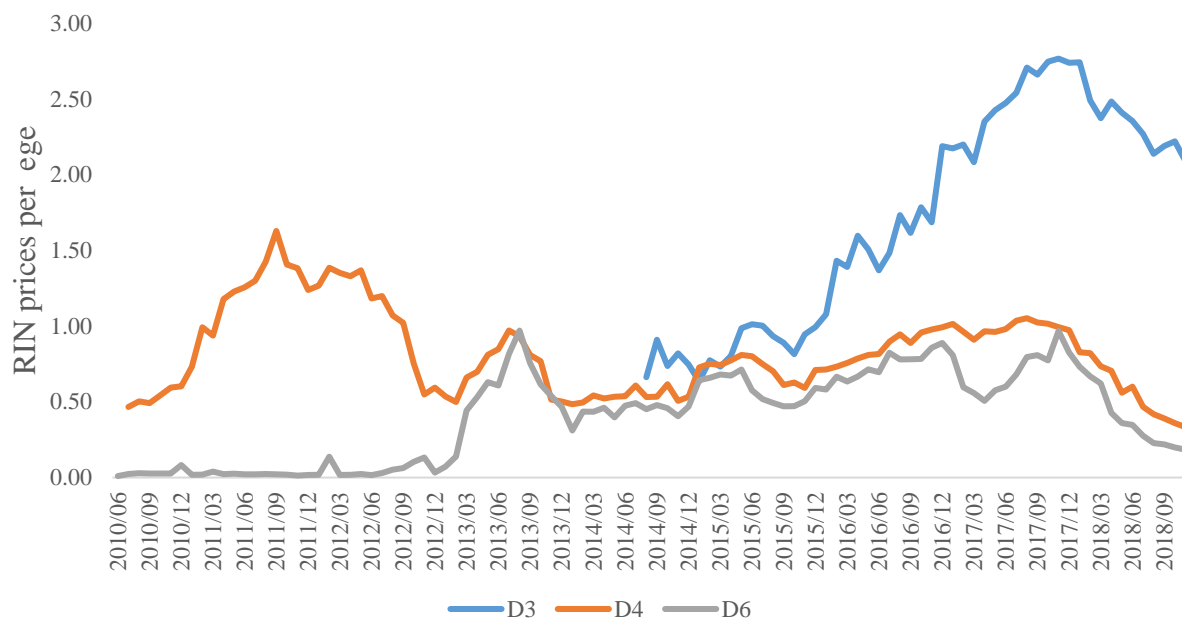


Figure 2 Comparison between cellulosic (D3), biodiesel (D4), and conventional (D6) RIN prices

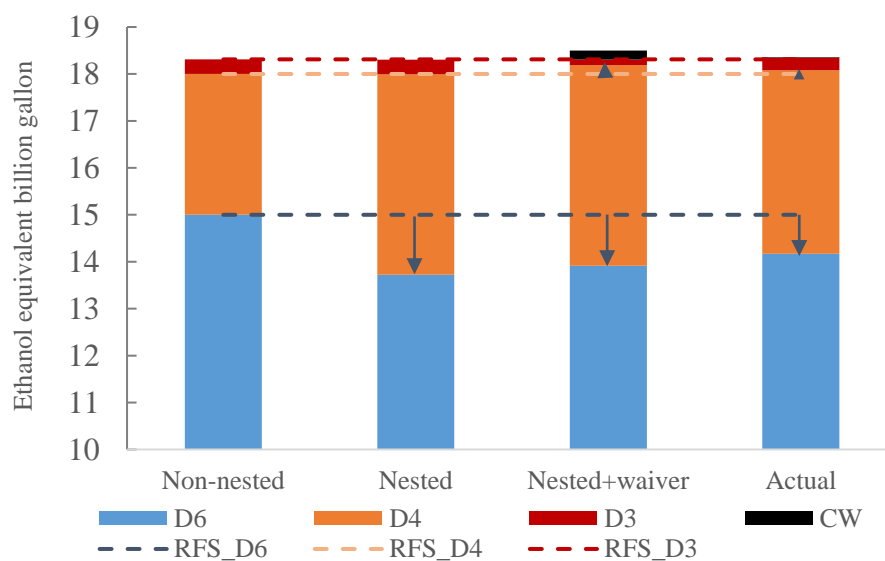


Figure 3. Volumetric compliance of RINs by simulated policy scenarios and actual retirement in 2017

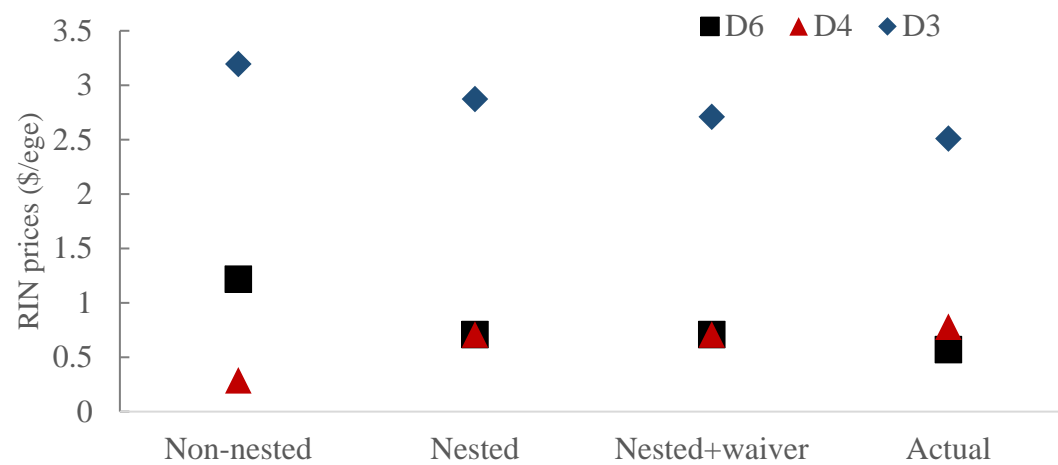


Figure 4. Effect of the design of RFS on RIN prices

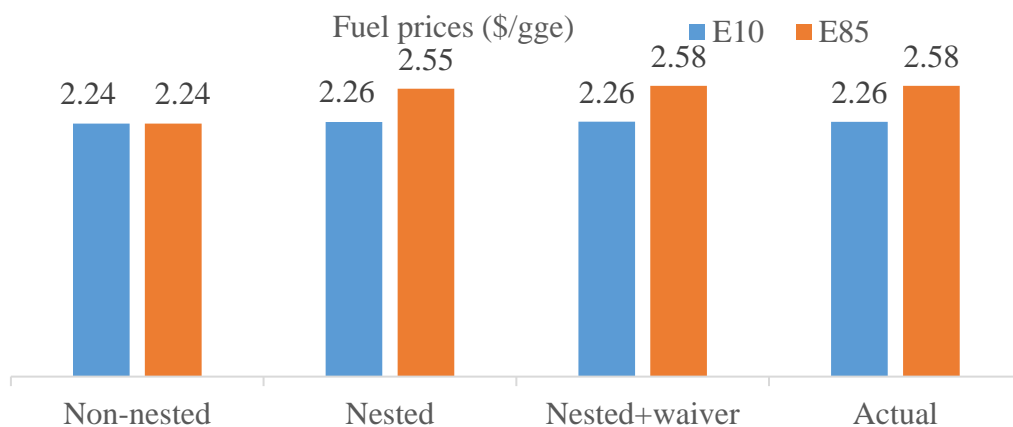


Figure 5. Retail prices of E10 and E85

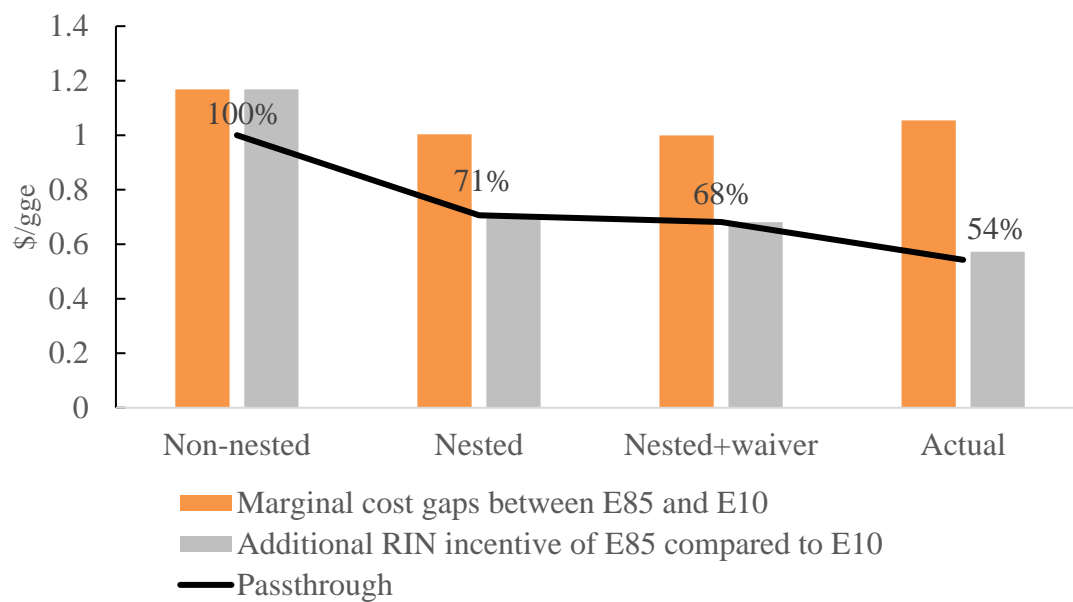


Figure 6. Effect of designs of RFS on RIN pass-through to E85



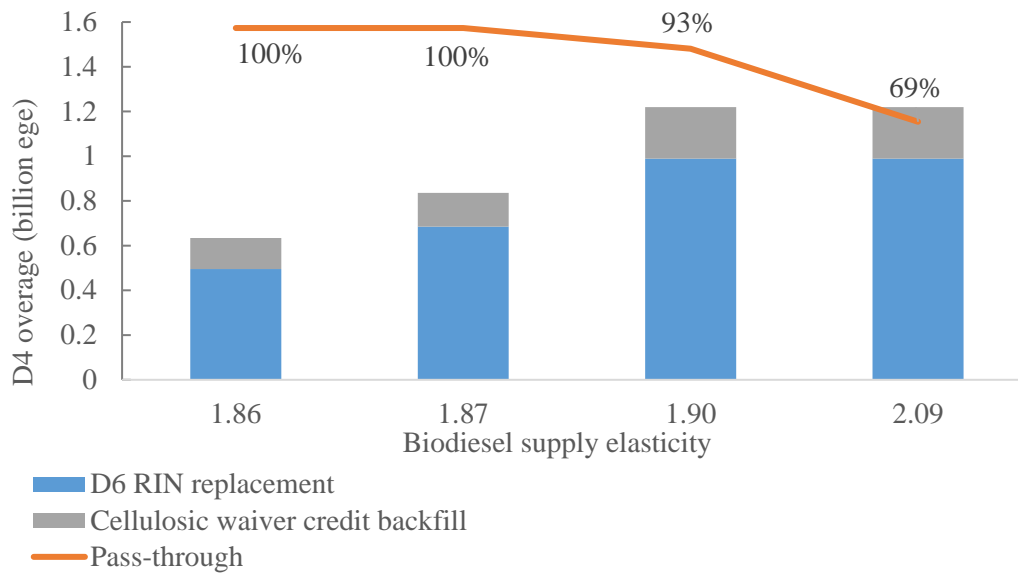


Figure 7. Effect of biodiesel supply elasticity on D4 overage and pass-through

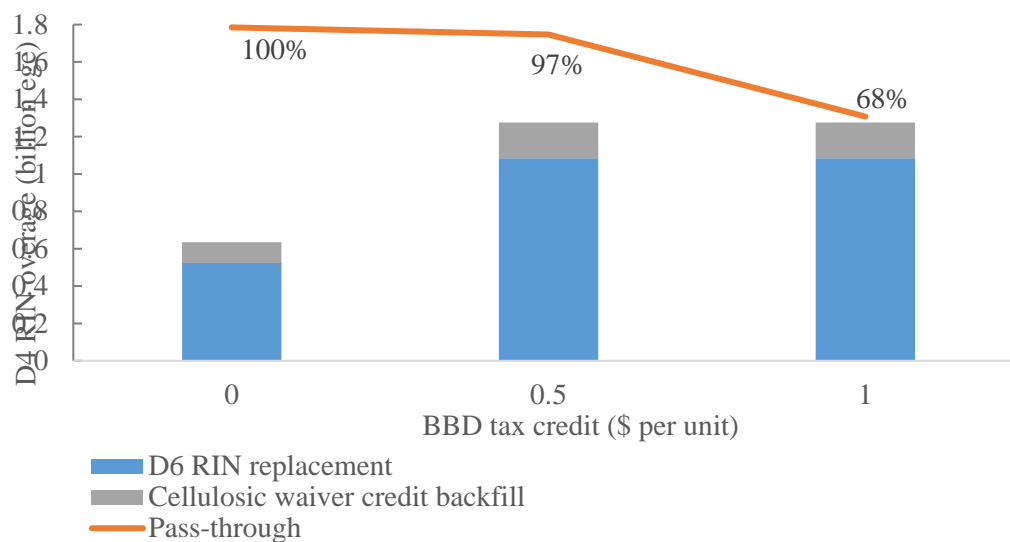


Figure 8. Effect of the biodiesel tax credit on D4 overage and pass-through

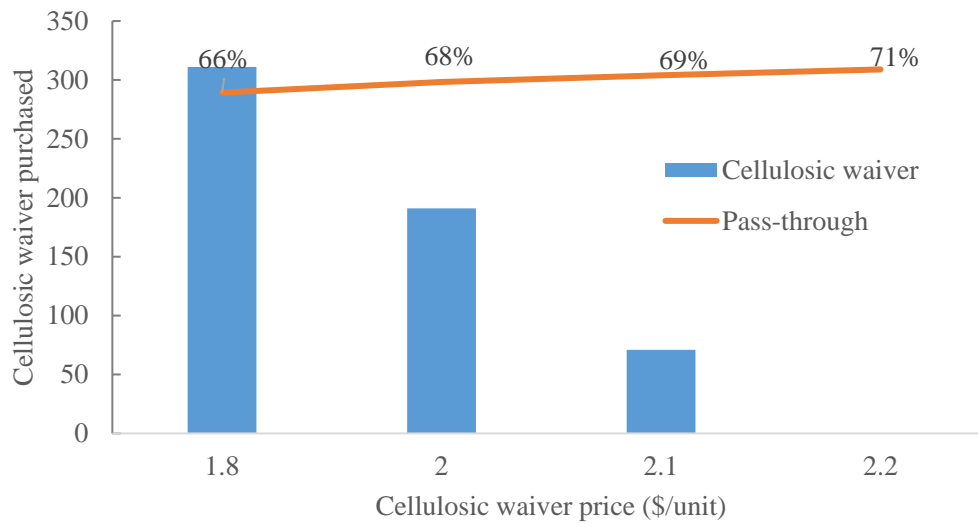


Figure 9. Effect of cellulosic waiver price on purchased credit and pass-through

Table 1 The volume standard in 2017 and required RIN in RFS (in billion)

	Cellulosic biofuel (D3)	Biomass-based diesel (D4)	Advanced fuel (D3+D4+D5)	Total renewable fuel (D3+D4+D5+D6)
Statutory target	5.5	1	9	24
Revised target	0.311	3	4.28	19.28
Achieved target	0.261	3.85	4.26	18.15

Table 2 The first-order condition of key variables with complete pass-through

Decision variable	First Order Condition*
Biofuel producers	
$q_e$	$p_E^{ws} = S_e(q_e) - p_{D6}$
$q_c$	$p_E^{ws} = S_c(q_c) - p_{D3}$
$q_b$	$p_d^{ws} = S_b(q_b) - 1.5p_{D4} - t_B$
Refiners	
$q_g$	$p_g^{ws} = S_g(q_g) + \lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r$
$q_d$	$p_d^{ws} = S_d(q_d) + \lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r$
Blenders	
$q_{E10}$	$p_{E10}^{rt} \gamma_{E10} = \left( 0.9 S_g(\cdot) + 0.1 \frac{S_e(\cdot) q_e + S_c(\cdot) q_c}{q_e + q_c} + w_{gf} \gamma_{E10} \right) -$ $0.1 \frac{p_{D6} q_e + p_{D3} q_c}{q_e + q_c} + 0.9 (\lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r)$
$q_{E85}$	$p_{E85}^{rt} \gamma_{E85} = \left( 0.26 S_g(\cdot) + 0.74 \frac{S_e(\cdot) q_e + S_c(\cdot) q_c}{q_e + q_c} + w_{gf} \gamma_{E85} \right) -$ $0.74 \frac{p_{D6} q_e + p_{D3} q_c}{q_e + q_c} + 0.26 (\lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r)$
$q_{gf}$	$p_{E10}^{rt} = p_{E85}^{rt} = D_{gf}(\cdot)$
$q_{df}$	$p_{df}^{rt} = D_{df}(\cdot) = p_d^{ws} + w_{df}$

\*ws stands for wholesale and rt stands for retail.

Table 3 The first order condition of RIN credit

	Nested RFS (with/without waiver)	Non-Nested RFS
$q_{D3}$	$P_{D3} = \lambda_c + \lambda_r$	$P_{D3} = \lambda_c$
$q_{D4}$	$P_{D4} = \lambda_b + \lambda_r$	$P_{D4} = \lambda_b$
$q_{D6}$	$P_{D6} = \lambda_r$	$P_{D6} = \lambda_e$
$q_{cw}$	$P_{cw} = \lambda_c$	

Table 4 The elasticities used in the study

	Elasticity	Range	Source
Gasoline fuel demand	-0.03	-0.02- -0.04	EIA, 2014
Diesel fuel demand	-0.37	-0.07 - -0.43	Winebrake et al., 2015
Gasoline supply	0.853	0.46-1.82	Chen, Huang, Khanna, & Önal, 2014; Cui, Lapan, Moschini, & Cooper, 2011; de Gorter & Just, 2009b
Diesel supply	0.8	0.046-0.25	Korting, Just, & De Gorter, 2018
Corn ethanol supply	0.8	0.22-5.01	Cui et al., 2011; Luchansky & Monks, 2009
Biodiesel supply	2.1	2	Korting et al., 2018

Table 5 Calibration result

Item	Unit	2017 observation	Model Output	Difference	Source
Prices					
Wholesale diesel	\$/dge	1.65	1.60	-3%	EIA
Wholesale biodiesel	\$/dge	3.55	3.73	5%	AFDC
Wholesale gasoline	\$/gge	1.98	1.96	-1%	EIA
Wholesale ethanol	\$/ege	1.62	1.56	-4%	Nebraska Ethanol Board
Retail E85	\$/gge	2.58	2.58	0%	AFDC
Retail E10	\$/gge	2.26	2.26	0%	AFDC
Retail diesel fuel	\$/dge	2.73	2.54	-7%	AFDC
D3	\$/ege	2.51	2.71	8%	EPA
D4	\$/ege	0.78	0.71	-9%	EPA
D6	\$/ege	0.57	0.71	25%	EPA
Volumes					
Diesel	Bgal	60.28	58.7	-3%	EIA
Biodiesel	Bgal	2.61	2.85	9%	EPA
Gasoline	Bgal	128.58	126.32	-2%	EIA
Ethanol	Bgal	14.43	14.03	-3%	EIA

Table 6 The carbon intensity and energy density used for GHG estimation

	Emission intensity (kg CO <sub>2</sub> per mmBtu)	Energy density (mmBtu per gallon)	Emission factor (kg CO <sub>2</sub> per gallon)
Corn ethanol	85	0.076	6.5
Cellulosic ethanol	-29	0.076	-2.2
Biodiesel	57	0.125	7.1
Gasoline	98	0.115	11.3
Diesel	97	0.131	12.7

Table 7 The GHG emission and fuel volumes of each policy design scenarios

	Non-nested structure	Nested structure without cellulosic waiver	Nested structure with cellulosic waiver
GHG emissions (M MT)	relative change compared to non-nested structure		
Gasoline	1414	9.58	9.58
Diesel	7567	-10.8	-10.8
Conventional biofuel	96.82	-8.23	-7.00
Biomass-based diesel	14.25	6.06	6.06
Cellulosic biofuel	-0.69	0.00	0.42
Summation	2,281	-3.39	-1.74
Fuel volumes (Bgal)	relative change compared to non-nested structure		
Gasoline	125.47	0.85	0.85
Diesel	59.55	-0.85	-0.85
Conventional biofuel	15	-1.28	-1.09
Biomass-based diesel	2	0.85	0.85
Cellulosic biofuel	0.311	0.00	-0.19

## Appendix

### A1. The Lagrangian framework and first-order condition

The Lagrangian framework is established as follows. Note that the shadow prices of the explicit RINs generation constraint show the market price of the RINs, traded at which the blenders get the credits and retire. The shadow prices of the constraints (such as  $P_E^{ws}, P_g^{ws}, P_d^{rt}, P_{D3}, P_{D4}, P_{D6}, \lambda_c, \lambda_b, \lambda_r$ ) reflect the marginal increase in the welfare with respect to the variables described by the constraints, which are the market-mediated price. The shadow prices are positive when the constraints are binding.

$$\begin{aligned} \mathcal{L} = & \int_0^{Y_{E10}q_{E10}+Y_{E85}q_{E85}} D_{gf}(\cdot)dq_{gf} + \int_0^{q_b+q_d} D_{df}(\cdot)dq_{df} - \int_0^{q_e} S_e(\cdot)dq_e - \int_0^{q_c} S_c(\cdot)dq_c \\ & - \int_0^{0.9q_{E10}+0.26q_{E85}} S_g(\cdot)dq_g - \int_0^{q_d} S_d(\cdot)dq_d - \int_0^{q_b} S_b(\cdot)dq_b - w_{gf}q_{gf} \\ & - w_{df}q_{df} + t_Bq_b - P_{cw}q_{cw} + P_E^{ws}(q_e + q_c - 0.1q_{E10} - 0.74q_{E85}) + P_g^{ws}(q_g \\ & - 0.9q_{E10} - 0.26q_{E85}) + P_d^{rt}(q_b + q_d - q_{df}) + P_{D3}(q_c - q_{D3}) \\ & + P_{D4}(1.5q_b - q_{D4}) + P_{D6}(q_e - q_{D6}) + \lambda_c[q_{D3} + q_{cw} - \theta_c(q_g + q_d)] + \lambda_b[q_{D4} \\ & - \theta_b(q_g + q_d)] + \lambda_r[q_{D3} + q_{D4} + q_{D6} - \theta_r(q_g + q_d)] \end{aligned}$$

First order conditions using Karush Kuhn-Tucker (KKT) theorem for each variable are listed for the interest of each stakeholder. The first order conditions satisfy the complementary slackness condition that only when the variables are interior solution would the equality hold.

#### 5.1 A1.1 Fuel producers

$$\frac{\partial \mathcal{L}}{\partial q_e} = S_e(q_e) - P_{D6} - P_E \geq 0$$

The corn ethanol producers receive the D6 RIN at  $P_{D6}$  per gallon and reduce the corn ethanol price from the marginal cost of  $S^e$  to the sales price at  $P_E$  to blenders. The intermediate blenders ethanol price is endogenously determined by the model. The wholesale price of corn ethanol is subsidized by D6 RIN value.  $P_E = S_e(q_e) - P_{D6}$ .

$$\frac{\partial \mathcal{L}}{\partial q_c} = S_c(q_c) - P_{D3} - P_E \geq 0$$

Similarly, cellulosic ethanol is subsidized by D3 RIN at  $P_{D3}$  per gallon, which lowers the wholesale price of the cellulosic ethanol to the same level at  $P_E$  as corn ethanol. It is because we assume the cellulosic ethanol is a perfect substitute for corn ethanol that blenders are indifferent to the feedstock of ethanol and price takers of the unified ethanol price. Only when the cellulosic ethanol is fully subsidized with  $P_{D3}$  that lowers the price of ethanol out of rack would it incentivize the cellulosic ethanol production.  $P_E = S_c(q_c) - P_{D3}$ .

$$\frac{\partial \mathcal{L}}{\partial q_b} = S_b(q_b) - 1.5P_{D4} - t_B - P_d \geq 0$$

The biomass-based diesel is subsidized at  $1.5P_{D4}$ . Plus the tax credit, the blenders use biodiesel at price of  $P_d$ . We assume that the biodiesel is a perfect substitute for petroleum diesel that has the same wholesale price as petroleum diesel.  $P_d = S_b(q_b) - 1.5P_{D4} - t_B$ .

$$\frac{\partial \mathcal{L}}{\partial q_g} = S_g(q_g) + \lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r - P_g \geq 0$$

Because of the joint compliance base in the three nested RFS mandate, the gasoline gets implicit tax from each of the mandates on the top of the marginal production cost. The wholesale price is raised to  $P_g$ . Note that the shadow price of the RFS mandate can also be reinterpreted in the forms of the RIN prices in section 2.3.  $P_g = S_g(q_g) + \lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r$ .

$$\frac{\partial \mathcal{L}}{\partial q_d} = S_d(q_d) + \lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r - P_d \geq 0$$

Due to the joint compliance, the diesel is also implicitly taxed at the same amount for each gallon of diesel blended, up until when the wholesale price is the same as the biodiesel. Thus, the blenders are indifferent between petroleum diesel and biodiesel.  $P_d = S_d(q_d) + \lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r$ .

$$\frac{\partial \mathcal{L}}{\partial q_{cw}} = P_{cw} - \lambda_c \geq 0$$

The compliance cost of the cellulosic waiver credit is  $P_{cw}$ , which is announced by EPA before every compliance year. However, only if the  $P_{cw}$  equals to  $\lambda_c$ , the incentive of using the cellulosic waiver to comply cellulosic biofuel mandate should the obligated party purchase the cellulosic waiver, which  $P_{cw} = \lambda_c$ .

## 5.2 A1.2 Blenders

$$\frac{\partial \mathcal{L}}{\partial q_{E10}} = 0.1P_E + 0.9P_g + w_{gf}\gamma_{E10} - P_{gf}\gamma_{E10} \geq 0$$

A blender produces E10 with an upper limit of blend rate at 10% when the marginal cost of blending ethanol and gasoline plus the marginal blending cost is covered by the retail price at the station gate per gallon of E10 at  $P_f\gamma_{E10}$  converted from the demand curve to E10 gallon. By plugging in the rack prices from the FOCs of fuel producers, we get the retail price of E10 at the

$$\text{energy equivalent basis. } P_{gf}^{E10} = \frac{1}{\gamma_{E10}} \left[ \left( 0.9S_g(q_g) + 0.1 \frac{S_e(q_e)q_e + S_c(q_c)q_c}{q_e + q_c} + w_{gf}\gamma_{E10} \right) - 0.1 \frac{P_{D6}q_e + P_{D3}q_c}{q_e + q_c} + 0.9(\lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r) \right].$$



$$\frac{\partial \mathcal{L}}{\partial q_{E85}} = 0.74P_E + 0.26P_g + w_{gf}\gamma_{E85} - P_{gf}\gamma_{E85} \geq 0$$

Likewise, when the retail price from blending ethanol and gasoline after the implicit cross-subsidization plus the marginal blending cost reduce down to  $P_f\gamma_{E85}$ , which is at the energy equivalent level with E10 ( $P_f$  in \$ per gasoline gallon equivalent), would driver choose to use E85 at the same price. By plugging in the rack prices from the FOCs of fuel producers, we get the retail price of E85 at the energy equivalent basis.

$$P_{gf}^{E85} = \frac{1}{\gamma_{E85}} \left[ \left( 0.26S_g(q_g) + 0.74 \frac{S_e(q_e)q_e + S_c(q_c)q_c}{q_e + q_c} + w_{gf}\gamma_{E85} \right) - 0.74 \frac{P_{D6}q_e + P_{D3}q_c}{q_e + q_c} + 0.26(\lambda_c\theta_c + \lambda_b\theta_b + \lambda_r\theta_r) \right]$$

$$\frac{\partial \mathcal{L}}{\partial q_{dg}} = D_{gf}(\gamma_{E10}q_{E10} + \gamma_{E85}q_{E85}) + w_{gf} - P_{gf} \geq 0$$

$$\frac{\partial \mathcal{L}}{\partial q_{df}} = D_{df}(q_b + q_d) + w_{df} - P_d \geq 0$$

To produce blended diesel fuel, the blending cost of fuels plus the blending operations cost should be at least covered by the retail price at  $P_{df}$  from the demand curve of the total diesel fuel.

### 5.3 A1.3 RINs traded

Nested

Non-nested

$$\frac{\partial \mathcal{L}}{\partial q_{D3}} = \lambda_c + \lambda_r - P_{D3} \geq 0 \quad \frac{\partial \mathcal{L}}{\partial q_{D3}} = \lambda_c - P_{D3} \geq 0$$

$$\frac{\partial \mathcal{L}}{\partial q_{D4}} = \lambda_b + \lambda_r - P_{D4} \geq 0 \quad \frac{\partial \mathcal{L}}{\partial q_{D4}} = \lambda_b - P_{D4} \geq 0$$

$$\frac{\partial \mathcal{L}}{\partial Q_{D4}} = \lambda_r - P_{D6} \geq 0 \quad \frac{\partial \mathcal{L}}{\partial Q_{D4}} = \lambda_e - P_{D6} \geq 0$$

The variable of RINs traded in the market are not only determined by the market prices, at which biofuel refiners produce them, but also the RFS mandate that requires them. The nested structure counts D3 and D4 towards the total renewable fuel standard that D3 and D4 are subsidized by both the individual biofuel mandate of cellulosic ethanol and biodiesel and also the total renewable mandate. It indicates that under the nested structure, the price of the advanced fuel is higher than the conventional fuel  $P_{D3} > P_{D6}$  and  $P_{D4} > P_{D6}$ . Furthermore, under cases of biodiesel overage, the biodiesel constraint become slack and  $\lambda_b = 0$ , which leads to  $P_{D4} = \lambda_r = P_{D6}$ .

However, under the non-nested structure, the shadow prices of each separate mandate are equal to its corresponding RIN prices.

## A2. Pass-through

### 5.4 A2.1 Non-nested structure

We add the biofuel mandates for corn ethanol and cellulosic ethanol under the nested structure on both sides and substitute the total ethanol and gasoline use by E10 and E85 based on their blending material:

$$0.1q_{E10} + 0.85q_{E85} = (\theta_c + \theta_e) \times (0.9q_{E10} + 0.15q_{E85} + q_d)$$

By plugging in the marginal breaking conditions of blend wall at  $\theta_c + \theta_e = 0.1q_g / [0.9(q_g + q_d)]$

into the equation above, the E85 consumption becomes  $q_{E85} = \frac{(0.9(\theta_c + \theta_e) - 0.1)q_{E10} + (\theta_c + \theta_e)q_d}{0.85 - 0.15(\theta_c + \theta_e)} =$

0. With the marginal change in blend rate  $d(\theta_c + \theta_e) > 0$ , the E85 consumption also become positive with  $dq_{E85} > 0$ . The interior solution of  $q_{E85}$  by KKT theory indicates the 100% pass-through that  $P_{gf}^{E85} = P_{gf}^{E10}$ , regardless of the biodiesel production. With the 100% pass-through,

$\mu \frac{P_{D6} \times q_e + P_{D3} \times q_c}{q_e + q_c} + v(\lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r) > 0$ . It is not hard to derive that E85 is subsidized

while E10 is taxed with the revenue neutral assumption.

## 5.5 A2.2 Nested structure

We subtract the mandated quantity of the biodiesel  $\theta_b(q_g + q_d)$  from both side of the total renewable fuel mandate, which indicates the total ethanol mandate from both conventional and cellulosic sources:  $q_{D3} + q_{D6} + q_{D4} - \theta_b(q_g + q_d) \geq (\theta_r - \theta_b)(q_g + q_d)$ . At the blend wall, the inequality constraint become binding. Using E85 and E10 consumption to substitute this condition we have the critical condition of E85 consumption at each level of the blend mandate:

$$0.1q_{E10} + 0.74q_{E85} + q_{D4} - \theta_b(q_g + q_d) = (\theta_r - \theta_b)(0.9q_{E10} + 0.26q_{E85} + q_d)$$

$$q_{E85} = \frac{(0.9(\theta_r - \theta_b) - 0.1)q_{E10} + (\theta_r - \theta_b)q_d - [q_{D4} - \theta_b(q_g + q_d)]}{0.74 - 0.26(\theta_r - \theta_b)}$$

The blend wall crossed on the margin when total ethanol blended is at  $\theta_r - \theta_b =$

$0.1q_g/[0.9(q_g + q_d)]$  and applies to the E85 consumption above.  $q_{E85} = \frac{-[q_{D4} - \theta_b(q_g + q_d)]}{0.74 - 0.26(\theta_r - \theta_b)}$ . The

marginal increase in the blend rate with may not reverse the negativity in solution of E85

volume. The solution with the marginal change is still zero.

## A3. The condition of Biomass-based diesel overage used by blenders

The fuel choice blenders used for compliance will change under the nested structure is mainly due to the total cost. Unlike Korting's analysis, the profit the blenders earn is driven down to zero by competition under perfectly competitive market with a free-entry blender industry. The total revenue generated from selling the blended products net the blending cost ( $TR = (P_{gf} - w_{gf})q_f + (P_{df} - w_{df})q_{df}$ ) evens out the total cost of purchasing the fuel from the refiners and

biofuel producers net the tax credit  $TC = P_E(q_e + q_c) + P_d(q_b + q_d) + P_g q_g - t_B q_b$ . The zero-profit condition holds for the blenders where  $\Pi = TR - TC = 0$ . Therefore, the blenders adjust the fuel choice bundles in order to minimize its fuel cost.

The first term of the total cost function on the right is further reorganized into  $(S_e(\cdot) - P_{D6})q_e + (S_c(\cdot) - P_{D3})q_c$ , with  $P_E = \frac{(S_e(\cdot) - P_{D6})q_e + (S_c(\cdot) - P_{D3})q_c}{q_e + q_c}$  jointly expressed by corn and cellulosic ethanol from the first order condition in 2.1. Similarly, the second term is extended into  $(S_d(q_d) + \lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r)q_d + (S_b(q_b) - 1.5P_{D4} - t_B)q_b$  with  $P_d = \frac{(S_d(\cdot) + \lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r)q_d + (S_b(\cdot) - 1.5P_{D4} - t_B)q_b}{q_d + q_b}$ ; fourth term into  $S_g(\cdot) + \lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r)q_g$  with  $P_g = S_g(\cdot) + \lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r$ . The total cost is expanded into:

$$\begin{aligned} TC &= (S_e(\cdot) - P_{D6})q_e + (S_c(\cdot) - P_{D3})q_c + (S_d(\cdot) + \lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r)q_d + (S_b(\cdot) - 1.5P_{D4} - t_B)q_b + (S_g(\cdot) + \lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r)q_g - t_B q_b \\ &= S_c(\cdot)q_c + S_e(\cdot)q_e + S_b(\cdot)q_b + S_g(\cdot)q_g + S_d(\cdot)q_d - P_{D3}q_c - P_{D6}q_e - 1.5P_{D4}q_b + (\lambda_c \theta_c + \lambda_b \theta_b + \lambda_r \theta_r)(q_d + q_g) \end{aligned}$$

From the nested structure  $q_{D3} \geq \theta_c (q_g + q_d)$ ;  $q_{D4} \geq \theta_b (q_g + q_d)$ ;  $q_{D3} + q_{D4} + q_{D6} \geq \theta_r (q_g + q_d)$  and  $\lambda_c + \lambda_r = P_{D3}$ ,  $\lambda_b + \lambda_r = P_{D4}$ ,  $\lambda_r = P_{D6}$ , the sixth to eighth term can be reorganized as:

$$P_{D3}q_c = (\lambda_c + \lambda_r)q_{D3} = (\lambda_c + \lambda_r)\theta_c (q_g + q_d)$$

$$P_{D6}q_e = \lambda_r q_{D6} = \lambda_r(\theta_r - \theta_c - \theta_b)(q_g + q_d)$$

$$1.5P_{D4}q_b = (\lambda_b + \lambda_r)q_{D4} = (\lambda_b + \lambda_r)\theta_b (q_g + q_d)$$

The summation of above equation on both sides  $P_{D3}q_c + P_{D6}q_e + 1.5P_{D4}q_b = (\lambda_c + \lambda_r)\theta_c (q_g + q_d) + \lambda_r(\theta_r - \theta_c - \theta_b)(q_g + q_d) + (\lambda_b + \lambda_r)\theta_b (q_g + q_d) = (\lambda_c\theta_c + \lambda_b\theta_b + \lambda_r\theta_r)(q_d + q_g)$ . This reduces the TC  $= S_c(q_c)q_c + S_e(q_e)q_e + S_b(q_b)q_b + S_g(q_g)q_g + S_d(q_d)q_d$  Using different policy scenario, TC will end up with the same formula. The hypothesis of the condition under which a blender use strategic biodiesel overage is when the marginal change is driven  $d(TC) < 0$  that  $d(TC) = d(S_c(q_c)q_c + S_e(q_e)q_e + S_b(q_b)q_b + S_g(q_g)q_g + S_d(q_d)q_d) < 0$ .

Note that the total differentiation of one typical term can be transferred in the form as below:

$$d(S(q) \times q) = dS(q) \times q + dq \times S(q) = \frac{S(q)}{q\eta} \times q \times dq + S(q) \times dq = (\frac{1}{\eta} + 1)S(q) \times dq.$$

The above marginal change in the cost becomes

$$d TC = (\frac{1}{\eta_c} + 1) S_c(q_c)dq_c + (\frac{1}{\eta_e} + 1) S_e(q_e)dq_e + (\frac{1}{\eta_b} + 1) S_b(q_b)dq_b + (\frac{1}{\eta_g} + 1) S_g(q_g)dq_g + (\frac{1}{\eta_d} + 1) S_d(q_d)dq_d$$

## 5.6 A3.1 Proposition 1 Proof

The difference in the fuel input is related to the policy constraint.  $dq_c = \theta_c (dq_g + dq_d)$ ;  $dq_e + dq_c + dq_b = \theta_r (dq_g + dq_d)$ .

Note that the nested structure provides an incentive for biodiesel overage that leaves the biodiesel mandate slack,  $dq_b \neq \theta_b (dq_g + dq_d)$ . This marginal overage enables us to use total differentiation to analyze the marginal change in the total fuel cost. We subtract the marginal condition of the cellulosic ethanol mandate from the marginal condition of total renewable fuel

mandate and reorganize and get  $dq_e = (\theta_r - \theta_c)(dq_g + dq_d) - dq_b$ . Plug it into the total differentiation cost, we have:

$$\begin{aligned} dTC &= \left(\frac{1}{\eta_e} + 1\right) S_e(q_e) [(\theta_r - \theta_c)(dq_g + dq_d) - dq_b] + \left(\frac{1}{\eta_c} + 1\right) S_c(q_c) \theta_c (dq_g + dq_d) + \\ &\quad \left(\frac{1}{\eta_b} + 1\right) S_b(q_b) dq_b + \left(\frac{1}{\eta_g} + 1\right) S_g(q_g) dq_g + \left(\frac{1}{\eta_d} + 1\right) S_d(q_d) dq_d \\ &= \left[\left(\frac{1}{\eta_b} + 1\right) S_b(q_b) - \left(\frac{1}{\eta_e} + 1\right) S_e(q_e)\right] dq_b + \left[\left(\frac{1}{\eta_e} + 1\right) S_e(q_e) (\theta_r - \theta_c) + \left(\frac{1}{\eta_c} + 1\right) S_c(q_c) \theta_c\right] (dq_g + dq_d) + \left(\frac{1}{\eta_g} + 1\right) S_g(q_g) dq_g + \left(\frac{1}{\eta_d} + 1\right) S_d(q_d) dq_d \end{aligned}$$

We note that the marginal increase in  $dq_b > 0$ , or the biodiesel overage, affect the total cost change. We assume that the only change on the margin when the biodiesel overage happened is  $dq_b$ , regardless of the change in the joint base of petroleum fuel base, where  $dq_g = dq_d = 0$ .

Only when the blenders lower the blending costs with the biodiesel overage that  $\left[\left(\frac{1}{\eta_b} + 1\right) S_b(q_b) - \left(\frac{1}{\eta_e} + 1\right) S_e(q_e)\right] dq_b < 0$ , where  $\left(\frac{1}{\eta_b} + 1\right) S_b(q_b) < \left(\frac{1}{\eta_e} + 1\right) S_e(q_e)$  or  $\frac{\frac{1}{\eta_b} + 1}{\frac{1}{\eta_e} + 1} < \frac{S_e(q_e)}{S_b(q_b)}$

would B be overproduced and be blended.

## 5.7 A3.2 Proposition 2 Proof

With additions of the cellulosic waiver, the nested policy structure with waiver becomes:

$$dq_c + dq_{cw} = \theta_c (dq_g + dq_d); dq_e + dq_c + dq_b = \theta_r (dq_g + dq_d).$$

Note that the refiners purchase cellulosic waiver credit for compliance if necessary by the obligated party, not the blenders. The marginal change in the fuel mandate can be reformed as  $dq_b + dq_e = (\theta_r - \theta_c)(dq_g + dq_d) + dq_{cw}$  or  $dq_b + dq_e = dq_{cw}$  on the margin. The use of

the waiver would require the extra production of biodiesel or corn ethanol to meet the total biofuel mandate.

$$\begin{aligned} dTC = & \left[ \left( \frac{1}{\eta_b} + 1 \right) S_b(q_b) - \left( \frac{1}{\eta_e} + 1 \right) S_e(q_e) \right] dq_b + \left[ \left( \frac{1}{\eta_e} + 1 \right) S_e(q_e) - \left( \frac{1}{\eta_c} + 1 \right) S_c(q_c) \right] dq_{cw} + \left[ \left( \frac{1}{\eta_e} + 1 \right) S_e(q_e) (\theta_r - \theta_c) + \left( \frac{1}{\eta_c} + 1 \right) S_c(q_c) \theta_c \right] (dq_g + dq_d) + \left( \frac{1}{\eta_g} + 1 \right) S_g(q_g) dq_g + \left( \frac{1}{\eta_d} + 1 \right) S_d(q_d) dq_d \end{aligned}$$

We consider two different conditions that the cellulosic waiver is used with the biodiesel.

- (1) When corn ethanol does not hit the 15 billion gallons cap, under the nested structure, corn ethanol is substituted by the biodiesel. The marginal condition of cellulosic waiver is when  $dq_b + dq_e = dq_{cw}$ . Every unit increase in cellulosic waiver purchased requires either the biodiesel or corn ethanol to backfill the waiver to meet the total renewable fuel mandate. The blenders choose to use biodiesel as a strategic overage when  $dTC = \left[ \left( \frac{1}{\eta_b} + 1 \right) S_b(q_b) - \left( \frac{1}{\eta_e} + 1 \right) S_e(q_e) \right] dq_b + \left[ \left( \frac{1}{\eta_e} + 1 \right) S_e(q_e) - \left( \frac{1}{\eta_c} + 1 \right) S_c(q_c) \right] dq_{cw} < 0$ . The marginal change of the total cost indicates  $\left( \frac{1}{\eta_b} + 1 \right) S_b(q_b) < \left( \frac{1}{\eta_e} + 1 \right) S_e(q_e) < \left( \frac{1}{\eta_c} + 1 \right) S_c(q_c)$  when  $dq_b > 0$  and  $dq_{cw} > 0$ .
- (2) When corn ethanol hit the 15 billion gallons cap ( $dq_e = 0$ ),  $dq_{cw} = dq_b > 0$ , the biodiesel is used only for waiver substitutes. We have  $dTC = \left[ \left( \frac{1}{\eta_b} + 1 \right) S_b(q_b) - \left( \frac{1}{\eta_c} + 1 \right) S_c(q_c) \right] dq_b < 0$  and  $\left( \frac{1}{\eta_b} + 1 \right) S_b(q_b) < \left( \frac{1}{\eta_c} + 1 \right) S_c(q_c)$ . When corn ethanol reaches the 15 billion gallons cap, the biodiesel is used only for waiver substitutes. The marginal condition of using overproduced biodiesel results in a shorter form  $\left( \frac{1}{\eta_b} + 1 \right) S_b(q_b) < \left( \frac{1}{\eta_c} + 1 \right) S_c(q_c)$ . That is when the total

cost of using biodiesel is less than using cellulosic ethanol. The condition is a subset of the conclusion from the first point.



## Table of Notation

Variables	$q_{E10}$ : Volume of E10, preblended gasohol (gallon)
	$q_{E85}$ : Volume of E85, higher blend (gallon)
	$q_{gf}$ : Volume of blended gasoline fuel from biomass-based diesel and petroleum diesel (gallon)
	$q_{df}$ : Volume of blended diesel fuel from biomass-based diesel and petroleum diesel (gallon)
	$q_e$ : Corn ethanol (gallon)
	$q_c$ : Cellulosic ethanol (gallon)
	$q_g$ : Gasoline (gallon)
	$q_d$ : Petroleum diesel (gallon)
	$q_b$ : Biomass-based diesel (gallon)
	$q_{cw}$ : Cellulosic waiver credit (unit)
	$q_{DX}$ : Quantity of D-coded RINs (unit)
	$P$ : price (\$ per unit)
	$\lambda$ : Shadow price/ Lagrangian multiplier (\$ per unit)
Parameters	$tb$ : Tax credit of biomass-based diesel \$1per gallon
	$P_{cw}$ : price of the waiver credit
	$w$ : Blending cost (\$ per unit)
	$\gamma$ : Gasoline gallon equivalent coefficient of the fuel
	$\theta$ : Blend rate mandate (%)
	$\eta$ : Elasticity of inverse supply curve
Units	gge: Gasoline gallon equivalent
	ege: Ethanol gallon equivalent