Who Will Pay for Increasing Biofuel Mandates? Incidence of the Renewable Fuel Standards Given a Binding Blend Wall

Christina Korting, Harry de Gorter, and David Just

Abstract

We show that the cost of increasing biofuel mandates given a binding ethanol blend wall will fall disproportionately on diesel fuel consumers. The extent of the burden on diesel fuel consumers is explained neither by their relatively more inelastic demand nor by blenders seeking to capitalize on the biodiesel tax credit. Relaxing the blend wall constraint by increasing the potential demand for high-ethanol blends is the only effective lever to insulate diesel fuel drivers from the one-sided welfare impacts of rising mandate levels. The independent effects of the nested mandate structure and the joint compliance base under the Renewable Fuel Standard (RFS) generate the link between motor gasoline and diesel fuel markets. Our results highlight the importance of evaluating the incidence of the RFS in a holistic framework taking both ethanol and biodiesel into account.

Key words: Biofuels, Renewable Fuel Standards, blend mandate, ethanol, E10, E85

JEL classification: H23, Q21, Q42

The U.S. Renewable Fuel Standard (RFS) was introduced with the joint objectives of (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 and creating new jobs (Rajagopal and Zilberman (2007); McCarl and Boadu (2009)). The recent shale gas boom and the consequent drop in oil prices have somewhat attenuated the concerns around the reliance on foreign fuel and its price. Findings regarding the RFS' performance with respect to the other two goals as well as its overall welfare impact have been mixed.

Work in progress by Meiselman (2016) notes that the RFS constitutes an expensive mechanism to reduce carbon emissions in the short run, with an estimated cost of USD 300 per metric ton of CO2 avoided. A working paper by Moschini, Lapan, and Kim (2016) finds a net positive welfare impact of the RFS at current mandate levels thanks to beneficial terms of trade effects, but their analysis also suggests significant distributional impacts, with farm sector surplus increasing while consumers experience significant welfare losses.

We contribute to this literature by focusing on the effects of the RFS on fuel consumer welfare. Building on work by Pouliot and Babcock (2016), we analyze the impact of ethanol blend mandates taking short term rigidities into account. In particular, our model explicitly accounts for the effects of the ethanol blend wall given constrained demand for high-ethanol blends and extends the Pouliot and Babcock (2016) framework to capture the nested mandate structure of the RFS.[1] Surprisingly, the welfare effects of rising mandate levels are most severely felt by diesel fuel consumers. This finding is in line with the welfare breakdown in the working paper by Moschini, Lapan, and Kim (2016).[2]

We rely on the partial equilibrium model proposed in Korting and Just (2017) to systematically investigate the drivers of this result. We show that most of the burden on diesel

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[1] Due to the corrosive nature of ethanol, cars have to be equipped with special tanks and fuel pumps in order to sustain the use of motor gasoline blends with a high ethanol content. As a result, the ethanol share in E10, the most common motor gasoline blend in the U.S., is legally capped at 10% ethanol, a fact often referred to as the ethanol blend wall. While so called flexible fuel vehicles (FFVs) can operate on blends of up to 85% ethanol (referred to as E85), these cars currently represent only a small fraction of the total U.S. fleet. According to Table 40 of the 2016 Annual Energy Outlook there were 18.3mn FFVs in 2015 compared to a total vehicle fleet of 240mn (U.S. Energy Information Administration 2016). The number of gas stations able to dispense high-ethanol blends is also limited. Additional blends such as E15 currently capture only a very small share of the consumer fuel market and are therefore omitted here for simplicity.

[2] Note that we restrict our model to a closed economy framework of U.S. biofuels markets in order to maintain the necessary flexibility to explore alternative mandate structures and demand scenarios. Unlike Meiselman (2016) and Moschini, Lapan, and Kim (2016), our model abstracts away from agricultural inputs and focuses exclusively on fuel markets. Readers interested in terms of trade effects, endogenous oil prices and food price impacts of the RFS are referred to their work. More details about the infrastructure constraints limiting the sale of high-ethanol blends can be found in Pouliot and Babcock (2014).

fuel consumers can be directly attributed to the ethanol blend wall. We support this result by highlighting that (i) in a model without a blend wall, the effect of rising total renewable mandates is largely borne by motor gasoline consumers; and (ii) neither the more inelastic diesel fuel demand nor the effect of the biodiesel tax credit can explain the extent of the burden placed on diesel fuel consumers.

In addition, we investigate how the particular structure of the RFS contributes to this result. While the nested mandate structure encourages efficient switching between biofuel sources to meet the total renewable fuel mandate, we show that this is not the only factor tying the fate of diesel fuel consumers to the ethanol blend wall. In fact, we obtain very similar welfare results in a model without nesting. This can be explained by the additional link between consumer fuels generated by the joint compliance base of the RFS.[3]

Since the main consumers of diesel fuel in the U.S. are trucks and trains[4], the relative burden share between fuel consumers is likely to have significant general equilibrium ramifications. The findings of this analysis therefore have important policy implications concerning the increase in biofuel mandate requirements in the face of continued demand side infrastructure constraints for high-ethanol blends.

This article is organized as follows. The next section provides an introduction to the RFS and discusses the particular policy aspects which shape the welfare results we uncover. The third section introduces our reference model and its adaptations to alternative market scenarios. Section four summarizes data sources and outlines our calibration approach. The penultimate section provides simulation results and explores the drivers behind the strong reliance on diesel fuel consumers to overcome the blend wall. The last section concludes.

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[3] All percentage blend mandate requirements under the RFS apply to the total imports or production of gasoline *and* diesel by obligated parties, see next section for details.

[4] According to tables 40 and 50 of EIA (2017), less than 1% of conventional cars and light trucks for personal use in 2015 consumed diesel, while 77% of the U.S. truck fleet relied on diesel as their main fuel source.

Renewable Fuel Standards

The Renewable Fuel Standards of 2005 (RFS1) and 2007 (RFS2), introduced as part of the Energy Policy Act (EPAct) and the Energy Independence and Security Act (EISA) respectively, contain annual volumetric targets for biofuel use in the transportation sector. In order to operationalize these targets, they are converted into percentage blend mandates 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[5] preceding the mandate year.

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

The RFS2 encompasses four distinct categories of biofuel requirements which are defined as a function of both the type of biofuel and the relative amount of greenhouse gas (GHG) savings achieved compared to the petroleum fuel being replaced. Table 1 introduces the different categories and compares mandate levels for 2015 and 2022. Cellulosic biofuel - produced from cellulose, hemicellulose or lignin - has to achieve GHG reductions of at least 60%. Biomass-based diesel (BBD) and advanced biofuels share a lifecycle GHG emissions reduction target of 50%. BBD is often made from soybean or canola oil while advanced biofuels can be made from any type of renewable biomass except corn starch. The remainder of eligible renewable fuels are required to reduce GHG emissions by 20% or more.

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

The four categories are nested within each other as shown in figure 1 (Korting and Just 2017). This structure allows for strategic overage from nested categories, if desirable, based on the relative cost of compliance. For example, additional units of BBD can be used to meet the advanced and total renewable mandate requirements.[6] Nesting thus enables the use of more efficient biofuels in GHG terms towards compliance with the larger mandate. Note that the RFS2 does not impose a specific ethanol mandate: in an extreme scenario, D3 and D4 RINs could be used to meet the entire total renewable mandate. As a result, both increased ethanol blending and increased biodiesel blending can help to overcome the ethanol blend wall.[7]

Table 1. RFS2 Mandates by Category

		2015		2022†
Mandate Category	RIN 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

Note: Volumetric mandates are shown in billion gallons of ethanol-equivalent except BBD which was originally introduced as a diesel standard and is therefore represented on a biodiesel-equivalent energy basis under the RFS. All percentage blend mandates, including D4, are shown in ethanol-equivalent terms.
†: Based on 2010 Final Rule (EPA 2010). The final 2022 mandates will likely be revised downward to reflect the slower than expected growth in cellulosic biofuel production and ethanol demand.
Source: EPA (2010) and EPA (2015)

Obligated parties under the RFS2 are refiners and importers of petroleum-based fuels rather than the blenders and distributors who ultimately control the final blends at the pump.

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

[7] According to Irwin (2016), the D4 / D6 price relationship indicates that biodiesel was the marginal gallon for compliance with the overall mandate in late 2015 and early 2016

As noted in the 2010 final rule, this decision was based on a desire to minimize the number of obligated parties (EPA 2010, p. 14722). To monitor compliance, financial instruments called Renewable Identification Numbers (RINs) were created: each RIN represents one ethanol-equivalent unit of biofuel blended for transportation. RINs are generated when biofuels are produced or imported and become detached and separately tradable once the biofuel has been blended for use in the transportation sector. Table 1 indicates the type of RIN earned per mandate category. At the end of each year, every obligated party has to present a number of RINs commensurate with each of the four mandate requirements. Based on the nested structure, the total renewable mandate can be met by a combination of D3, D4, D5 or D6 RINs.

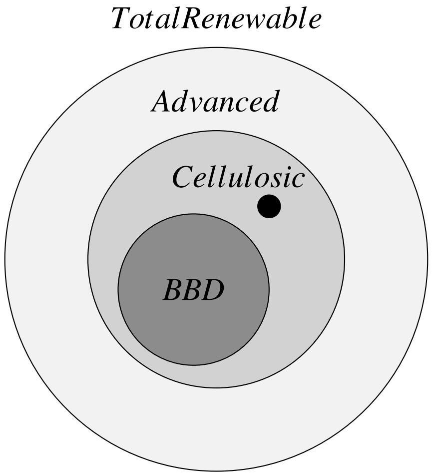

Figure 1. Nested mandate structure under the RFS2 (Korting and Just 2017)

The nature of the RFS2 and its implications for fuel and agricultural input markets have been a subject of active research: McCarl and Boadu (2009), McPhail, Westcott, and Lutman (2011) and Verleger (2013) study the regulatory framework and provide insights on the nature of RINs. de Gorter and Just (2009) and Lapan and Moschini (2012) explore the nature of blend mandates and derive their incidence and general market effects. de Gorter, Just, and Drabik (2015) analyze the economic relationships created by biofuel blending and highlight the resulting link between crude oil and agricultural markets.

Recent work has focused particularly on the feasibility and incidence of the RFS2 given the ethanol blend wall: Pouliot and Babcock (2014) provide estimates of potential demand for high-ethanol blends (E85) given current infrastructure constraints, which Pouliot and Babcock (2016) integrate into a partial equilibrium model accounting for short term market rigidities. Work by Knittel, Meiselman, and Stock (2015) analyzes the pass-through of RIN prices to fuel consumers and fuel producers. They find evidence of a limited pass-through of RIN prices to end consumers in the form of an E10-E85 discount. Korting and Just (2017) study the available channels of mandate compliance under the RFS2 and provide a formula for the core value of RIN prices. A working paper by Lade, Lin Lawell, and Smith (2015) explores the dynamic nature of the mandates: since RINs are bankable and borrowable across compliance years subject to constraints, blenders face an inter-temporal arbitrage opportunity, adding a speculative component to RIN prices.

In this article, we ignore the dynamic component of the RFS2 mandates and focus on a closed economy, one period setting with short term market rigidities such as the ethanol blend wall and limited demand for high-ethanol blends. We explicitly model the relationship between D4 and D6 RINs in order to capture the relative effects of the RFS2 on motor gasoline and diesel fuel consumers, while D3 and D5 RINs are omitted for simplicity.[8] Using a number of alternative market and policy scenarios, we are able to disentangle the aspects of the current market environment which shift the burden of the ethanol blend wall onto diesel fuel consumers.

Model

We rely on the partial equilibrium model of U.S. biofuel markets first introduced in Korting and Just (2017). The static, closed economy model is based on a representative blender and

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[8] D5 RINs are largely generated from sugarcane ethanol imports from Brazil, which are not captured in our closed economy setting. D3 RINs are derived from cellulosic biofuels. Since growth in this sector has lagged significantly behind expectations, the EPA has provided waiver credits in recent years which may be purchased by obligated parties instead of obtaining D3 RINs from blenders.

refiner who operate in a non-integrated setting[9] and trade D4 and D6 RINs for compliance. The model captures the nested mandate structure of the RFS2 and allows for strategic overage: the refiner can choose to retire more D4 RINs than required under the percentage BBD mandate (κ_{BBD}) to meet the overall total renewable mandate (κ_{TR}).

Note that our treatment of the compliance obligation as a direct constraint on the refiner's profit maximization problem differs from Moschini, Lapan, and Kim (2016) and Meiselman (2016), who instead introduce the blend mandates as a market clearing constraint. Our model therefore most closely follows the actual incentive structure of the RFS. In addition, we allow for joint blending and joint refining operations, while Meiselman (2016) introduces a separate blender and refiner for each fuel type.

Our model has an annual time horizon and does not allow for uncertainty or intertemporal considerations such as the banking and borrowing of RINs. For the sake of parsimony, the cellulosic and advanced mandate categories are not explicitly modeled. Throughout this paper, quantities, prices and blend ratios are represented by the letters q, p and θ respectively. The subscripts S, D and C distinguish between supply, demand and cost parameters. Product types are shown in (double) subscripts, while superscripts denote the refiner and blender (R, B). A summary of the notation can be found in tables A1 - A3 in the appendix.

The Korting and Just (2017) model has the advantage of being parsimonious thanks to its exclusive focus on fuel market equilibria. Korting and Just (2017) use this model among other things provide an explicit formula for the core value of RINs. They show that the price of RINs represents the marginal cost of compensating the blender for employing one additional ethanol-equivalent unit of biofuel.

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[9] This assumption is consistent with the majority of active market participants as shown by NERA (2015): 40% of US refiners in 2015 were neither integrated with blenders nor retailers. In addition, Pouliot and Babcock (2016) show that the incentives facing integrated blenders and refiners are the same as the incentives of a non-integrated blender trading RINs with a separate refiner.

The Refiner's Problem

The representative refiner maximizes his profit by selling gasoline and diesel net of production costs $C^R(q_G, q_D)$ which capture both input and operational costs. We assume a constant cost of crude oil in our simulations. The refiner also purchases RINs from the blender for compliance. The quantity of RINs chosen by the refiner is denoted by (q^R_{D4}, q^R_{D6}). Throughout this paper, we will refer to petroleum-based diesel and gasoline simply as diesel (D) and gasoline (G), while the final blends at the pump including biofuels are designated as diesel fuel (DF) and motor gasoline (MG). Since refiners are the obligated party under the RFS2, the profit maximization is subject to the constraint of meeting the nested mandate requirement by providing a sufficient number of D4 and D6 RINs against the total compliance base of petroleum fuel sales $(q_G + q_D)$.[10] Consistent with the RFS2, RIN quantities and percentage mandates are represented in ethanol equivalent terms.

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

We allow for strategic overage by adding the mandate requirements as inequality constraints to the refiner's problem rather than pre-specifying the chosen compliance strategy in the form of a RIN bundle (see for example Stock (2015)). Note that it is easy to transform the refiner's problem to consider a non-nested mandate: The refiner's constraints in this case no longer allow for the retirement of D4 RINs towards the total renewable

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[10] See the discussion about the nested mandate structure under the RFS in the previous section.

mandate requirement. Refiners therefore face an effective ethanol mandate requirement of $(\kappa_{TR} - \kappa_{BBD})$.

$$
\begin{aligned}
& q^R_{D4} \geq \kappa_{BBD}(q_G + q_D) \\
& q^R_{D6} \geq (\kappa_{TR} - \kappa_{BBD})(q_G + q_D)
\end{aligned}
\tag{2}
$$

Since the EPA's reasons for introducing nested mandates and a joint compliance base are independent, we maintain the assumption of a joint compliance base of $(q_G + q_D)$ in our model without nesting.

The Blender's Problem

The blender purchases gasoline and diesel as well as ethanol (E) and biodiesel (BD) as inputs to the blending of motor gasoline and diesel fuel. For simplicity, we only consider two distinct types of motor gasoline: E10, with a blend ratio of up to 10%, and E85, which we assume to have a constant blend ratio of 74% ethanol in line with the average blend assumed by the EPA and used in the literature (e.g. Knittel, Meiselman, and Stock (2015)).[11] The blender can endogenously determine the blend ratios in E10 and diesel fuel $(\theta_{E10}, \theta_{DF})$, but θ_{E10} is capped at 10% by the ethanol blend wall. The blender incurs separate blending costs for motor gasoline and diesel fuel.

The blender's revenue is based on his fuel sales net of taxes (t_G, t_D), his sale of RINs to the refiner, as well as the biodiesel tax credit which he earns on the amount of biodiesel blended (tc_{BD}). This tax credit was extended through December 2016.[12] The two equality constraints of the blender reflect the process of RIN generation by detaching them from the biofuels used for blending. Recall that biodiesel has a higher energy value than ethanol and that RINs are measured in ethanol equivalent terms. We therefore apply an equivalence

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[11] In practice, some gas stations also offer ethanol-free motor gasoline (E0), as well as E15 which contains up to 15% ethanol, is approved for use in models newer than 2001, but does not meet some car manufacturer warranties. Note that an increase in the E10 blend ratio could also be viewed as a reduction in E0 sales.

[12] House of Representatives Bill 2029, Section 185

value of 1.5 to transform the amount of biodiesel blended into the available amount of D4 RINs.

$$
\begin{aligned}
\max_{\substack{\{q_{E10},\, q_{E85},\, \theta_{E10} \\ q_{DF},\, q^B_{D4},\, q^B_{D6},\, \theta_{DF}\}}} \quad \Pi^B = {} & q_{E10}(p_{E10} - t_{MG}) + q_{E85}(p_{E85} - t_{MG}) + q_{DF}(p_{DF} - t_{DF}) \\
& + p_{D6}q^B_{D6} + p_{D4}q^B_{D4} + \theta_{DF}q_{DF}tc_{BD} \\
& - ((1-\theta_{E10})q_{E10} + 0.26q_{E85})p_G - (\theta_{E10}q_{E10} + 0.74q_{E85})p_E \\
& - (1-\theta_{DF})q_{DF}p_D - \theta_{DF}q_{DF}p_{BD} \\
& - C^B_{MG}(q_{E10}, q_{E85}) - C^B_{DF}(q_{DF}) \\
s.t. \quad & q^B_{D4} = 1.5\theta_{DF}q_{DF} \\
and \quad & q^B_{D6} = \theta_{E10}q_{E10} + 0.74q_{E85} \\
and \quad & \theta_{E10} \leq 0.1
\end{aligned}
\tag{3}
$$

If we want to simulate a world without a blend wall, it suffices to drop the blend wall constraint and consider a single type of motor gasoline (q_{MG}) with a freely determined blend ratio (θ_{MG}). This scenario is represented in equations 4. The two equality constraints once again represent the process of RIN generation by detaching them from the biofuels used for blending.

$$
\begin{aligned}
\max_{\substack{\{q_{MG},\, \theta_{MG} \\ q_{DF},\, q^B_{D4},\, q^B_{D6},\, \theta_{DF}\}}} \quad & q_{MG}(p_{MG} - t_G) + q_{DF}(p_{DF} - t_D) \\
& + p_{D6}q^B_{D6} + p_{D4}q^B_{D4} + \theta_{DF}q_{DF}tc_{BD} \\
& - (1-\theta_{MG})q_{MG}p_G - \theta_{MG}q_{MG}p_E - C^B_{MG}(q_{MG}) \\
& - (1-\theta_{DF})q_{DF}p_D - \theta_{DF}q_{DF}p_{BD} - C^B_{DF}(q_{DF}) \\
s.t. \quad & q^B_{D4} \leq 1.5\theta_{DF}q_{DF} \\
and \quad & q^B_{D6} \leq \theta_{MG}q_{MG}
\end{aligned}
\tag{4}
$$

All other agents in the model are represented by their respective supply and demand curves. For simplicity, ethanol and biodiesel supply as well as the demand for diesel fuel are assumed to be of the constant elasticity form $q = Ap^{\varepsilon}$ where ε is the relevant supply or demand elasticity and A represents a scaling parameter. The elasticity estimates chosen to parametrize these functions were obtained from the literature as discussed in the data section.

Motor Gasoline Demand

Our E10 and E85 demand functions are local quadratic regression approximations of the fuel demand relationships derived in Pouliot and Babcock (2014) and employed in Pouliot and Babcock (2016), who kindly shared their demand data with us. Pouliot and Babcock (2014) use locational data of FFV ownership in combination with the exact location of fuel stations in order to account for supply side infrastructure constraints such as (i) limited E85 pump capacities at the retail level; as well as (ii) the effort cost of finding E85 stations given the relative location of FFV vehicles in the U.S. They also allow for heterogeneous preferences for E10 and E85, based for example on environmental concerns or the relative range of the two fuels (Anderson (2012), Salvo and Huse (2013)). In our simulation results, we show that the constraints on E85 demand play an important role for the relative burden share between motor gasoline and diesel fuel consumers. Ignoring this effect leads to an understatement of the impact of the blend wall at high mandate levels.

The functional form employed in Meiselman (2016) also accounts for heterogeneous preferences for the two ethanol blends, but does not capture the demand constraints implied by the interplay of limited supply side infrastructure and effort costs of finding E85. However, we show in the appendix that this demand specification performs similarly for total renewable mandate levels of up to 12%. Moschini, Lapan, and Kim (2016), like Korting and Just (2017), assume that consumers value fuel purely based on miles traveled (de Gorter and Just 2010). In addition, they assume a linear functional form for fuel demand. We show that the first assumption does not significantly change simulation results at high mandate levels using the conditional demand specification employed in Korting and Just (2017): demand functions derived from heterogeneous preferences behave like a smoothed version of the demand functions implied by discrete price-based switching (see appendix). The linearity assumption on E85 demand on the other hand likely underestimates the stringency of the blend wall in the short term. Scenario results in Moschini, Lapan, and Kim (2016) at high mandate levels should therefore be viewed as long-term analyses.

The appendix provides a graphical comparison of the three functional forms of E85 demand employed in Korting and Just (2017), Meiselman (2016) and Pouliot and Babcock (2016) (figure 6).

Cost Function Choice

Unlike Korting and Just (2017), we impose nonjoint CES cost functions of the form $A_C q_C^{\varepsilon_C}$ for blenders and refiners, see equations 5.

$$
\begin{aligned}
&\text{Refiner:} && C^R(q_G, q_D) = A^R_{C_G} q_G^{\varepsilon^R_C} + A^R_{C_D} q_D^{\varepsilon^R_C} \\
(5)\quad &\text{Blender (MG):} && C^B_{MG}(q_{E10}, q_{E85}) = A^B_{C_{E10}} q_{E10}^{\varepsilon^B_{C_{MG}}} + A^B_{C_{E85}} q_{E85}^{\varepsilon^B_{C_{MG}}} \\
&\text{Blender (DF):} && C^B_{DF}(q_{DF}) = A^B_{C_{DF}} q_{DF}^{\varepsilon^B_{C_{DF}}}
\end{aligned}
$$

This form avoids the problem of diseconomies of scope in joint production while maintaining an exponent $\varepsilon_C \geq 1$ to ensure convexity.[13]

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[13] An alternative cost function specification allowing for joint outputs is the translog cost function, see for example Ray (1982). Assuming a constant returns to scale production process for two outputs, q_1 and q_2, this specification reduces to the form $log(C) = ln(k) + a\ ln(q_1) + (1-a)ln(q_2) + 0.5d\left[ln(q_1)^2 + ln(q_2)^2\right] - d\ ln(q_1)ln(q_2)$ with only three parameters. We calibrated this function to 2015 data assuming a coefficient $a = 1.25$ in line with our baseline specification for the nonjoint CES cost functions. However, this results in a negative coefficient d on the quadratic terms for the refiner, which implies no cost complementarity between gasoline and diesel. This is unlikely since both products are obtained in the same refining process by cracking crude oil. We therefore work with nonjoint CES production functions as our preferred specification.

In total, our reference model consists of 25 behavioral equations consisting of first order, complementary slackness and market clearing conditions. A complete list of equations is provided in the appendix (equations 11). We will now discuss our data sources and provide details on the calibration assumptions we make in our simulations. We will then present the results of our partial equilibrium analysis at varying mandate levels.

Data

Our model is calibrated to annual data from 2015 by finding the parameter values that minimize the error on the first order conditions for the blender and refiner. Table A1 in the appendix lists the data sources and provides an overview of the average prices and annual quantities we employ. To calibrate the constant elasticity supply and demand functions, we rely on elasticity estimates from the literature as outlined in table 2. The blender and refiner cost functions in our baseline result are assumed to have an exponent of $\varepsilon_{C_R} = \varepsilon_{C_B} = 1.25$ to ensure convexity. A sensitivity analysis with respect to this parameter revealed that simulation results do not change significantly for values between $\varepsilon_{C_R} = \varepsilon_{C_B} = 1$ and our assumed value of 1.25.

Table 2. Elasticity Estimates from the Literature

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

Note that we maintain E85 demand estimates exactly as provided in Pouliot and Babcock (2016), but recalibrate E10 demand to match our observations for 2015 in table A1. To do so, we uniformly shift the whole E10 demand surface up by a constant.

In order to calculate the amount of carbon savings from biofuels, we use the lifecycle analysis emission factors shown in table 3 provided by the EPA.[14] These emission factors account for all 'well-to-wheel' and 'field-to-wheel' emissions including feedstock production and the resulting land use change, fuel production and distribution as well as emissions generated during the combustion of the finished fuel. The emission factor for corn ethanol assumes a dry mill production process using natural gas. The biodiesel emission factor represents results for a transesterification process of soybean oil. We use the 2015 central social cost of carbon estimate of USD 36 per metric ton of CO2 to convert emission reductions into the value of carbon savings.[15]

Table 3. Lifecycle Emission Factors by Fuel Type

Fuel Type	Net Emissions (kgCO2e / mmBtu)	Net Emissions (kgCO2e / GAL)	% Saving
Gasoline	98.2	11.83	-
Ethanol	77.2	6.54	21%
Diesel	97.0	13.33	-
Biodiesel	42.2	5.38	57%

Note: Percentage savings reflect the percent reduction in CO2 emissions compared to the petroleum-based fuel being replaced.

Table A2 in the appendix highlights the calibration results for model parameters such as the supply and cost function multipliers. Table 4 provides a comparison of simulation results at 2015 mandate levels to the observed market data for the same year. Overall, our simulation results provide a good fit for the 2015 data. Some differences to note are the relatively higher E10 blend ratio and the lower price of D6 RINs in our simulations. Due to the low average price of ethanol compared to gasoline in 2015, our model pushes the E10 blend ratio to its maximum level of 10%. We therefore have an excess of D6 RIN

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[14] https://www.epa.gov/fuels-registration-reporting-and-compliance-help/lifecycle-greenhouse-gas-results

[15] In 2007 dollars assuming a central discount rate of 3%. Impact analysis revised July 2015: https://www3.epa.gov/climatechange/Downloads/EPAactivities/social-cost-carbon.pdf

generation compared to the 2015 total renewable mandate level of 9.52%, leading to a D6 RIN price of zero.

In addition, E85 demand in our model is higher than the demand observed in the data. We believe that this is due to inconsistencies in data reporting between the sources for E85 demand in Pouliot and Babcock (2014) and our paper. Our E85 quantity inputs rely on the sum of (i) EIA data on Weekly Refiner & Blender Net Production of conventional gasoline with an ethanol content of more than 55% and (ii) EIA data on motor gasoline supply by renewable fuel and oxygenate plants from the Petroleum & Other Liquids report.[16] Pouliot and Babcock (2014) derive the demand for E85 using locational data on FFV ownership and retail fuel stations.

Table 4. Empirical Verification

Variable	Description	2015	Simulated	Units
q_G	Gasoline in Transport. excl. Ethanol	124.72	124.62	bGAL
q_E	Ethanol in Transport	13.38	13.94	bGAL
q_{E10}	E10 Consumption	138.02	138.43	bGAL
q_{E85}	E85 Consumption	0.07	0.13	bGAL
θ_{E10}	Implied E10 Ethanol Content	9.65%	10%	Percent
q_D	Diesel Fuel in Transport. excl. Biodiesel	43.17	43.03	bGAL
q_{BD}	Biodiesel in Transport.	1.48	1.65	bGAL
q_{DF}	Distillate Fuel Oil in Transport.	44.65	44.69	bGAL
θ_{DF}	Implied Biodiesel Content	3.31%	3.75%	Percent
p_G	Refiner Price of Motor Gasoline for Resale	1.72	1.68	USD/GAL
p_E	Ethanol Nebraska Rack, FOB Omaha	1.61	1.64	USD/GAL
p_{E10}	Regular Motor Gasoline, All Areas	2.43	2.45	USD/GAL
p_{E85}	E85 Prices	1.96	2.43	USD/GAL
p_D	Refiner Price of No. 2 Diesel Fuel for Resale	1.66	1.62	USD/GAL
p_{BD}	U.S. Retail Fuel Prices B99/B100	3.65	3.88	USD/GAL
p_{DF}	On-Highway Diesel Fuel Price	2.71	2.67	USD/GAL
κ_{TR}	Final Percentage Standards: Renewable Fuel	9.52%	9.5%	Percent
κ_{BBD}	Final Percentage Standards: BBD	1.49%	1.5%	Percent
p_{D6}	Ethanol RINs (D6)	0.55	0.00	USD/RIN
p_{D4}	Biodiesel RINs (D4)	0.72	0.84	USD/RIN

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[16] This is in line with the measurement of E85 quantities in industry reports (e.g. API and AFPM (2015)).

We now turn to the results of our fuel market simulations.

Simulation Results

Figure 2 presents the evolution of welfare outcomes under our reference model as a function of total renewable blend mandate levels. Throughout this section, we hold the BBD blend mandate constant at its 2015 level of $\kappa_{BBD} = 1.5\%$. Note that the figure does not have a time component. Instead, the graph reflects the simulated results given the U.S. market environment in 2015 under varying assumed levels of κ_{TR}. We thus provide market and welfare outcomes holding all exogenous components of the model except for the total renewable mandate level constant.

The fourth panel of this figure highlights the unequal effects of rising mandate levels on diesel fuel and motor gasoline consumers.[17] The x-axis in this graph reflects levels of κ_{TR} varying from 1.5% (the 2015 BBD mandate level) to 12%. The blend wall generates sharp losses in diesel fuel consumer surplus as the biodiesel blend ratio increases, leading to a higher price at the pump and discouraging demand. Motor gasoline consumers on the other hand temporarily benefit from lower prices as blenders try to encourage E85 sales by decreasing its price, leading to higher motor gasoline sales overall.

It is important to note that the ethanol blend wall does not become binding at a particular total renewable mandate level. As emphasized previously, the RFS2 does not mandate specific amounts of ethanol use. Rather, ethanol is used to fill the gap between the BBD and total renewable mandate not met through BBD overage. In addition, the joint compliance base implies that the amount of ethanol blended is measured against the sum of petroleum gasoline and diesel, rather than gasoline alone. The blend wall on the other hand is a

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[17] Since E10 and E85 are substitutes whose demands each depend on the two prices, (p_{E10}, p_{E85}), the consumer surplus calculations based on Marshallian demand functions are subject to path dependence. To minimize the approximation error, we calculate consumer surplus as a sequence of line-integrals along linear paths between the successive equilibrium results for different mandate levels. Havranek and Kokes (2015) estimate a publication bias-corrected income elasticity of motor gasoline demand of 0.1. This low estimate implies that Willig's condition, which guarantees a small approximation error from using consumer surplus measures under certain conditions, is satisfied in the context of motor gasoline demand (see for example Just, Hueth, and Schmitz (2008), p. 138)

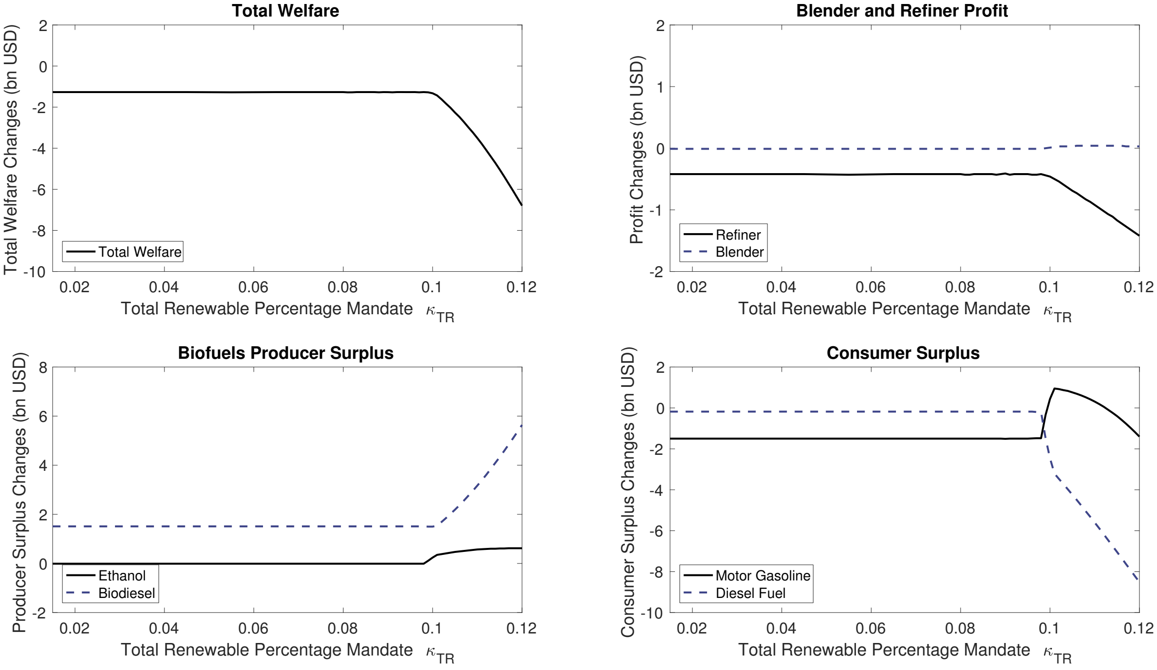

Figure 2. Welfare results under the reference model for total renewable mandate levels up to 12% (bn USD)

function of the amount of ethanol relative to gasoline. This means that the total renewable mandate level at which the blend wall starts binding is endogenous. The rise of D6 RIN prices in panel 2 of figure 3 offers a reliable indication of when the blend wall is reached.

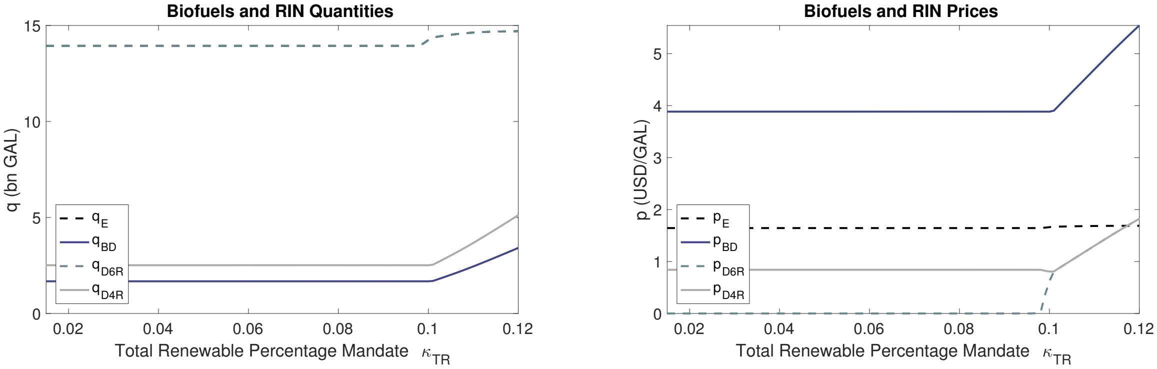

Figure 3. Price and quantity changes for biofuels
Notes: All prices are shown in USD/GAL. All quantities are shown in bn GAL.

Throughout this section, we will refer to tables 5 - 7 which provide a comparison of simulated market outcomes under the reference model to the different market and policy frameworks we explore. Tables 8 - 10 summarize the corresponding welfare results. Each table presents a snapshot of results at a different total renewable mandate level, rising from the 2015 level of around 9.5% to 11.5% in 1% increments.

As mentioned previously, we argue that the welfare loss of diesel fuel consumers is largely attributable to the effects of the ethanol blend wall. We show that (i) in a model without a blend wall, the effect of rising total renewable mandates is largely borne by motor gasoline consumers; and (ii) neither the more inelastic diesel fuel demand nor the effect of the biodiesel tax credit can explain the extent of the burden placed on diesel fuel consumers. Our simulation results indicate that only an expansion of E85 demand, and hence a relaxation of the ethanol blend wall, can alleviate the consumer surplus losses by diesel fuel consumers. Finally, the last part of this section highlights the dual link between motor gasoline and diesel fuel consumers generated by the particular nature of the RFS2. Both the nested mandate structure and the joint compliance base drive the burden share between consumer types.

Effects of the Ethanol Blend Wall

First, we will show that the welfare losses that diesel fuel consumers experience are indeed a consequence of the ethanol blend wall. For this purpose, we compare welfare results from our reference model to a model without blend wall. The 'No Blend Wall' column in tables 8 - 10 highlights the corresponding simulated welfare results. As mentioned in previous sections, this alternative model assumes that there is only one type of motor gasoline with freely varying ethanol content. Without the blend wall constraint and assuming that total renewable mandates are equal to their nested BBD mandates, blenders choose an optimal ethanol blend ratio of 10.6% while the biodiesel share in diesel fuel remains at the reference level of 3.6%.

As total renewable mandate levels rise, we see roughly stable diesel fuel blend ratios of 3.7%, while motor gasoline blend ratios rise to as much as 11.9% ethanol content at the 11.5% mandate level. Diesel fuel consumers in this case experience a welfare loss of only

USD -0.6bn compared to the USD -7bn under the reference model. The blend wall thus clearly represents the bulk of diesel fuel consumer surplus losses.

In the model with blend wall on the other hand, we see a steady uptick in diesel fuel blend ratios as total renewable mandate levels increase (see figure 4). The biodiesel share in diesel fuel rises from 3.7% to as much 6.6% as total renewable mandates increase from 9.5% to 11.5%. Recall that the required BBD blend mandate itself is held constant at 1.5%, meaning that we are seeing an increase in BBD overage. D4 and D6 RIN prices reach parity once the blend wall is hit and rise to 1.57 USD/GAL at the 11.5% mandate level. This indicates that ramping up biodiesel blending is the preferred compliance channel in the presence of a binding blend wall.[18]

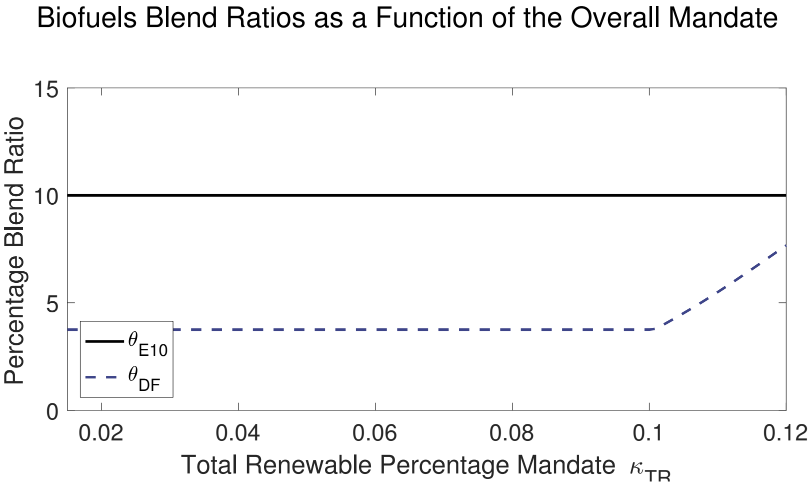

Figure 4. Changes in fuel blend ratios (percent)

The total deadweight cost of the blend wall at 11.5% mandate levels is USD -4.1bn.

Alternative Explanations for the Relative Burden Share by Diesel Fuel Consumers

There are two possible alternative explanations for why diesel fuel consumers shoulder most of the effect of the ethanol blend wall. First, the more inelastic demand for diesel fuel could make blenders more prone to target these consumers for price increases. Second, the biodiesel tax credit could add to the relative attractiveness of biodiesel blending compared

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[18] See Korting and Just (2017) for an analysis of the four compliance channels available under the RFS2, and their relative importance at different mandate levels.

to larger E85 price discounts. However, we show that neither of these two factors can explain the disproportional incidence on diesel fuel consumers.

- *Effect of the Biodiesel Tax Credit*

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

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

- *Effect of Equal Consumer Fuel Demand Elasticities*

  We also consider a model in which diesel fuel demand elasticity is increased to be on par with the elasticity of motor gasoline demand. In this case, we choose $\varepsilon_{D_{DF}} = -0.25$ as in Pouliot and Babcock (2014) and obtain a corresponding cost function multiplier of $A_{D_{DF}} = 57.27$ based on calibrations to 2015 data. We find almost no welfare changes at the 9.5 and 10.5% total renewable mandate level relative to the baseline results. At 11.5%, we see a slight increase in the diesel fuel consumer surplus of USD 0.2bn, largely offset by reductions in blender and refiner profits.

This suggests that an increased diesel fuel demand elasticity changes the burden share between blenders/refiners and diesel fuel consumers, but does not significantly alter the trade-off between ethanol and biodiesel use. As table 7 suggests, most quantities and prices are unchanged with the exception of a net reduction in diesel fuel. The composition of diesel fuel remains unchanged at 6.6% biodiesel as in the reference case.

Relaxing the Blend Wall Constraint through Additional E85 Demand

Having ruled out the relative elasticity of diesel fuel demand as well as the effect of the biodiesel tax credit as dominant factors determining the diesel fuel consumer surplus loss, we now show that an increase in E85 demand can mitigate the welfare impacts of rising mandates. Note that such an increase effectively makes the ethanol blend wall less binding. We consider the effect of scaling up the level of E85 demand by fixed multipliers while adjusting down the demand for E10 to maintain the net motor gasoline demand levels observed in 2015.

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

No Nesting

Do the differential welfare impacts disappear if biodiesel overage can no longer be used to meet the total renewable mandate? Our simulation results for a model without nesting show that the link between motor gasoline and diesel fuel consumers is not just an artifact of nesting, but also of the joint compliance base. Due to this dual link, the added flexibility provided by the nested mandate structure actually acts as a net welfare enhancement for diesel fuel consumers and the biofuel sector overall.

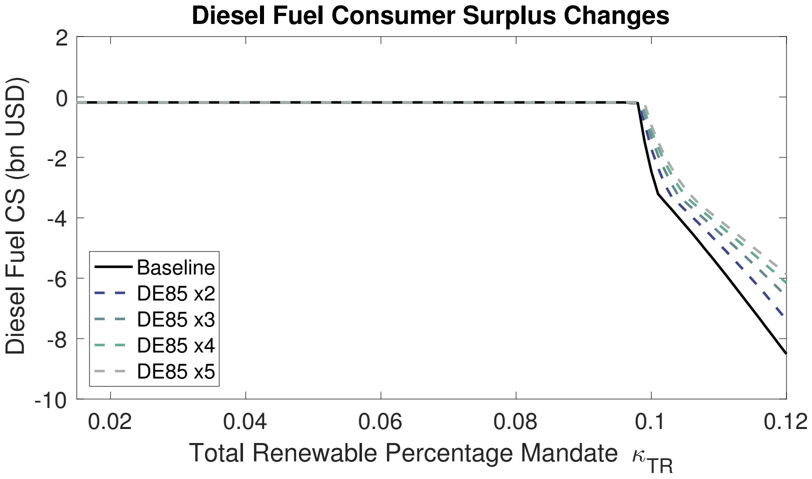

Figure 5. Diesel fuel consumer surplus under the reference model as a function of E85 demand levels

As discussed previously, the EPA's reasons for imposing a joint compliance base were distinct from the nested mandate structure choice. When designing our market framework without nesting, we therefore maintain the assumption of a joint gasoline and diesel compliance base. In this case, consumer surplus losses for diesel fuel consumers are significantly more severe than in the reference case at the 10.5% mandate level. The model no longer solves at the 11.5% mandate level without nested mandates.

To understand why this is the case, note that blenders do generate much higher E85 sales for compliance by driving E85 prices close to zero. As expected, they also maintain a lower diesel fuel blend ratio of 4%. However, by comparing the results in the 'No Nesting' column of table 6 to the 'Reference' column in table 5, it becomes evident that blenders charge higher relative diesel fuel prices given the price of diesel and biodiesel inputs. The blender's first order condition with respect to the quantity of diesel fuel is given by equation 6.

$$(6) \qquad p_{DF} - t_{DF} = \underbrace{\frac{\partial C_B^{DF}}{\partial q_{DF}}}_{\substack{\text{Marginal Cost}\\ \text{of Blending}}} + \underbrace{(1-\theta_{DF})p_D + \theta_{DF}(p_{BD} - tc_{BD})}_{\text{Input Costs}} - \underbrace{1.5\theta_{DF}p_{D4}}_{\substack{\text{Value of}\\ \text{RINs detached}}}$$

D4 RINs no longer increase in value as the free-market diesel fuel blend ratio of 3.7% exceeds the BBD mandate requirement and the additional D4 RINs can no longer be used to meet the total renewable mandate (see tables 5 - 7). This means that D4 RIN prices no longer represent a cap for D6 RIN prices. Accordingly, all else equal the blender now has to charge a higher diesel fuel price to maintain equality of marginal benefits (LHS) and marginal costs (RHS). Note in table 6 that the price of D6 RINs is more than six times as high as the price of D4 RINs under the no nesting scenario.

Table 5. Simulation Results at Total Renewable Mandate Level $\kappa_{TR} = 9.5\%$

	Reference	No Tax Credit		Equal Elasticities		No Blend Wall		No Nesting	
	Result	Result	Change	Result	Change	Result	Change	Result	Change
				Blend Ratios (%)					
θ_{E10}	10.0%	0.1	0.0%	10.0%	0.0%	-	-	10.0%	0.0%
θ_{DF}	3.8%	3.7%	-0.1%	3.8%	0.0%	3.7%	0.0%	4.0%	0.3%
θ_{MG}	-	-	-	-	-	10.5%	-	-	-
				Quantities (bGAL)					
q_{E10}	138.4	138.3	-0.1	138.4	0.0	-	-	138.4	0.0
q_{E85}	0.1	0.1	0.0	0.1	0.0	-	-	0.1	0.0
q_{MG}	138.6	138.4	-0.1	138.6	0.0	138.5	0.0	138.6	0.0
q_{DF}	44.7	44.7	0.0	44.8	0.1	44.7	0.0	44.7	0.0
q_G	124.6	124.5	-0.1	124.6	0.0	123.9	-0.7	124.6	0.0
q_D	43.0	43.0	0.0	43.1	0.1	43.0	0.0	43.0	0.0
q_E	13.9	13.9	0.0	13.9	0.0	14.6	0.6	13.9	0.0
q_{BD}	1.7	1.7	0.0	1.7	0.0	1.7	0.0	1.7	0.0
q_{D4}	2.5	2.5	0.0	2.5	0.0	2.5	0.0	2.5	0.0
q_{D6}	13.9	13.9	0.0	13.9	0.0	14.6	0.6	13.9	0.0
				Prices (USD/GAL)					
p_{E10}	2.45	2.46	0.00	2.45	0.00	-	-	2.45	0.00
p_{E85}	2.43	2.43	0.00	2.43	0.00	-	-	2.43	0.00
p_{MG}	-	-	-	-	-	2.45	-	-	-
p_{DF}	2.67	2.68	0.01	2.67	0.00	2.67	0.00	2.67	0.00
p_G	1.68	1.69	0.01	1.68	0.00	1.68	0.00	1.68	0.00
p_D	1.62	1.63	0.01	1.62	0.00	1.62	0.00	1.62	0.00
p_E	1.64	1.64	0.00	1.64	0.00	1.68	0.04	1.64	0.00
p_{BD}	3.88	3.88	0.00	3.89	0.01	3.88	0.00	3.88	0.00
p_{D4}	0.84	1.50	0.66	0.84	0.00	0.84	0.00	0.84	0.00
p_{D6}	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00

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

Table 6. Simulation Results at Total Renewable Mandate Level $\kappa_{TR} = 10.5\%$

	Reference	No Tax Credit		Equal Elasticities		No Blend Wall		No Nesting	
	Result	Result	Change	Result	Change	Result	Change	Result	Change
				Blend Ratios (%)					
θ_{E10}	10.0%	10.0%	0.0%	10.0%	0.0%			10.0%	0.0%
θ_{DF}	4.5%	4.2%	-0.3%	4.5%	0.0%	3.7%	-0.8%	4.0%	-0.5%
θ_{MG}	-	-	-	-	-	10.8%	-		-
				Quantities (bGAL)					
q_{E10}	138.0	137.8	-0.1	138.0	0.0	-	-	138.9	1.0
q_{E85}	1.0	1.2	0.3	1.0	0.0			1.5	0.5
q_{MG}	138.9	139.1	0.1	138.9	0.0	138.5	-0.4	140.4	1.5
q_{DF}	44.6	44.5	-0.1	44.5	-0.1	44.7	0.1	44.3	-0.3
q_G	124.4	124.4	-0.1	124.4	0.0	123.5	-0.9	124.8	0.3
q_D	42.6	42.6	0.1	42.4	-0.1	43.0	0.5	42.6	0.1
q_E	14.5	14.7	0.2	14.5	0.0	15.0	0.5	15.0	0.5
q_{BD}	2.0	1.9	-0.1	2.0	0.0	1.7	-0.3	1.7	-0.3
q_{D4}	3.0	2.8	-0.2	3.0	0.0	2.5	-0.5	2.5	-0.5
q_{D6}	14.5	14.7	0.2	14.5	0.0	15.0	0.5	15.1	0.6
				Prices (USD/GAL)					
p_{E10}	2.43	2.43	0.00	2.43	0.00	-	-	2.38	-0.05
p_{E85}	1.93	1.59	-0.34	1.93	0.00	-	-	0.00	-1.93
p_{MG}	-	-	-	-	-	2.45	-	-	-
p_{DF}	2.76	2.82	0.06	2.76	0.00	2.67	-0.09	3.00	0.24
p_G	1.78	1.83	0.05	1.78	0.00	1.68	-0.10	2.03	0.25
p_D	1.71	1.77	0.06	1.71	0.00	1.62	-0.09	1.96	0.25
p_E	1.68	1.69	0.01	1.68	0.00	1.70	0.02	1.70	0.02
p_{BD}	4.26	4.13	-0.13	4.25	-0.01	3.87	-0.39	3.89	-0.37
p_{D4}	1.03	1.57	0.54	1.02	-0.01	0.83	-0.20	0.62	-0.41
p_{D6}	1.03	1.57	0.54	1.02	-0.01	0.02	-1.01	3.84	2.81

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

Table 7. Simulation Results at Total Renewable Mandate Level $\kappa_{TR} = 11.5\%$

	Reference	No Tax Credit		Equal Elasticities		No Blend Wall		No Nesting	
	Result	Result	Change	Result	Change	Result	Change	Result	Change
Blend Ratios (%)									
θ_{E10}	10.0%	10.0%	0.0%	10.0%	0.0%	-	-	-	-
θ_{DF}	6.6%	6.5%	-0.1%	6.6%	0.0%	3.7%	-2.9%	-	-
θ_{MG}	-	-	-	-	-	11.9%	-	-	-
Quantities (bGAL)									
q_{E10}	137.7	137.6	0.0	137.7	0.0		-	-	-
q_{E85}	1.2	1.3	0.1	1.2	0.0	-	-	-	-
q_{MG}	138.9	138.9	0.1	138.9	0.0	138.5	-0.4	-	-
q_{DF}	44.5	44.4	-0.1	44.2	-0.3	44.7	0.2	-	-
q_G	124.2	124.2	0.0	124.2	0.0	122.0	-2.2	-	-
q_D	41.6	41.6	0.0	41.3	-0.3	43.0	1.4	-	-
q_E	14.7	14.7	0.1	14.7	0.0	16.5	1.8	-	-
q_{BD}	2.9	2.9	0.0	2.9	0.0	1.7	-1.3	-	-
q_{D4}	4.4	4.3	-0.1	4.4	0.0	2.5	-1.9	-	-
q_{D6}	14.7	14.7	0.1	14.7	0.0	16.5	1.8	-	-
Prices (USD/GAL)									
p_{E10}	2.44	2.45	0.005	2.44	0	-	-	-	-
p_{E85}	1.59	1.18	-0.41	1.6	0.01	-	-	-	-
p_{MG}	-	-	-	-	-	2.45	-	-	-
p_{DF}	2.82	2.89	0.07	2.82	0	2.68	-0.14	-	-
p_G	1.85	1.92	0.068	1.85	0	1.68	-0.17	-	-
p_D	1.78	1.85	0.066	1.77	-0.01	1.63	-0.15	-	-
p_E	1.69	1.69	0	1.69	0	1.79	0.1	-	-
p_{BD}	5.13	5.09	-0.036	5.11	-0.02	3.85	-1.28	-	-
p_{D4}	1.57	2.17	0.596	1.56	-0.01	0.81	-0.76	-	-
p_{D6}	1.57	2.17	0.596	1.56	-0.01	0.1	-1.47	-	-

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

Table 8. Welfare Changes Compared to Free-Market Reference Scenario at Total Renewable Mandate Level $\kappa_{TR} = 9.5\%$ (bn USD)

	Reference	No Tax Credit		Equal Elasticities		No Blend Wall		No Nesting	
	Result	Result	Change	Result	Change	Result	Change	Result	Change
Producer Surplus									
Refiner	-0.42	-0.65	-0.23	-0.41	0.01	-0.51	-0.09	-0.42	0.00
Blender	-0.01	-0.02	-0.01	-0.02	-0.01	-0.01	0.00	-0.01	0.00
Ethanol	-0.01	-0.02	-0.01	-0.01	0.00	0.16	0.17	-0.01	0.00
Biodiesel	1.51	2.01	0.50	1.51	0.00	1.49	-0.02	1.51	0.00
Consumer Surplus									
Motor Gasoline	-1.50	-2.68	-1.18	-1.52	-0.02	-1.57	-0.07	-1.50	0.00
Diesel Fuel	-0.18	-0.43	-0.25	-0.18	0.00	-0.18	0.00	-0.18	0.00
Government Revenue and Value of Carbon Savings									
Tax Revenue	-0.98	-0.12	0.86	-0.99	-0.01	-0.98	0.00	-0.98	0.00
Value of CO2 Savings	0.32	0.51	0.19	0.33	0.01	0.36	0.04	0.32	0.00
Total	-1.27	-1.41	-0.14	-1.29	-0.02	-1.23	0.04	-1.27	0.00

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

Table 9. Welfare Changes Compared to Free-Market Reference Scenario at Total Renewable Mandate Level $\kappa_{TR} = 10.5\%$ (bn USD)

	Reference	No Tax Credit		Equal Elasticities		No Blend Wall		No Nesting	
	Result	Result	Change	Result	Change	Result	Change	Result	Change
Producer Surplus									
Refiner	-0.69	-0.87	-0.18	-0.77	-0.08	-0.69	0.00	-0.54	0.15
Blender	0.03	0.05	0.02	0	-0.03	-0.01	-0.04	0.13	0.10
Ethanol	0.47	0.62	0.15	0.47	0.00	0.52	0.05	0.87	0.40
Biodiesel	2.19	2.44	0.25	2.17	-0.02	1.48	-0.71	1.52	-0.67
Consumer Surplus									
Motor Gasoline	0.76	1.45	0.69	0.74	-0.02	-1.65	-2.41	10.88	10.12
Diesel Fuel	-4.24	-6.60	-2.36	-4.08	0.16	-0.27	3.97	-15.19	-10.95
Government Revenue and Value of Carbon Savings									
Tax Revenue	-1.20	0.08	1.28	-1.33	-0.13	-0.98	0.22	-0.35	0.85
Value of CO2 Savings	0.42	0.53	0.11	0.54	0.12	0.44	0.02	0.20	-0.22
Total	-2.27	-2.31	-0.04	-2.26	0.01	-1.15	1.12	-2.48	-0.21

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

Table 10. Welfare Changes Compared to Free-Market Reference Scenario at Total Renewable Mandate Level $\kappa_{TR} = 11.5\%$ (bn USD)

	Reference	No Tax Credit		Equal Elasticities		No Blend Wall		No Nesting	
	Result	Result	Change	Result	Change	Result	Change	Result	Change
				Producer Surplus					
Refiner	-1.17	-1.37	-0.2	-1.31	-0.14	-1.33	-0.16	-	-
Blender	0.04	0.04	0	-0.02	-0.06	-0.02	-0.06	-	-
Ethanol	0.61	0.66	0.05	0.61	0	1.84	1.23	-	-
Biodiesel	4.33	4.74	0.41	4.28	-0.05	1.45	-2.88	-	-
				Consumer Surplus					
Motor Gasoline	-0.40	-0.20	0.20	-0.43	-0.03	-2.04	-1.64	-	-
Diesel Fuel	-7.04	-9.88	-2.84	-6.74	0.30	-0.63	6.41	-	-
				Government Revenue and Value of Carbon Savings					
Tax Revenue	-2.17	-0.02	2.15	-2.37	-0.20	-0.98	1.19	-	-
Value of CO2 Savings	0.76	0.91	0.15	0.96	0.20	0.75	-0.01	-	-
Total	-5.03	-5.12	-0.09	-5.02	0.01	-0.96	4.07	-	-

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

Concluding Remarks

We study a detailed model of current U.S. biofuel policy and find that under 2015 market conditions, diesel fuel consumers are disproportionately affected by the cost of increasing blend mandates given a binding ethanol blend wall. If 2015 total renewable blend mandates had been 2% higher, diesel fuel consumers would have suffered significant welfare losses while motor gasoline consumers would have remained largely unaffected. Using a series of simulation results under alternative market and policy scenarios, we are able to show that only an increase in potential demand for high-ethanol blends can effectively alleviate the pressure on this consumer group.

Our results underscore the importance of information campaigns targeted at FFV drivers as well as of E85 infrastructure projects at the pump and distribution level. The Renewable Fuel Standards were designed to be 'technology-forcing', inducing blenders and refiners to provide adequate infrastructure to achieve mandate compliance. From this perspective, the EPA's decision to alleviate short-term pressure by cutting 2014-2016 mandate requirements was potentially self-defeating. On the other hand, diesel fuel consumer surplus losses are likely to have important general equilibrium ramifications: since heavy trucks and trains account for most of the diesel fuel consumption in the U.S., the increased cost of transportation will likely be passed on in the form of consumer good price inflation.

It is therefore becoming increasingly clear that industry and policy makers need to find a joint way forward to keep the mandates both physically and economically feasible. The USDA's commitment of USD 100mn towards industry projects investing in additional E15 and E85 infrastructure under its Biofuel Infrastructure Partnership (BIP), requiring matching contributions from industry partners, may prove to be an important first step in that direction.[19]

Our results also highlight the importance of evaluating the incidence of the Renewable Fuel Standards in a holistic framework taking both ethanol and biodiesel into account.

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

While ethanol-only models can add important intuition about the nature of blend mandates, they do not adequately capture the nuances of the burden share between consumer groups implied by the dual link generated by the nested mandate structure and the joint compliance base under the RFS.

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Data and Calibration Results

Table A1 summarizes the data sources used in our calibrations. Table A2 highlights the corresponding calibration results.

Table A1. Data Sources

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

Demand Function Choice

In this section, we compare the demand specifications employed in (i) Pouliot and Babcock (2016), (ii) Korting and Just (2017), and (iii) Meiselman (2016). Our simulation results indicate that the most important factor determining the shift of the welfare losses from motor gasoline to diesel fuel consumers is the constraint on E85 demand, and hence the degree to which the blend wall is binding. We show that Pouliot and Babcock (2016) and Korting and Just (2017) demands lead to very similar simulation results, while the

Table A2. Calibration Results

Variable	Description	Value
$A^R_{C_G}$	Cost Refiner (Gasoline)	0.454
$A^R_{C_D}$	Cost Refiner (Diesel)	0.438
$A^B_{C_{E10}}$	Cost Blender (E10)	0.125
$A^B_{C_{E85}}$	Cost Blender (E85)	0.111
$A^B_{C_{DF}}$	Cost Blender (Diesel Fuel)	0.164
A_{S_E}	Supply Ethanol	5.161
$A_{S_{BD}}$	Supply Biodiesel	0.111
$A_{D_{DF}}$	Demand Diesel Fuel	47.872

Table A3. 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

functional form used in Meiselman (2016) slightly underestimates the welfare impact on diesel fuel consumers at high mandate levels. Note that the simulation results in this section are extended to total renewable blend mandate levels of up to 16%. The three demands lead to similar simulation results for mandate levels of up to 12%.

Pouliot and Babcock (2016)

The demand functions in Pouliot and Babcock (2016) are locally weighted quadratic regression estimates of the detailed demands derived in Pouliot and Babcock (2014). Pouliot and Babcock (2014) employ a choice model to estimate E85 demand by FFV drivers taking into account (i) heterogeneous preferences for the two fuels; (ii) the effort cost of finding E85 given the distribution of gas stations offering E85 relative to the location of FFVs; and (iii) constrained E85 distribution infrastructure.

Korting and Just (2017)

Korting and Just (2017) use a simplified demand specification in which FFV drivers value fuel purely based on the miles per gallon they provide, and do not have heterogeneous tastes for E10 and E85. As a result, drivers switch between E10 and E85 based purely on the relative price of the two fuels in energy equivalent terms. In line with the EPA RFS2 rule documents, we assume that a price discount of at least 22% relative to E10 is necessary for E85 to be attractive on an energy-equivalent basis. We therefore apply an energy-equivalence factor of $\lambda = 1 - 0.22$ to E10 prices to make the fuel prices comparable. FFV consumers will consume only E10 when $p_{E85} > \lambda p_{E10}$, purchase only E85 when $p_{E85} < \lambda p_{E10}$ and are indifferent between the two types of fuel otherwise. The corresponding demand for E85 is shown in equation 7.

$$(7) \quad D_{E85}(p_{E10}, p_{E85}) \begin{cases} = 0 & if\ p_{E85} > \lambda p_{E10} \\ \in [0, A_{D_{FFV}} p_{E10}^{\varepsilon_{D_{MG}}}] & if\ p_{E85} = \lambda p_{E10} \\ = A_{D_{FFV}} \left(\frac{1}{\lambda} p_{E85}\right)^{\varepsilon_{D_{MG}}} & otherwise \end{cases}$$

When prices are exactly equal in energy equivalent terms, consumers are completely indifferent between the two types of fuel. As in Korting and Just (2017), we choose $\varepsilon_{D_{MG}} = -0.25$ and $A_{D_{FFV}} = 1.2$ for our simulation results.

Similarly, equation 8 shows the demand for E10 which is made up of both consumer types, just conventional car owners or conventional car owners and some share of FFV owners in case prices are equal in energy equivalent terms.

$$
(8) \quad D_{E10}(p_{E10}, p_{E85}) \begin{cases} = A_{D_{FFV}} p_{E10}^{\varepsilon_{D_{MG}}} + A_{D_C} p_{E10}^{\varepsilon_{D_{MG}}} & if\ p_{E85} > \lambda p_{E10} \\ = A_{D_{FFV}} p_{E10}^{\varepsilon_{DMG}} + A_{DC} p_{E10}^{\varepsilon_{D_{MG}}} - D_{E85} & if\ p_{E85} = \lambda p_{E10} \\ = A_{DC} p_{E10}^{\varepsilon_{DMG}} & otherwise \end{cases}
$$

Meiselman (2016)

Meiselman (2016) provides inverse demand functions for E10 and E85 of the form

$$
(9) \quad p_{E10} = \alpha \phi_{MG} q_{E10}^{\frac{1-\sigma}{\sigma}} \left[\alpha q_{E10}^{\frac{1}{\sigma}} + (1-\alpha)\left(\gamma q_{E85}\right)^{\frac{1}{\sigma}} \right]^{\left(\sigma - \frac{\sigma}{\varepsilon_{D_{MG}}} - 1\right)}
$$

$$
(10) \quad p_{E85} = (1-\alpha)\phi_{MG}\left(\gamma q_{E85}\right)^{\frac{1-\sigma}{\sigma}} \left[\alpha q_{E10}^{\frac{1}{\sigma}} + (1-\alpha)\left(\gamma q_{E85}\right)^{\frac{1}{\sigma}} \right]^{\left(\sigma - \frac{\sigma}{\varepsilon_{D_{MG}}} - 1\right)}
$$

These demand functions are derived from the maximization of a quasilinear utility function subject to a budget constraint. The functional forms allow for heterogeneous fuel preferences. We recalibrate these demand functions to our 2015 data for comparison. The resulting parameter estimates are given in table A4.

Simulation Results under Different Demand Specifications

Figure 6 plots the different E85 demand specifications. Note that unlike Pouliot and Babcock (2016) and Korting and Just (2017), Meiselman (2016) relies on inverse demand functions for motor gasoline. We therefore have to invert the corresponding system of E10 and E85 demands for the graphical representation in figure 6. Since the system of equations

Table A4. Calibration Results for Inverse Demand Functions Employed in Meiselman (2016)

Parameter	Value	Source
$\varepsilon_{D_{MG}}$	-0.25	Pouliot and Babcock (2014)
λ	0.78	EPA RFS2 rule documents
σ	1.15	Meiselman (2016)
α	0.7293	Calibrated
$log(\phi_{MG})$	19.51	Calibrated

cannot be inverted symbolically in Matlab, the Meiselman demand function in this figure is calculated by holding the quantity of E10 constant at its 2015 level and varying the quantity of E85 to determine the corresponding price. The underlying demand should therefore increase even more as E85 prices decline, since we mainly capture the *intensive margin* induced by lower E85 prices, rather than the additional demand caused by E10/E85 switching.

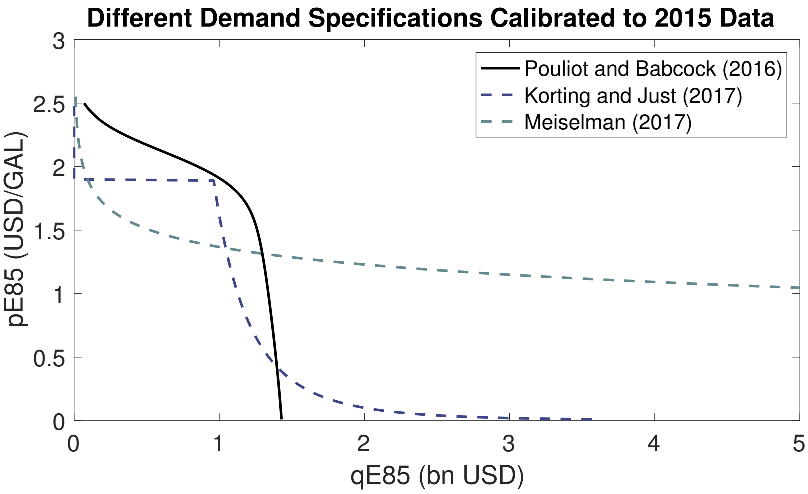

Figure 6. E85 demand under different demand specifications
Notes: All prices are shown in USD/GAL. All quantities are shown in bn GAL.

Figure 7 highlights the resulting diesel fuel consumer surplus losses under the three different demand functions. The simulation results in this section have been extended to the 16% total renewable mandate level to highlight the differential impact of E85 demand specifications at high mandate levels. Pouliot and Babcock (2016) and Korting and Just (2017) generate very similar welfare results. The heterogeneous demand functions in Pouliot and

Babcock (2016) effectively act like a smoothed version of the discrete switching assumed in Korting and Just (2017). Figure 8 provides the corresponding comparison of E85 price and quantity simulation results.

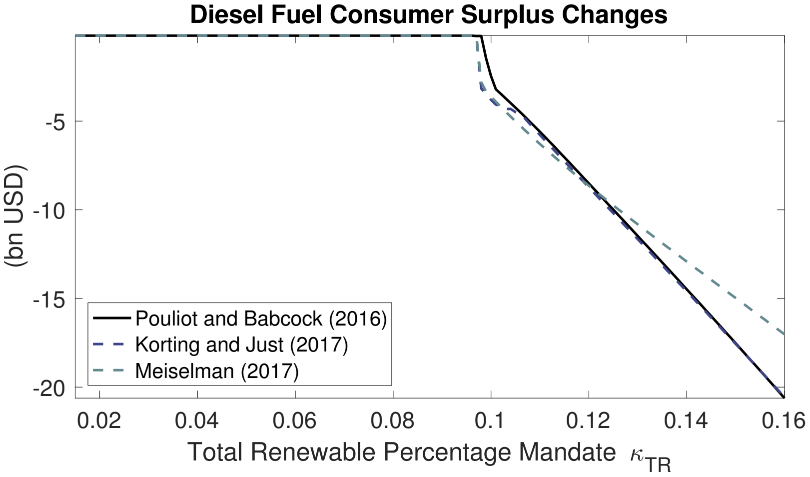

Figure 7. Diesel fuel consumer surplus changes under different demand specifications

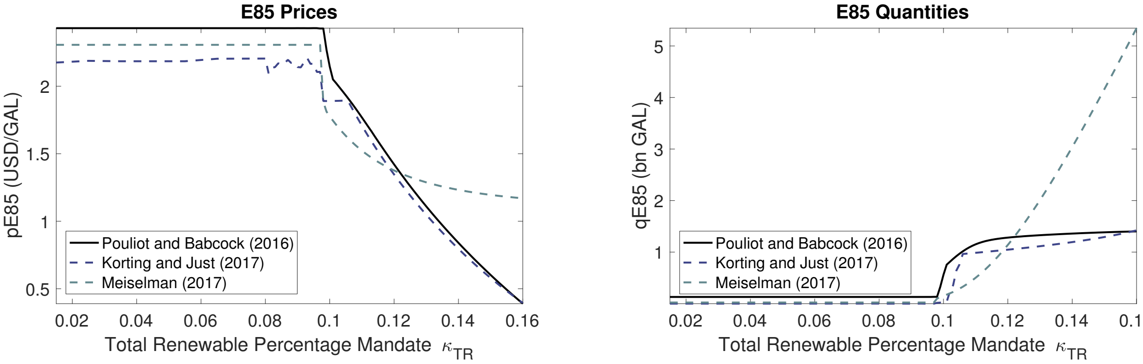

Figure 8. E85 price and quantity changes under different demand specifications
Notes: All prices are shown in USD/GAL. All quantities are shown in bn GAL.

Behavioral Equations under the Reference Model

In total, the reference 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 system of equations 11.

(11)

First Order Conditions

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

Market Clearing

$$\begin{aligned}
MC\ Motor\ Gasoline \qquad & q_{E10} - D_{E10}(p_{E10}, p_{E85}) = 0 \\
MC\ Motor\ Gasoline \qquad & q_{E85} - D_{E85}(p_{E10}, p_{E85}) = 0 \\
MC\ Diesel\ Fuel \qquad & q_{DF} - A_{D_{DF}} p_{DF}^{\varepsilon_{D_{DF}}} = 0 \\
MC\ Gasoline \qquad & q_G - (1-\theta_{E10})q_{E10} - 0.26q_{E85} = 0 \\
MC\ Ethanol \qquad & S_E(p_E) - \theta_{E10}q_{E10} - 0.74q_{E85} = 0 \\
MC\ Diesel \qquad & q_D - (1-\theta_{DF})q_{DF} = 0 \\
MC\ Biodiesel \qquad & S_{BD}(p_{BD}) - \theta_{DF}q_{DF} = 0 \\
MC\ D4\ RINs \qquad & q^B_{D4} - q^R_{D4} = 0 \\
MC\ D6\ RINs \qquad & q^B_{D6} - q^R_{D6} = 0
\end{aligned}$$

Complementary Slackness

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