

Impact of Ethanol Mandates on Fuel Prices when Ethanol and Gasoline are Imperfect Substitutes

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Abstract

Past studies that examine the impact of ethanol mandates on fuel prices make the assumption that ethanol and gasoline are perfect substitutes because they are both sources of energy in transportation fuels. These studies, however, have been of limited use in informing current policy debates because the short- to medium-run reality is one of strong regulatory and infrastructure rigidities that restrict how ethanol can be consumed in the United States. Our objective here is to improve understanding of how these rigidities change the findings of existing studies. We accomplish this by estimating the impacts of higher ethanol mandates using a new open-economy, partial equilibrium model of gasoline, ethanol, and blending whereby motorists buy one of two fuels: E10, which is a blend of 10 percent ethanol and 90 percent gasoline, or E85 which is a high ethanol blend. The model is calibrated to recent data to provide current estimates. We find that the effects of increasing ethanol mandates that are physically feasible to meet on the price of E10 are close to zero. This result is robust to different gasoline supply elasticities and gasoline export demand elasticities. The impact of the size of the corn harvest on E10 prices is much larger than the effects of mandates. Increased mandates can have a large effect on the price of E85 if the mandates are increased to levels that approach consumption capacity. These findings show that concern about the consumer price of fuel do not justify a reduction in feasible ethanol mandates.

Keywords: Biofuel, Ethanol, Gasoline, Mandate.

JEL codes: Q18, Q41, Q42.

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Economists seem to have a good understanding of the effects of biofuel mandates on blended fuel prices. Lapan and Moschini (2012) and de Gorter and Just (2009) show that higher ethanol mandates will lead to higher fuel prices under perfect competition when ethanol and gasoline are perfect substitutes and if gasoline supply is perfectly elastic. These assumptions characterize a market in long-run equilibrium in a small country that imports gasoline. This is a straightforward result under these assumptions because the cost of complying with increased mandates must be borne by consumers. Rajagopal and Plevin (2013) and Bento, Klotz, and Landry (2014) also study the impact of biofuel mandates on fuel prices, making similar assumptions that best hold in long-run equilibrium. They find that mandates can either increase or decrease blended fuel prices depending on what supply and demand elasticities are assumed, findings that are consistent with the Lapan and Moschini (2012) and de Gorter and Just (2009) results.

Despite these findings the debate about the impact of the Renewable Fuels Standard (RFS) on fuel prices continues. Throughout 2013, the oil industry cited NERA (2012), which predicted sharp increases in blended fuel prices if oil companies were forced to comply with biofuel mandates contained in the RFS. The Congressional Budget Office (CBO) (2014) was tasked in part with determining the impact of the RFS on fuel prices. CBO analysts did not rely on the existing economic literature because the underlying assumptions abstract too much from current market drivers and compliance issues that CBO wanted to account for. What is common to both the CBO study and the NERA study is a focus on short- and medium-run rigidities in the market for blended fuels and the impact of mandates on the price of Renewable Identification

Numbers (RINs). The important rigidities in fuel markets include an inability to blend more than 10 percent ethanol with gasoline (the so-called E10 blend wall), the lack of fueling stations that sell E85 (a gasoline-ethanol blend containing up to 83 percent ethanol), and a lack of flex vehicles that can use E85. Both Lapan and Moschini (2012) and de Gorter and Just (2009b) do not need to address any impact of these market rigidities because they assume that ethanol and gasoline are perfect substitutes. Under this assumption it makes no difference whether RIN prices are included in the price of ethanol or whether they are modeled as a tax on gasoline production because consumers ultimately pay the tax so there was no need to model RIN prices explicitly.

The issue of biofuel mandates effects on fuel prices has taken on heightened importance because of heated debates about whether the Environmental Protection Agency (EPA) should allow ethanol mandates to continue to grow. Many in the oil industry have used the specter of higher pump prices to argue against increased mandates. For example, Tom O'Malley, chairman of PBF Energy, is quoted in a Reuters article as saying that the price of RINs is a hidden tax on consumers because his company will have to pass the rising costs of RINs on to consumers.¹ Mr. O'Malley is also quoted in a Platts article: "This price increase will be passed along to consumers, raising the pump price [...]."² According to other press reports, the concern about high RIN prices was also expressed by White House officials who weighed in on the review of EPA's proposed reductions in mandate levels for 2014. Amanda Peterka reported on January 6, 2014 that Office of Management and Budget reviewers wrote, "If volumes are too low, no harm no foul. If volumes are too high, then the prices of RINs will be high and we will face a real

¹Article available at <http://www.reuters.com/article/2013/05/02/pbf-earnings-rins-idUSL2N0DJ23820130502>.

² Platts. April 20, 2013. "RINs are a disaster for US consumers: PBF Energy chairman." Article available at <http://www.platts.com/latest-news/oil/newyork/rins-are-a-disaster-for-us-consumers-pbf-energy-21944290>.

problem.”³ Peterka’s article did not detail exactly what problems high RIN prices were supposed to lead to, but lower profits for oil companies or higher pump prices for consumers seem likely.

Our objective here is to reduce the level of abstraction in existing models of blended fuel markets to enhance understanding of how short- and medium-term market realities impact how biofuel mandates will affect blended fuel prices. Anderson (2009) finds consumer attitudes towards E85 in Minnesota that are inconsistent with the assumption of ethanol and gasoline being perfect substitutes. Salvo and Huse (2013) demonstrate that, even in Brazil, ethanol and gasoline are not perfect substitutes because of heterogeneity of consumer attitudes towards ethanol. Pouliot and Babcock (2014) demonstrate how a lack of fueling stations in the United States limits the degree of substitution even further. In addition, important restrictions exist on the ability to blend ethanol and gasoline. Almost all gasoline in the United States is E10. The gasoline that is used as a blendstock in E10 has been formulated to take advantage of ethanol’s high octane content. Thus, ethanol is primarily used in fixed proportions with gasoline. Most consumers would continue to consume E10 even if ethanol mandates were set at levels that could not be achieved through E10 consumption alone. At least initially, fuel would not be sold as E11 or E12 to meet higher mandate levels because most automotive emission systems were designed to run on E10 and there are few fuel retailers who sell blends with more than 10 percent ethanol. It was not until 2012 and 2013 model years that some automobile manufacturers released cars that are warrantied to run on blends that contain up to 15 percent ethanol. Thus, at least in the medium-term, it is likely that if ethanol mandates exceed the level that can be met through E10

³ Peterka, A. Jan. 6, 2014. “White House urged EPA restraint on 2014 RFS targets.” Available at <http://www.eenews.net/stories/1059992426>.

consumption then compliance would be achieved through increased consumption of E85 in flex fuel vehicles (CBO 2014).⁴

The model we employ to better understand the impact of ethanol mandates is an open-economy, partial equilibrium model of the markets for ethanol, gasoline, and blending. Trade in gasoline is included to enable evaluation of the prediction by NERA (2012) that higher ethanol mandates will cause US gasoline producers to increase exports as a compliance strategy rather than supply the domestic market with gasoline. The model contains three features that enable it to be used for medium-run policy analysis. First, it includes separate fuel demand functions for a low-ethanol blended fuel (E10) and a high-ethanol blended fuel (E85). The two fuels are imperfect substitutes because of a lack of fueling infrastructure for E85 and consumer heterogeneity. The equilibrium effects of increased mandates that can only be met with increased consumption of E85 are estimated, as in CBO (2014). Second, ethanol and gasoline are demanded in fixed proportions in E10 because of medium-run costs of obtaining gasoline that does not require ethanol to raise its octane value. Third, the incidence of high RIN prices is modeled explicitly by modeling zero-profit blenders who buy gasoline from oil refineries and ethanol and RINs from biofuel plants. Blenders sell their RINs to domestic refineries who have endogenous RIN obligations that depend on the quantity of gasoline consumed domestically. Thus, our model is able to analyze the claims of some in the oil industry that compliance with ethanol mandates that cannot be met through E10 consumption will lead to sharply higher gasoline exports and higher domestic fuel prices.

We find that compliance with ethanol mandates that are feasible to meet with current infrastructure would have small, if any, effects on the retail price of E10. Because increased E85

⁴ See Qiu, Colson, and Wetzstein (2014) for an analysis of the effects of widespread adoption of E15 on the demand for E85 and gasoline.

consumption would be the primary compliance mechanism, the retail price of E85 would depend on the level of mandate, sharply declining as mandate levels approach their maximum feasible limits.

The Model

The overall purpose of our model is to estimate the price impacts of compliance with increased ethanol mandates implemented under the RFS. Details about the RFS can be found in Schnepf and Yacobucci (2013). Because compliance involves three parts of the fuel supply chain, our model includes producers of gasoline and ethanol, fuel blenders who buy wholesale gasoline and ethanol to produce fuels to be sold at retail outlets, and final fuel consumers. Figure 1 illustrates the structure of the model. Upstream firms are refineries producing gasoline and ethanol plants producing ethanol from corn. Blenders are middlemen that purchase gasoline and ethanol to produce two gasoline blends, E10 and E85. Motorists buy E10 and E85, and owners of flex vehicles can choose either fuel so they are substitutes in demand. The market for RINs runs parallel to the markets for fuel. RINs are attached to each gallon of ethanol produced. When ethanol is blended with gasoline, RINs are detached from ethanol by blenders and can then be sold in the RIN market. Refineries create a Renewable Volume Obligation (RVO) when they produce gasoline that is consumed domestically. Each refinery's RVO is proportionate to the amount of gasoline they produce. Compliance with an RVO is demonstrated by submitting RINs to EPA.

It is possible to derive analytical results if simple-enough functional forms are adopted. However, the solutions are cumbersome and are difficult to interpret, so they give limited insight into the problem. Instead, we specify functional forms, calibrate the model to recent data, and

solve the model numerically to show the impacts of RFS compliance on fuel prices under alternative values of key parameters.

Refineries

Refineries process crude oil into gasoline. As obligated parties, refineries show compliance by submitting to EPA RINs equal to their RVO. The RVO equals the product of the percentage standard κ and the quantity of gasoline that each refinery produces that is sold domestically:

$x_g^d \geq 0$. Given a RIN price ρ , the compliance cost of a refinery is $\rho\kappa x_g^d$ and marginal

compliance cost is $\rho\kappa$ assuming that a refinery's sales are too small to affect the price of RINs.

Because the United States has become a net exporter of gasoline we denote a refinery's export quantity as $x_g^w \geq 0$. Exports do not affect a refinery's RVO so the profit of a competitive refinery

is

$$\pi_r = w_g^d x_g^d + w_g^w x_g^w - \rho\kappa x_g^d - c_r [x_g^d + x_g^w],$$

where w_g^d is the domestic price of gasoline at wholesale, w_g^w is the world price of gasoline and

$c_r [x_g^d + x_g^w]$ is the cost of producing a quantity $x_g^d + x_g^w$ of gasoline.

The first order conditions for profit maximization are

$$\frac{\partial \pi_r}{\partial x_g^d} = w_g^d - \rho\kappa - c'_r = 0;$$

$$\frac{\partial \pi_r}{\partial x_g^w} = w_g^w - c'_r = 0.$$

When these conditions hold with equality, the domestic wholesale gasoline price commands a premium over the world price to cover the cost of RINs to refineries such that

$$(1) \quad w_g^d = w_g^w + \rho\kappa.$$

That is, because refineries are free to export gasoline, the marginal return on domestic gasoline must at least equal the marginal return on gasoline exported. The size of the price difference equals marginal compliance cost. Inverting the marginal cost function, the supply curve of refineries is a function of the world gasoline price: $x_g^d + x_g^w = c_r^{t-1} [w_g^w]$. For model calibration purposes we assume US gasoline supply has constant elasticity:

$$(2) \quad x_g^d + x_g^w = \alpha (w_g^w)^\varepsilon,$$

where $\varepsilon \geq 0$ is the supply elasticity and α is a calibrating parameter.

The United States has been a net exporter of gasoline since 2009. Trade volumes are small compared to the size of the US domestic market, with net exports representing about three percent of US gasoline consumption in 2013. Trade occurs throughout the year and import and export prices for gasoline are nearly identical. We write the export demand for US gasoline as

$$(3) \quad x_g^w = \beta (w_g^w)^\eta.$$

where $\eta \leq 0$ is the elasticity of export demand for US gasoline and β is a calibrating parameter.

We perform sensitivity analysis on the value of η , allowing the export demand to vary from perfectly elastic, in which the United States is a small exporting country, to scenarios where the United States is a large exporting country facing a downward-sloping export demand curve.

Ethanol Plants

Almost all ethanol in the United States is produced from corn. As ethanol production relies on fermentation of sugar in corn, the technology allows for little input substitution. Other than corn, inputs in the production of ethanol include natural gas, labor, enzymes and denaturant. Corn is by far the largest cost of ethanol plants and thus production decisions largely depend on the price of corn. One bushel of corn yields about 2.8 gallons of ethanol.

Ethanol plants produce a quantity of ethanol x_e that they sell wholesale to blenders at price w_e^p . This price is the sum of the two components: the value that blenders place on ethanol in the fuel market, w_e^b , and the price of the RIN that is attached to the ethanol

$$(4) \quad w_e^p = w_e^b + \rho .$$

We describe later what determines the fuel value of ethanol to blenders. Profit to an ethanol plant is

$$\pi_e = w_e^p x_e - c_e [x_e] ,$$

where $c_e [x_e]$ is the cost of producing a quantity x_e of ethanol. For simplicity, we assume that this cost function is net of revenues generated through byproduct sales. The cost of producing ethanol increases with respect to quantity because increased ethanol production increases the price of corn and because of cost heterogeneity between ethanol plants.

The first order condition for profit maximization is

$$(5) \quad \frac{\partial \pi_e}{\partial x_e} = w_e^p - c_e' = 0 .$$

That is, in equilibrium, the sum of the value of ethanol as a fuel and the price of RINs equals the marginal cost of producing ethanol.

Equation (5) shows that at equilibrium, the price of ethanol equals the marginal cost of ethanol, thus defining the inverse supply curve. Taking the horizontal sum of ethanol plants' marginal cost curve yields the aggregate inverse supply curve of ethanol. We derive a quadratic supply curve of ethanol following the methodology described in Babcock (2013). We calibrate the supply of ethanol to the May 2014 USDA World Agriculture Supply and Demand Estimates report (USDA Office of the Chief Economist 2014). In the base case, the US average corn yield is set at 161 bushels per acre. The inverse supply curve of ethanol is

$$(6) \quad w_e^p = 1.2064 + 0.0475x_e + 0.0019x_e^2.$$

We investigate the impact of lower and higher corn yields on this supply curve. If corn yield falls to 130 bushels per acre, the inverse supply curve of corn becomes

$w_e^p = 1.6271 + 0.0534x_e + 0.0040x_e^2$. If corn yield increases to 170 bushels per acre because of favorable growing conditions then the inverse supply curve of ethanol becomes

$$w_e^p = 1.0881 + 0.0340x_e + 0.0018x_e^2.$$

Blenders

Almost all gasoline sold in the United States is E10, a blend that contains no more than 10 percent ethanol. Other gasoline blends containing a larger share of ethanol are also distributed in a relatively small number of fuel stations. Among alternative gasoline blends, E85 which contains between 51 and 83 percent ethanol, offers the greatest potential to move the most ethanol per volume of motor fuel sold at retail. The share of ethanol in E85 varies across regions and throughout the calendar year, with E85 containing less ethanol to facilitate cold start when temperatures are low. E85 contains on average about 75 percent ethanol.

Our model assumes that E10 and E85 are available at retail. Competitive blenders purchase wholesale gasoline and ethanol to produce retail gasoline blends. The production of E10 and E85 use fixed proportion technologies. Ethanol has an octane level of 113. Thus, an 87 octane E10 blend is created when it is blended with 84 octane refinery gasoline. It is technically possible for refineries to produce gasoline with higher octane without ethanol but ethanol appears to be the low cost way of formulating an 87 octane final fuel as long as ethanol is priced not more than 10 percent greater than gasoline (United States Department of Energy 2012). Our model assumes that E10 contains exactly 10 percent ethanol.

Octane level is not an issue for E85 because of the large share of ethanol. The model assumes that E85 contains 75 percent ethanol because with a binding mandate, E85 would be used to move as much ethanol as possible. As such it is reasonable to assume that E85 contains 75 percent ethanol, the apparent feasible maximum.

We assume a competitive blending industry earning zero profit. In addition, we assume no cross-subsidization between E10 and E85 such that zero profit conditions hold for both fuels. The formulations of the fuel blends and the zero profit conditions imply

$$(7) \quad p^{10} = 0.9w_g^d + 0.1w_e^b,$$

$$(8) \quad p^{85} = 0.25w_g^d + 0.75w_e^b,$$

where p^{10} is the wholesale price of E10 and p^{85} is the wholesale price of E85. The quantity of each blend equals the quantity of ethanol and gasoline contained in the blends:

$$(9) \quad q^{10} = q_g^{10} + q_e^{10},$$

$$(10) \quad q^{85} = q_g^{85} + q_e^{85}.$$

The formulations of the fuel blends imply that $q_g^{10} = 9q_e^{10}$ and $3q_g^{85} = q_e^{85}$. At equilibrium, the quantity of gasoline purchased by blenders, $q_g^{10} + q_g^{85}$, equals the quantity of gasoline sold domestically by refineries, x_g^d , and the quantity of ethanol purchased by blenders $q_e^{10} + q_e^{85}$ equals the quantity of ethanol produced x_e . We assume no trade in ethanol.

As Figure 1 shows, one role of blenders is to detach RINs from ethanol and transfer them to refineries that use them to show compliance with their RVOs. In keeping with our assumption of competitive markets we assume that blenders detach RINs from ethanol and sell them to refineries at zero cost earning zero profit. The RIN market clears from the difference in the value of ethanol in blended fuels (7) and (8) and the cost of producing ethanol in (4) and (5). The mandate specifies that

$$(11) \quad q_e^{10} + q_e^{85} \geq \kappa (q_g^{10} + q_g^{85}).$$

If equation (11) holds with equality, then the mandate is binding and the price of RINs is greater than zero. Otherwise, the mandate does not bind and the price of RINs is zero.

Consumer Demand for Fuel

Most light vehicles in the United States are certified to run on gasoline blends that contain no more than 10 percent ethanol. However, a growing number of vehicles are flex fuel vehicles (FFV) that can run on gasoline blends that contain more than 10 percent ethanol. According to EIA (2014), there were approximately 218 million light-duty vehicles running on gasoline in the United States. Pouliot and Babcock's (2014) data show that there were about 14.6 million FFVs in the United States in early 2013. Our model takes into account the degree of substitution that

can occur between E10 and E85 given this number of FFVs. In addition, our model accounts for the limited number of stations that actually sell E85.

Motorists driving conventional vehicles can only consume E10, which is widely distributed and can be found at a virtually zero search cost. The demand for E10 by conventional motorists is a decreasing function of the retail price of E10:

$$(12) \quad q^{c10} = N^c \beta^c (\tilde{p}^{10})^\phi,$$

where $\tilde{p}^{10} = p^{10} + m$ is the price of E10 at the pump accounting for a constant wholesale to retail price markup m . The parameter $\phi \leq 0$ is the elasticity of demand, β^c is a demand parameter that we calibrate based on observed values of q^{c10} and \tilde{p}^{10} for an individual motorist, and N^c is the number of conventional vehicles.

The demand for fuel by owners of FFVs is not as straightforward. FFV owners can fuel with either E10 or E85. When modeling the demand for E10 and E85 by FFV motorists, it is paramount to correct prices and volumes for the relative energy contents of these fuels. Ethanol contains about two-thirds the energy per volume of gasoline. As such, gasoline blends with a larger share of ethanol yield lower fuel economy. For example, for E85 that contains 75 percent ethanol and 25 percent gasoline and for E10 that contains 10 percent ethanol and 90 percent gasoline, E85 contains 77.6 percent of the energy of E10 (i.e. $0.776 = (0.75 * 2/3 + 0.25 * 1) / (0.1 * 2/3 + 0.9 * 1)$).

We do not derive the demand for E10 and E85 by flex motorists here. Instead, we borrow the demand estimates from Pouliot and Babcock (2014). Their estimates build from the choice model in Anderson (2012) and from similar models used to explain Brazil's motor fuel demand in Salvo and Huse (2013), Du and Carriquiry (2013), and Pouliot (2013). We describe briefly below how Pouliot and Babcock (2014) derive the demand for E85.

Pouliot and Babcock (2014) consider that motorists internalize the cost of driving extra distance to find an E85 pump. We write that the total costs of fueling with fuel $j = \{10, 85\}$ is \hat{p}^j . That cost accounts for difference in fuel efficiency relative to E10 and for the convenience cost of selecting a specific fuel. The convenience cost of E10 is zero because it is widely distributed and available wherever E85 is available such that $\hat{p}^{10} = \tilde{p}^{10}$. E85 is sparsely distributed such that many motorists who want to buy E85 must drive out of their way to find an E85 pump. The total cost of E85 is $\hat{p}^{85} = \alpha \tilde{p}^{85} + c(d)$ where $\alpha = 1/0.776$ transforms E85 into an energy equivalent price of E10 and $c(d)$ is the convenience cost of driving a distance d to find an E85 pump. Pouliot and Babcock (2014) calculate the distance d from the zip code location of all US FFVs to the nearest location of the nearly 2,500 fuel stations that offer E85 in the United States.

Using a choice model similar to Anderson (2012), Pouliot and Babcock (2014) estimate the demand by owners of FFVs in all continental US zip codes based on the price of E85 and the difference between the price of E85 and the price of E10. The expression for the aggregated US demand for E85 by FFVs from Pouliot and Babcock (2014) is

$$q^{f85} = N^f \int_0^{d_{\max}} \beta^{f85} (\hat{p}^{85})^\phi (1 - H(\hat{p}^{85} - \hat{p}^{10})) g(x) dx ,$$

where N^f is the number of FFVs, $H(\hat{p}^{85} - \hat{p}^{10})$ is the share of FFV motorists who fuel with E10 such that $1 - H(\hat{p}^{85} - \hat{p}^{10})$ is the share of FFV motorists that fuel with E85, $\beta^{f85} (\hat{p}^{85})^\phi$ is the demand for motor fuel by individual FFV motorists, $g(x)$ is the marginal distribution function of the distance between FFVs and E85 fuel stations per zip code, and d_{\max} is the maximum distance observed to an E85 pump. We assume that the elasticity of demand for fuel

of individual FFV motorists is the same as motorists driving conventional cars. The demand for E10 by FFV motorists is

$$q^{f10} = N^f \int_0^{d_{\max}} \beta^{f10} (\hat{p}^{10})^\phi H(\hat{p}^{85} - \hat{p}^{10}) g(x) dx.$$

We calibrate the value of the parameters β^{f85} and β^{f10} such that an FFV motorist would consume a volume of E85 that yields the same distance driven as E10 if the two gasoline blends are priced at parity.

The expressions above do not fully characterize the reality of the distribution of E85. In particular, fuel stations have limited capacity to dispense E85 because they have only one or two pumps installed or because of limited capacity to accommodate large traffic. Pouliot and Babcock (2014) incorporates capacity limits by retailers by assuming that each fuel station cannot dispense more than 45,000 gallons of E85 per month. The demand we use accounts for the limited E85 distribution capacities.

At equilibrium, the supply of E10 equals the demand for E10 by conventional and FFV motorists

$$(13) \quad q^{10} = q^{c10} + q^{f10},$$

and the supply of E85 equals the demand for E85 by FFV motorists

$$(14) \quad q^{85} = q^{f85}.$$

Model Calibration

We calibrate the model based on observed data for the 2013 calendar year and from parameter estimates from the literature. Table 1 shows parameter values and sources of data we use to calibrate the model. For the world price of gasoline, we use the average transaction price of US

imports and exports of gasoline in 2013. From USITC (2014) we obtain a 2013 average gasoline price of \$2.87/gal and US net exports of gasoline of 4.1 billion gallons. Data on consumption and prices of gasoline blends at retail and on the number of vehicles are from EIA (2014). We use the number of flex vehicles reported by Pouliot and Babcock (2014) because they have the most detailed data on the number and location of flex vehicles.⁵ Lin and Prince (2013) offer a concise review of the literature and report that several meta-analyses find short-run demand elasticity for gasoline at around -0.25. Note that given the ethanol supply curve in (6) we do not need values for the ethanol and RIN prices to calibrate the model.

Our base case scenario assumes that the United States is a small country in the world gasoline market and that US refining capacity is fixed. These assumptions mean that the demand curve for US gasoline exports is perfectly elastic and the US supply curve is perfectly inelastic. In alternative scenarios, we explore the implications of these assumptions by letting the export demand elasticity equal -10 and -1 and by letting the US supply elasticity increase to 0.1 and 1. These wide ranges of elasticities values are meant to capture the extent to which our results are sensitive to variations in the values of these parameters. Our ranges of elasticities include values for these elasticities used in other calibrated models. For example, de Gorter and Just (2009) assume a value of 0.2 for the domestic gasoline supply and a value of 2.63 for the elasticity of import supply.⁶ Similarly, Cui et al. (2011) calibrate their model also using a value of 0.2 for the domestic gasoline supply and use a foreign oil elasticity of 3.⁷

⁵ EIA (2014) reports a total of 13.8 million FFV in the United States in 2013, 800,000 less than Pouliot and Babcock (2014).

⁶ The model in de Gorter and Just (2009) was developed at a time when the United States was an importer of gasoline.

⁷ Cui et al. (2011) assume a fixed coefficient technology for the production of gasoline from oil such that there is a direct correspondence between the elasticity of gasoline supply and the elasticity of oil supply.

Table 2 details intermediate steps and final parameter calculation for our calibrated model. For parameters of US gasoline supply and export demand we do not report specific values because we will conduct sensitivity analysis for the values of gasoline supply elasticity and the export demand elasticity.

Calibration of the demands for E10 and E85 is based on average consumption per vehicle. Conventional vehicles comprise cars and light duty vehicles, commercial light trucks and freight trucks while flex vehicles are cars and light duty vehicles. This means that flex vehicles are on average smaller than conventional vehicles and as such we expect the average consumption by flex vehicles to be less than conventional vehicles. We calculate the average consumption by flex vehicles by dividing the total consumption of E10 by light-duty vehicles by the number of cars and light trucks. This calculation ignores consumption of E85, but historical volumes of E85 are small enough compared to volumes of E10 that they have a negligible impact on our calculation. We calculate the average consumption by conventional vehicles by dividing the total consumption of E10 of all vehicles net of the consumption by flex vehicles by the number of conventional vehicles. These calculations yield an average consumption of E10 of 574 gallons for flex vehicles and 587 gallons for conventional vehicles for 2013. We use these values to calculate the parameters for the demand expressions for each vehicle category.

Figure 2 shows the wholesale demand curve for E85. The price on the vertical axis is p^{85} and is calculated assuming that the wholesale-to-retail markup m is \$0.75 per gallon. The retail price of E10 is either \$3.95, \$3.65, or \$3.25 per gallon (wholesale prices of \$3.20, \$2.90, or \$2.50 per gallon). Figure 2 shows that the demand curves for E85 are quite flat for prices of E85 between \$2 and \$3 per gallon. Those prices are near parity prices with E10 after accounting for relative energy content. Between \$2 and \$3 per gallon, a large share of FFV motorists respond to

fuel prices and thus readily switch from one fuel to the other for a small change in the price of E85. Thus, in this range the demand for E85 and ethanol is fairly elastic. Further declines in the price of E85 will cause some existing stations to hit their capacity limit making the wholesale demand for E85 much more inelastic. With about 2,500 fuel stations in the United States dispensing E85, the maximum volume of E85 that can be sold in the United States is about 1.25 billion gallons.

Table 1 reports that EIA estimated 196 million gallons of E85 were consumed in 2013 at an average price of \$3.22 per gallon. Assuming a \$0.75 per gallon wholesale-to-retail markup, this implies a wholesale price of E85 of \$2.47 per gallon. At that price, the demand curve in Figure 2 predicts consumption of E85 that is almost double EIA's estimate. The demand for E85 derived by Pouliot and Babcock (2014) assumes that the price of E85 is the same at all stations. In reality, there are large differences in the price of E85. The average price and the volumes of E85 reported by EIA might reflect heterogeneous conditions across regions and time, which explains the difference. The demand estimates by Pouliot and Babcock (2014) is appropriate for our study because we are interested in ethanol mandates that are binding so that the price of E85 is set low enough at enough stations to induce adequate consumption.

Results

We consider several scenarios regarding ethanol mandates and parameter values to gain insight into the effect of mandates on fuel prices. We limit our analysis to considering mandates that are physically feasible to meet given the current fueling infrastructure. Thus, this analysis is appropriate to use to evaluate EPA's proposal to reduce ethanol mandates to levels that can easily be met using E10. In our base case, we assume that gasoline export demand is perfectly

elastic and US gasoline supply is perfectly inelastic. We then consider the impacts of shifts in the ethanol supply curve due to the size of the corn crop. The sensitivity of impacts to alternative gasoline export demand elasticities and US gasoline supply elasticity is then explored.

The model is solved by calculating the RVO using a volume of gasoline equal to $0.9q^{10} + 0.25q^{85} = 119.4$ billion gallons. Hence, if the mandate equals 14 billion gallons, the percentage obligation of refineries equals $14/119.4=11.7\%$. Compliance is met with the percentage obligation rather than with the volume mandate. Model solutions may therefore show ethanol volumes that do not equal the volume mandate and yet the mandate is binding because of the percentage obligation.

Base case results

The base case scenario of a perfectly elastic export demand curve and perfectly inelastic domestic supply curve for gasoline assumes that the volume of US exports is too small to affect world gasoline prices and that US refineries are operating at capacity. The implication of these assumptions for our result is that gasoline export volumes are given by the difference between the refining capacity and US domestic use of gasoline. The results are derived assuming a corn yield of 161 bushels per acre, which was the yield implied for the 2014 given USDA predicted yield for the 2014–15 crop year.⁸

Table 3 shows the results of the base case scenario for mandates varying between 13 billion gallons and 14.2 billion gallons. The market-clearing quantity of ethanol is 13.67 billion

⁸ Corn yield for the 2013–14 crop year was 158.8 bushels per acre, and as of June 2014 USDA predicted corn yield of 165.3 bushels per acre for the 2014–15 crop year. Corn supplies for the first eight months of the 2014 calendar year come from the 2013–14 crop, while the last four months will be covered by the 2014–15 crop year. Weighting the yields by the number of months for each of the crop years, we find an average yield of 161 bushels per acre for the 2014 calendar year.

gallons. Thus, a mandate below 13.67 billion gallons is not binding and the price of RIN is zero. At a non-binding mandate, the quantity of E10 is 133.13 billion gallons priced at a retail price of \$3.55/gal. The market-clearing volume of E85 is 480 million gallons at a retail price of \$3.12/gal. The total E10 equivalent consumption of motor gasoline is 133.5 billion gallons at an E10 equivalent price of \$3.55/gal.

Compliance with a mandate of 13.8 billion gallons is met with the blending of 13.85 billion gallons of ethanol, and a 14 billion gallon mandate is met with the blending of 14.03 billion gallons of ethanol. The effect of increasing the ethanol mandate beyond 13.67 billion gallons on the price and quantity of E10 is small. Compliance with higher mandates is accomplished with sharply higher sales of E85 volumes, which occurs because of a significant decrease in the price of E85. The total E10 equivalent consumption of motor gasoline marginally declines and the average E10 equivalent price increases by only one cent per gallon with mandates of 13.8 or 14 billion gallons. The mandate causes a small increase in gasoline exports at the constant world price. The value of ethanol to blenders significantly declines with the ethanol mandate. Thus, a binding mandate causes the price of RINs to increase to bridge the gap between the value of ethanol to blenders and the cost of producing ethanol.

Table 3 shows model outcomes for a mandate of 14.2 billion gallons. These reported outcomes are not exact solutions because all equations of the model cannot hold with equality with a 14.2 billion gallons mandate. The market does not have the capacity to accommodate ethanol volumes to comply with a 14.2 billion gallons mandate given production costs for E10 and E85 and the physical limit on the distribution of E85. Table 3 shows E10 volumes of about 132.5 billion gallons when the mandate is binding, which implies that 13.25 billion gallons of ethanol are consumed as E10. Figure 2 shows that the physical limit on E85 sales equals 1.25

billion gallons. With E85 containing 75 percent ethanol, this implies that a maximum of 940 million gallons of ethanol can be consumed in E85. In total, this places a physical limit on the blending ethanol at about 14.18 billion gallons.

Even though the model does not yield exact solutions for a 14.2 billion gallons mandate, it suggests that pushing the mandate to the limit of capacity to blend ethanol would have a small impact on the total motor gasoline volumes and on the average price of motor gasoline. The reported results also show that with an ethanol mandate at or above the capacity of the market to use ethanol drives the value of ethanol to blenders down to zero, which implies that the price received by ethanol plants is constituted solely of the price RIN.

Impact of corn yield

Weather conditions impact corn yields by setting quantities and prices in a crop year, and thus impacting the cost of producing ethanol. We explore the implications of low corn yields that provide the equivalent of 130 bushels per acre in a calendar year and the implications of a bumper crop that increases corn yields to 170 bushels per acre in a calendar year.

Table 4 shows solutions for the two alternative corn yield scenarios. We maintain the assumption that the United States is a small country in gasoline trade and that US production of gasoline is fixed. With corn yields of 130 bushel per acre, the model finds a no-mandate consumption of ethanol of 13.31 billion gallons. The smaller quantity of ethanol compared to the base case reflects the higher wholesale price of ethanol caused by higher corn prices. Higher wholesale ethanol prices result in higher prices and lower quantities for both E10 and E85.

As in the base case scenario, increasing the mandate has a small impact on the price and quantity of E10 but a significant impact on the price and quantity of E85. Refineries meet their

percentage obligation, however, with the high ethanol price the obligation is met with the blending of ethanol quantities smaller than the mandated volume. With lower corn yield, an increase in the ethanol mandate causes a sharp increase in the price of RINs. The market limit to absorb ethanol is, again, slightly below 14.2 billion gallons, and our model does not solve exactly with a 14.2 billion gallons mandate.

With corn yields of 170 bushels per acre, 13.87 billion gallons of ethanol are blended with gasoline with no mandate. The price of wholesale ethanol drops which brings down the price of E10 to \$3.52/gal and the price of E85 to \$2.89/gal. Even without a binding mandate, the quantity of E85 is 730 million gallons. As in previous scenarios, a binding mandate causes a small increase in the price of E10 but a sharp decline in the price of E85. The model does not solve for a 14.2 billion gallon mandate as corn yields do not impact the market's capacity to blend ethanol into gasoline.

Comparing the results in Tables 3 and 4 shows that a drought, such as the one in 2012–13 when corn yield fell to about 122 bushels per acre, could increase the weighted average of retail E10 and E85 fuel prices expressed in E10-equivalent energy units (henceforth referred to simply as the average fuel price) by about 10 cents per gallon compared to the base case. A bumper corn crop would lower average fuel price by about three cents per gallon. Variability in corn yields thus can have a greater impact on retail fuel prices than changes in the mandate levels of biofuel within feasible volumes.

Sensitivity analysis to elasticity choices

Table 5 shows model outcomes for alternative values for the elasticity of the export demand for gasoline and for the gasoline supply elasticity. We present four elasticity scenarios that relax the

assumption that the United States is a small-country exporter and that its refineries run at capacity. All four scenarios in Table 5 keep corn yields at 161 bushels per acre. The first two scenarios in Table 5 consider gasoline export demand elasticities of -10 and -2, respectively, and keep the assumption of a perfectly inelastic gasoline supply. The results of these scenarios are similar to the base case scenario except that the price of E10 and the average price of fuel decrease slightly with increases in the ethanol mandates. In the last two scenarios in Table 5, gasoline export elasticity is set at -10 and the gasoline supply elasticity is either 0.1 or 1. In these scenarios, results are similar to the base case scenario. Unlike the previous two cases where the average fuel price declined with respect to the mandated volumes, making gasoline supply more elastic causes the average fuel price to increase a small amount with ethanol mandates.

Change in retail fuel price

As shown in the results tables, the effect of increased ethanol mandates on the average fuel price depends on demand and supply elasticities. Scenarios in Table 5 show that a less elastic export demand creates conditions favorable for the fuel price to decline. A less-than-perfectly-elastic export demand elasticity yields a smaller increase in the quantity of gasoline that is exported in response to an increase in the ethanol mandate. This implies that more gasoline is kept in the domestic market, thereby depressing domestic gasoline prices. We can calculate the gasoline supply elasticity facing US blenders as

$$(15) \quad \varepsilon_g = \frac{x_g^d + x_g^w}{x_g^d} \varepsilon - \frac{x_g^w}{x_g^d} \eta .$$

This expression says for a less-than-perfectly-elastic export demand η , the smaller the US gasoline supply elasticity ε the more inelastic the supply of gasoline facing blenders. If the

export demand is perfectly elastic, the supply of gasoline facing blenders to the United States is perfectly elastic because they can simply bid gasoline away from the export market. The results in Tables 3 and 5 and the expression for the gasoline supply elasticity facing US blenders together say that if the supply of gasoline to the United States is sufficiently inelastic, then an increase in the ethanol mandate will cause a decline in the price of E10 and the average price of fuel.

This result is similar to de Gorter and Just (2009) and Lapan and Moschini (2012) who find for some ethanol and gasoline prices that if ethanol supply is more elastic than the gasoline supply then increasing the ethanol mandate lowers the price of retail gasoline. In our model, the conditions are different because previous studies assume that the value of ethanol being blended equals the value of gasoline. This assumption implies that the elasticity of the wholesale demand for ethanol is the same as the wholesale demand for gasoline. In contrast, in our model gasoline and ethanol are imperfect substitutes and the marginal value of ethanol may either be lower or higher than gasoline depending on the preference of the marginal motorist purchasing E85. In particular, if the volume of E85 is near distribution capacity limit, the demand for E85 is inelastic and the value of ethanol declines rapidly, making the demand for ethanol more inelastic than the demand for gasoline.

The condition for the retail gasoline price to decline depends on the elasticities of supply and demand for both gasoline and ethanol. We derive that condition (see the Appendix) using a model that is consistent with the model of de Gorter and Just (2009). We show that the more inelastic is the demand for ethanol, the more likely it is for an increase in the mandate to cause the retail price of fuel to increase. In parallel, an elastic demand for ethanol facilitates the

condition for an increase in mandated ethanol volumes to cause a decline in the price of retail gasoline.

Intuitively, we can break down the impact of mandated ethanol volumes on the price of blended fuel into four parts. First, the more elastic the ethanol supply, the smaller the impact of an increase in the ethanol mandate on the price of RINs. Second, the more elastic the demand for ethanol the less RIN prices increase for a given increase in the mandate. That is, the elasticities of demand and supply for ethanol determine the size of the increase in RIN prices from an increase in mandated ethanol volumes. Third, a more inelastic supply of gasoline implies that refineries absorb a larger share of the cost of RINs. Fourth, the more inelastic the demand for gasoline, the larger the share of the cost of RINs paid by motorists. The third and fourth points say that it is the relative magnitudes of the elasticities of demand and supply for gasoline that determine the relative burden to motorists and refineries of the cost of RINs.

De Gorter and Just (2009) derive the condition that determines when an increase in ethanol mandates results in an increase in the fuel price when gasoline and ethanol are perfect substitutes. Their condition does not depend on the elasticities of demand for gasoline and ethanol because they are equal by assumption. We derive an analogous condition when this assumption does not hold (see the Appendix). In our model, substitution between E10 and E85 by FFV motorists makes the total demand for retail fuel more elastic than the demand for an individual fuel when volumes for E85 are sufficiently low. However, as Figure 2 shows, capacity constraints eventually make the demand for E85 by fuel stations more inelastic than the demand for E10. As E85 contains relatively more ethanol per volume than E10, the implication is that the inelastic demand for E85 makes the demand for ethanol at wholesale more inelastic than the demand for gasoline. Everything else being equal, constraints on the distribution of E85 makes it

more likely that an increase in mandates will increase retail fuel prices. Relaxing these constraints would make the demand for ethanol more elastic, which makes it more likely that increases in mandates will reduce retail fuel prices.

To demonstrate the relevance of accounting for a lack of perfect substitution between ethanol and gasoline, we compare how fuel prices would be affected by a 13.8 billion gallon ethanol mandate in our model to how they would be affected under the assumption of perfect substitution for each of the combinations of elasticities used in this study. The results are given in Table 6. As shown, when the export demand elasticity for gasoline is -10 and the domestic supply elasticity is 0.1, our model predicts that the average fuel price will increase, whereas it would decrease under the assumption that ethanol and gasoline are perfect substitutes. This difference is caused by a more inelastic demand for ethanol when quantities of E85 approach their consumption limit. Thus, the calibration of a simple model that does not account for the specificity of the demand for E10 and E85 would then over-predict a decline in the average fuel price from an increase in the mandate. Pouliot and Babcock (2014) show that the installation of new E85 pumps would shift out the demand for E85. By pushing the maximum volume of E85 that can be distributed in the United States, the demand for E85 would become more elastic. As such, the installation of new E85 pumps would create conditions more favorable for increased mandates to lower consumer fuel prices.

Welfare

It is straightforward to determine who benefits and who loses from an increase in ethanol mandates by simply observing the direction of price and quantity changes. If the average price of fuel increases due to a mandate, then consumers' surplus declines. The surplus of ethanol plants

and corn farmers always increases. Oil companies' surplus declines because they bear the cost of compliance. Nevertheless, for policy analysis it is useful to measure the size of welfare changes. Measurement and the interpretation of welfare in a general equilibrium model of a supply chain differ from that of a partial equilibrium model (Just and Hueth 1979). Given the nature of our model, we do not claim that we calculate exact measures of welfare but the measures we present below provide a reasonable approximation.

Simple diagrams can give insight into our welfare calculations. We perform our analysis by focusing on the wholesale gasoline and ethanol markets. Figure 3a shows the wholesale market for gasoline assuming the United States is a small exporting country. Without an ethanol mandate, the market clearing domestic price, P_d equals the world P_w and domestic refineries produce Q_s , exporting $Q_s - Q_w$. With an ethanol mandate that results in a RIN price of ρ and an RVO of κ , the domestic price of gasoline increases to $P_w + \kappa\rho$ and domestic gasoline consumption declines to Q'_d . Domestic consumer surplus that accrues to motorists from gasoline consumption declines by the area under the domestic demand curve between the higher domestic price and the world price. The loss in consumer surplus from higher wholesale gasoline prices equals the rectangle $Q'_d\kappa\rho$ plus triangle abc . Producer surplus to refineries is unchanged.

Figure 3b shows the ethanol market assuming no trade in ethanol. With a binding mandate, M , which is approximately equal to $Q'_d\kappa$, the supply price increases from P^* to P_s and the demand price decreases to P_d . The resulting RIN price is ρ . Ethanol producers gain the area P_sdeP^* . Ethanol consumers (motorists) gain the area P^*efP_d .

The net change in consumer surplus is the sum of consumer surplus in the gasoline market and in the ethanol market. Note that the sum of producer and consumer surplus in the

ethanol market equals $Q'_d \kappa \rho$ minus triangle def . If the supply of ethanol is perfectly elastic then there is a net loss in motorist surplus equals the sum of the triangles abc and def . Additional losses accrue to motorists as the supply of ethanol becomes less elastic.

Table 7 shows changes in welfare for mandates of 13.8 and 14 billion gallons with respect to the case with no binding mandate for two scenarios on the export demand elasticity. All columns show changes in surplus except for the column for RIN which shows the total value of RINs. The total value of RINs, through changes in domestic and world prices for gasoline, is paid by motorists and refineries. Given that the increase in the mandate induces only a small change in gasoline volumes, changes in consumer surplus and producer surplus in the gasoline market are nearly rectangular. As such, the total change in surplus in the gasoline market is almost equal to the total value of RINs.

In the scenario with a perfectly elastic export demand and a perfectly inelastic supply of gasoline, refineries are not impacted by increased ethanol volumes as they receive the same price and sell the same volume regardless of the biofuel mandate. Motorists gain on the ethanol market but lose a bit more on the gasoline market. The net welfare loss to motorists is \$260 million with a 13.8 billion gallon mandate and \$620 million dollars with a 14 billion gallon mandate. As expected, ethanol plants gain with their surplus increasing by \$235 million and \$488 million dollars with mandates of 13.8 and 14 billion gallons, respectively. The total change in welfare is small at \$28 million with a 13.8 billion gallons mandate and \$145 million with a 14 billion gallon mandate.

In the scenario with an export demand elasticity of -10 and a perfectly inelastic domestic gasoline supply, welfare changes in the ethanol market are similar to those in the previous scenario. Observe that the value of RIN and the total change in welfare are also similar to that in

the previous scenario. In the gasoline market however, with the export demand for gasoline being less than perfectly elastic the world price of gasoline is impacted by the increase in mandated ethanol volumes. As a result, refineries pay a share of the cost of RINs. With a 13.8 billion gallon mandate, the surplus of refineries declines by \$781 million. With a 14 billion gallons mandate the surplus of refineries declines by \$1.658 billion. In this scenario, with refineries paying for a share of the cost of RINs, the retail price of gasoline at retail declines and the surplus of motorists increases.

Policy Implications

Our analysis demonstrates that the impact of US ethanol mandates on the price of E10 will be small because the impact of higher RIN prices on the price of gasoline is largely offset by a lower ethanol price (net of the value of RINs) that results from the lower E85 prices that are needed to increase E85 consumption. Our prediction of lower E85 prices is consistent with CBO (2014) which predicts that E85 prices in 2017 will be up to 51 percent lower because of higher mandates. However, our finding that the price of E10 will not be much affected by expanded ethanol mandates conflicts with CBO's prediction that E10 prices will increase by between four and nine percent if mandates are allowed to increase. One reason for this difference is that CBO's (2014) analysis assumes that all biofuel mandates are increased as scheduled in the Energy Independence and Security Act. This would require that 24 billion ethanol-equivalent gallons of biofuels would need to be consumed—a level that far exceeds the existing capacity to consume, produce, or import biofuels in the United States. Thus, CBO's (2014) analysis was necessarily based on assumptions about what RIN prices would be, what mix of biofuels would be used to meet mandates, and the degree to which lower net values of biofuels due to high RIN

prices offset higher costs caused by compliance. CBO (2014) did not use an equilibrium model of supply and demand of fuels to derive their estimates.

Extending our model to consider much higher ethanol mandates than considered here would be straightforward as long as increased mandates are made feasible by expanded E85 fueling infrastructure that increases the demand for E85, as in Pouliot and Babcock (2014). Such an analysis would not change our overall conclusion that the effects of ethanol mandates on the price of E10 would be small and that the price of E85 would be set at a low enough level to induce adequate ethanol consumption.

Appendix

In this appendix, we modify the model in de Gorter and Just (2009) to show how the mandate the impact retail gasoline price when including a second retail fuel category. We could derive this result from our model the simple modification of the model in de Gorter and Just (2009) yield more manageable solutions.

Let us begin by showing the model in de Gorter and Just (2009) and their result on the impact of expanding the mandate on retail gasoline price. The model assumes perfect competition, does not consider the RIN market explicitly, assumes domestic supply of ethanol and assumes no distinction between domestic and imported gasoline. Relative energy contents of gasoline and ethanol are not accounted for in the model, but it can be assumed that ethanol price and volume are measured in terms of gasoline equivalent. In de Gorter and Just (2009), the equations include variables for taxes and tax credit which we ignore here because ethanol is now taxed at the same rate as gasoline. With slight modifications to the notation, equations (7), (8) and (9) in de Gorter and Just (2009) are

$$(A.1) \quad p_f = \lambda w_e^p + (1 - \lambda) w_g^w ;$$

$$(A.2) \quad D_f(p_f) = S_g(w_g^w) + S_e(w_e^p) ;$$

$$(A.3) \quad \lambda D_f(p_f) = S_e(w_e^p),$$

where p_f is the price of fuel made of gasoline and ethanol, $D_f(p_f)$ is the demand for fuel, $S_g(w_g^d)$ is the supply of gasoline, $S_e(w_e^p)$ is the supply of ethanol, w_g^w is the world price of wholesale gasoline and w_e^p is the price of wholesale ethanol paid to ethanol plants. In appearance, equation (A.1) does not account for the price of RIN as it is calculated using the world price of gasoline and the supply price of ethanol. However, with the weighting on gasoline and ethanol prices, the value of RIN cancels out in the equation. De Gorter and Just (2009) express the percentage standard as the share of ethanol in the total quantity of fuel. This is equivalent to our method of expressing the percentage standard as the ratio of ethanol over gasoline and we can write that $\kappa = \lambda/(1 - \lambda)$. Equation (A.1) says that the price of retail gasoline is a weighted sum of the price of wholesale gasoline and wholesale ethanol. Equation (A.2) says that the total volume of fuel equals the sum of the volumes of gasoline and the volume of ethanol. Equation (A.3) says that the mandate holds with equality.

Totally differentiating (A.1)-(A.3) and writing the expressions in terms of elasticities de Gorter and Just (2009) find

$$(A.4) \quad \frac{dp_f}{d\lambda} = \frac{w_g^w \left(1 + \frac{1}{\varepsilon_g}\right) - w_e^p \left(1 + \frac{1}{\varepsilon_e}\right)}{\frac{w_e^p}{\varepsilon_e} \left[\lambda \frac{\theta}{p_f} - \frac{\varepsilon_e}{w_e^p} \right] + (1 - \lambda) \frac{\theta}{p_f} \frac{w_g^w}{\varepsilon_g}},$$

where θ is the elasticity of demand for retail gasoline, ε_e is the elasticity of supply of ethanol and ε_g is the elasticity of supply for gasoline. The denominator is always negative and we can thus focus on the numerator to find the sign of the impact of an increase in the mandate on the price of fuel. De Gorter and Just (2009) find that the price of fuel increases with a rise in the mandate if the price weighted elasticity of gasoline is relatively larger than the price weighted elasticity of ethanol (i.e., $w_g^w(1+1/\varepsilon_g) < w_e^p(1+1/\varepsilon_e)$). Otherwise, an increase in the mandate causes a decline in the price of fuel.

Our model considers E10 and E85 that contain different proportions of gasoline and ethanol. Although substitutes, limits on the ability of most vehicles to use E85 and limits on the availability of E85 cause the elasticity of demand for E10 and E85 to differ. As they contain different relative amounts of gasoline and E85, the implication is that the elasticity of demand for ethanol does not equal the elasticity of demand for gasoline. To account for this, we can re-write the equations in the model of de Gorter and Just (2009) as

$$(A.5) \quad p_f = \lambda w_e^p + (1 - \lambda) w_g^w ;$$

$$(A.6) \quad D_f(w_g^w, w_e^p) = S_g(w_g^w) + S_e(w_e^p) ;$$

$$(A.7) \quad \lambda D_f(w_g^w, w_e^p) = S_e(w_e^p).$$

That is, the demand for fuel now differentiates between the price of gasoline and on the price of ethanol. Equation (A.5) then becomes a measure of the average price of fuel although it is not that average price that impacts the demand but the individual prices for ethanol and gasoline.

Total differentiation of (A.5)-(A.7) and writing the equations in terms of elasticities yields

$$(A.8) \quad dp_f = d\lambda w_e^p + \lambda dw_e^p + d\lambda w_g^w + (1 - \lambda) dw_g^w ;$$

$$(A.9) \quad \eta_g \frac{dw_g^w}{w_g^w} + \eta_e \frac{dw_e^p}{w_e^p} = (1-\lambda)\varepsilon_g \frac{dw_g^w}{w_g^w} + \lambda\varepsilon_e \frac{dw_e^p}{w_e^p};$$

$$(A.10) \quad d\lambda + \lambda\eta_g \frac{dw_g^w}{w_g^w} + \lambda\eta_e \frac{dw_e^p}{w_e^p} = \lambda\varepsilon_e \frac{dw_e^p}{w_e^p}.$$

Solving these equations, we find that

$$(A.11) \quad \frac{dp_f}{d\lambda} = \frac{\lambda w_e^p \left(\theta_g + (1-\lambda)(\varepsilon_e \theta_g - \varepsilon_g (1 + \varepsilon_e - \theta_e)) \right) + (1-\lambda) w_g^w \left(\theta_e + \lambda(\varepsilon_g \theta_e - \varepsilon_e (1 + \varepsilon_g - \theta_g)) \right)}{\lambda(1-\lambda)(\varepsilon_g \theta_e - \varepsilon_e (\varepsilon_g - \theta_g))},$$

where θ_g is the elasticity of demand for gasoline and θ_e is the elasticity of demand for ethanol.

The denominator in (A.11) is always negative such that a rise in the mandate lowers the price of fuel if the numerator is positive.

Equation (A.11) relates to the result from de Gorter and Just (2009) in (A.4). In both equations, the condition at the numerator are elasticities weighted by ethanol and gasoline prices. On our case however, in addition to supply elasticities, the conditions include the elasticity of demand for gasoline, the elasticity of demand for ethanol and the mandated ratio of ethanol over gasoline. To check the impact of the elasticity of demand for ethanol on the condition at the numerator, with the numerator in (A.11) denoted as N , we take the partial derivative with respect to θ_e :

$$\frac{\partial N}{\partial \theta_e} = (1-\lambda) \left(w_e^p \lambda \varepsilon_g + w_g^w (1 + \lambda \varepsilon_g) \right) > 0.$$

This derivative says that the more inelastic the demand for ethanol (i.e., $\theta_e \leq 0$ tends toward zero), the more likely the numerator N takes a positive value. That is, an inelastic demand for ethanol contributes to an increase in the mandate to cause an increase in the price of fuel. In the

opposite way, an elastic demand for ethanol contributes to an increase in the mandate to cause a decline in the price of fuel.

Similarly, we can take the partial derivative of the numerator with respect to θ_g and we find that

$$\frac{\partial N}{\partial \theta_g} = \lambda w_e^p (1 + (1 - \lambda) \varepsilon_e) + (1 - \lambda) w_g^w \varepsilon_e > 0.$$

As with the elasticity of demand for ethanol, this expression says that an elastic demand for gasoline contributes to an increase in the mandate to cause a decline in the price of gasoline at retail.

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Tables

Table 1. Parameters used to calibrate the model

Parameter	Symbol	Value	Source/calculation
Wholesale Price of gasoline (2013)	w_g^w	\$2.87/gal	Calculated from USITC (2014)
Net exports of gasoline (2013)	x_g^w	4.1B gal	Calculated from USITC (2014)
Price of E10 (2013)	\tilde{p}^{10}	\$3.65/gal	EIA (2014) table 3
Price of E85 (2013)	\tilde{p}^{85}	\$3.22/gal	EIA (2014) table 3
Consumption of E85 (2013) ^a	q^{85}	196M gal	EIA (2014) table 37
Consumption of E10 (2013) ^a	q^{10}	132.6B gal	EIA (2014) table 37
Consumption of E10 by light-duty (2013) ^a	q^{10l}	126.5B gal	EIA (2014) table 37
Number of gasoline cars and light trucks (2013)	N^{clt}	220.4M	EIA (2014) table 40
Number of gasoline commercial light-truck (2013)	N^{lt}	3.88M	EIA (2014) table 46
Number of gasoline freight trucks (2013)	N^t	1.72M	EIA (2014) table 49
Number of FFVs (2013)	N^f	14.6M	Pouliot and Babcock (2014)
Number of conventional vehicles (2013)	N^c	211.4M	$N^{clt} + N^{lt} + N^t - N^f$
Elasticity of demand for retail gasoline	ϕ	-0.25	Lin and Prince (2013)

Notes: ^aEIA estimates of consumption are reported in trillion btu. We convert consumption in gallons assuming that gasoline contains 5.253 million Btu per barrel and that ethanol contains 3.539 Btu per barrel (<http://www.eia.gov/totalenergy/data/annual/pdf/sec12.pdf>).

Table 2. Calculated parameters used in the model

Parameter	Symbol	Value	Calculation
Gasoline supply intensity	α	Depends on selected value of ε	$(0.9q^{10} + 0.25q^{85} + x_g^w)/(w_g)^\varepsilon$
US gasoline export demand intensity	β	Depends on selected value of η	$x_g^w (w_g^w)^{-\eta}$
Consumption of E10 per flex vehicles	q^{f10}	574 gallons	$1000(q^{10l}/N^{ct})$
Consumption of E10 per conventional vehicles	q^{c10}	587 gallons	$1000(q^{10} - N^f q^{f10})/N^c$
E10 demand intensity by conventional vehicles	β^c	812.2	$q^{c10} (\tilde{p}^{10})^{-\phi}$
E10 demand intensity by flex vehicles	β^{f10}	793.3	$q^{f10} (\tilde{p}^{10})^{-\phi}$
E85 demand intensity by flex vehicles	β^{f85}	959.6	$(q^{f10}/0.776)(0.776 * \tilde{p}^{10})^{-\phi}$

Table 3. Model solutions for base case (161 bushels per acre corn yield, perfectly elastic export demand, and perfectly inelastic gasoline supply)

Volumes (billion gallons)							Prices (\$/gallon)					
Mandate	Ethanol	Gasoline					Wholesale			Wholesale		RIN
		Gasoline	exports	E10	E85	Total	E10	E85	Average	gasoline	ethanol	
13.0	13.67	119.94	3.55	133.13	0.48	133.50	3.55	3.12	3.55	2.87	2.20	0.00
13.2	13.67	119.94	3.55	133.13	0.48	133.50	3.55	3.12	3.55	2.87	2.20	0.00
13.4	13.67	119.94	3.55	133.13	0.48	133.50	3.55	3.12	3.55	2.87	2.20	0.00
13.6	13.67	119.94	3.55	133.13	0.48	133.50	3.55	3.12	3.55	2.87	2.20	0.00
13.8	13.85	119.80	3.69	132.90	0.74	133.48	3.56	2.91	3.56	2.87	1.91	0.31
14.0	14.03	119.65	3.84	132.66	1.02	133.45	3.56	2.57	3.56	2.87	1.43	0.81
14.2*	14.18	119.55	3.94	132.50	1.23	133.45	3.57	1.53	3.56	2.87	0.00	2.25

Note: * Not an exact solution.

Table 4. Model solutions for alternative corn yields (perfectly elastic export demand and perfectly inelastic gasoline supply)

Volumes (Billion gallons)							Prices (\$/gallon)					
Mandate	Ethanol	Gasoline					Wholesale			Wholesale		
		Gasoline	exports	E10	E85	Total	E10	E85	Average	gasoline	ethanol	RIN
Corn yield = 130 bushels per acre												
13.0	13.31	119.44	4.05	132.69	0.06	132.74	3.64	3.75	3.64	2.87	3.04	0.00
13.2	13.31	119.44	4.05	132.69	0.06	132.74	3.64	3.75	3.64	2.87	3.04	0.00
13.4	13.40	119.36	4.13	132.57	0.19	132.72	3.64	3.47	3.64	2.87	2.65	0.40
13.6	13.58	119.20	4.29	132.31	0.46	132.67	3.64	3.20	3.64	2.87	2.28	0.80
13.8	13.76	119.03	4.46	132.05	0.74	132.63	3.65	2.98	3.65	2.87	1.98	1.13
14.0	13.94	118.87	4.62	131.79	1.01	132.58	3.66	2.65	3.65	2.87	1.51	1.63
14.2*	14.09	118.75	4.74	131.60	1.23	132.56	3.67	1.56	3.66	2.87	0.00	3.16
Corn yield = 170 bushels per acre												
13.6	13.87	120.08	3.41	133.22	0.73	133.79	3.52	2.89	3.52	2.87	1.90	0.00
13.8	13.87	120.08	3.41	133.22	0.73	133.79	3.52	2.89	3.52	2.87	1.90	0.00
14.0	14.06	119.94	3.55	132.98	1.02	133.77	3.53	2.54	3.53	2.87	1.40	0.51
14.2*	14.22	119.86	3.62	132.82	1.25	133.80	3.54	1.52	3.53	2.87	0.00	1.93

Note: * Not an exact solution.

Table 5. Model solutions with less than perfectly elastic export demand (161 bushels per acre corn yield)

Volumes (Billion gallons)							Prices (\$/gallon)					
Mandate	Ethanol	Gasoline	Gasoline				E10	E85	Average	Wholesale	Wholesale	RIN
			exports	E10	E85	Total				gasoline	ethanol	
Export demand elasticity = -10 and gasoline supply elasticity is 0.00												
13.6	13.66	119.74	3.75	132.90	0.49	133.29	3.58	3.13	3.58	2.90	2.20	0.00
13.8	13.83	119.65	3.84	132.74	0.74	133.32	3.57	2.92	3.57	2.89	1.92	0.30
14.0	14.02	119.65	3.93	132.56	1.02	133.35	3.57	2.58	3.57	2.88	1.44	0.80
14.2*	14.17	119.50	4.00	132.43	1.24	133.39	3.58	1.54	3.57	2.88	0.00	2.27
Export demand elasticity = -2 and gasoline supply elasticity is 0.00												
13.6	13.65	119.53	3.96	132.67	0.51	133.07	3.60	3.13	3.60	2.92	2.20	0.00
13.8	13.81	119.50	3.99	132.57	0.74	133.15	3.59	2.94	3.59	2.91	1.94	0.28
14.0	14.01	119.46	4.03	132.45	1.02	133.24	3.58	2.59	3.58	2.90	1.45	0.79
14.2*	14.16	119.44	4.05	132.36	1.23	133.32	3.59	1.54	3.58	2.89	0.00	2.26
Export demand elasticity = -10 and gasoline supply elasticity is 0.10												
13.6	13.66	119.77	3.81	132.94	0.49	133.32	3.57	3.13	3.57	2.89	2.20	0.00
13.8	13.83	119.68	3.88	132.77	0.74	133.35	3.57	2.92	3.57	2.89	1.92	0.30
14.0	14.02	119.57	3.96	132.58	1.02	133.37	3.57	2.57	3.57	2.88	1.44	0.80
14.2*	14.16	119.53	4.00	132.47	1.22	133.41	3.58	1.54	3.57	2.88	0.00	2.22
Export demand elasticity = -10 and gasoline supply elasticity is 1.00												
13.6	13.67	119.87	3.98	133.06	0.48	133.43	3.56	3.12	3.56	2.88	2.20	0.00
13.8	13.84	119.75	4.01	133.85	0.74	133.43	3.56	2.92	3.56	2.88	1.92	0.30
14.0	14.03	119.62	4.04	132.63	1.02	133.42	3.57	2.57	3.56	2.87	1.44	0.80
14.2*	14.17	119.54	4.06	132.48	1.23	133.44	3.58	1.54	3.56	2.87	0.00	2.25

Note: * Not an exact solution.

Table 6. Elasticities of demand and supply of gasoline (13.8 billion gallon mandate and 161 bushels per acre corn yield)

	Prediction from de Gorter and Just (2009)	Change in price of retail fuel
$\eta \rightarrow -\infty$ & $\varepsilon = 0$	> 0	> 0
$\eta = -10$ & $\varepsilon = 0$	< 0	< 0
$\eta = -2$ & $\varepsilon = 0$	< 0	< 0
$\eta = -10$ & $\varepsilon = 0.1$	< 0	> 0
$\eta = -10$ & $\varepsilon = 10$	> 0	> 0

Table 7. Change in welfare compare to non-binding mandate in billion dollars (161 bushels per acre corn yield)

Mandate	Ethanol		Gasoline		(5)	(6)	(7)
	(1) Motorists	(2) Producers	(3) Motorists	(4) Refineries	Motorists (1+3)	RIN -(3+4)	Welfare (1+2+3+4)
Export demand elasticity = $-\infty$ and gasoline supply elasticity is 0.00							
13.8	4.219	0.235	-4.482	0.000	-0.261	4.482	-0.028
14.0	10.835	0.488	-11.454	0.000	-0.620	11.468	-0.145
Export demand elasticity = -10 and gasoline supply elasticity is 0.00							
13.8	4.032	0.228	-3.528	-0.781	0.504	4.285	-0.026
14.0	10.691	0.490	-9.712	-1.658	0.978	11.325	-0.144

Figures

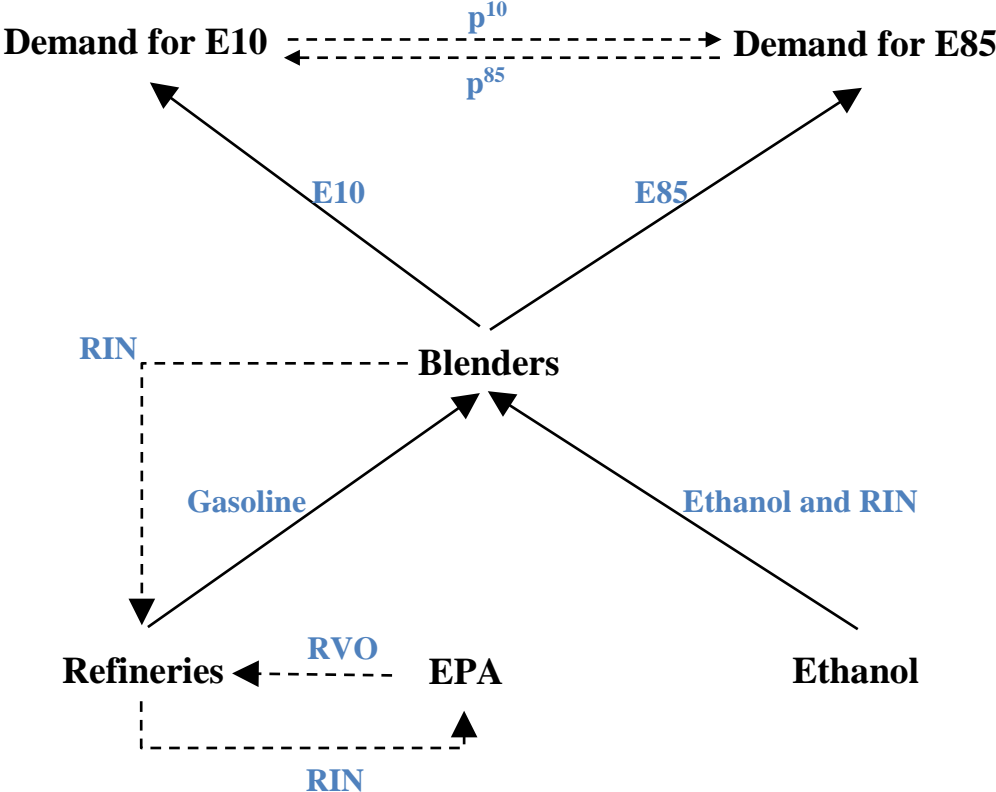


Figure 1. Model structure

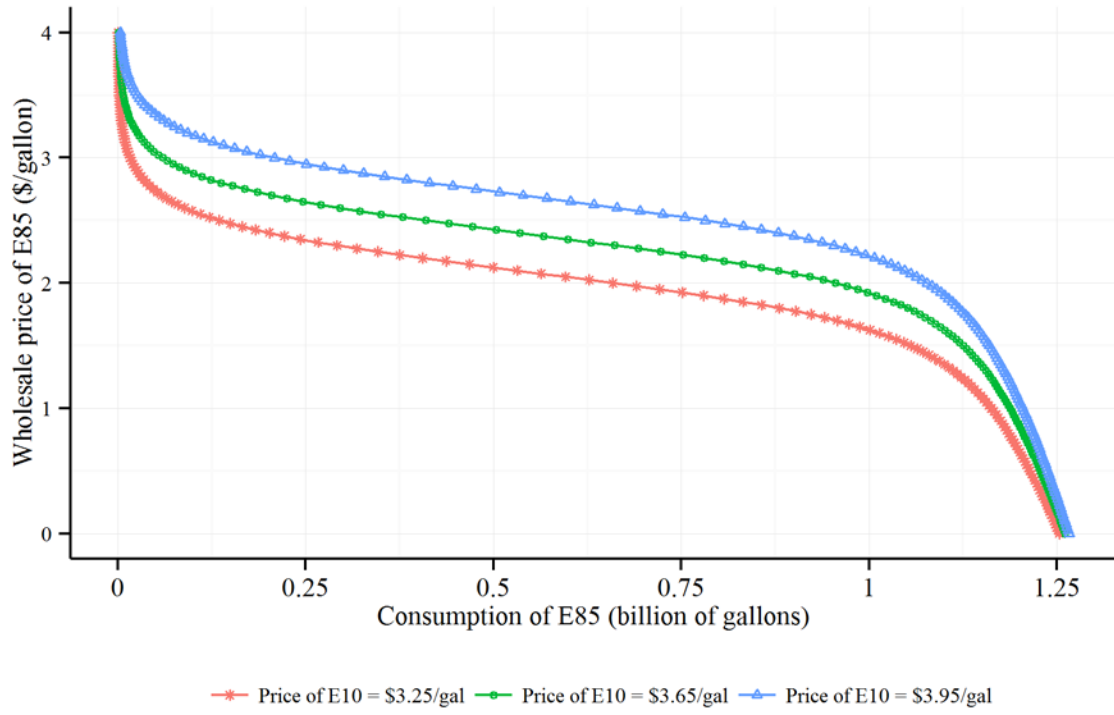


Figure 2. Wholesale demand for E85

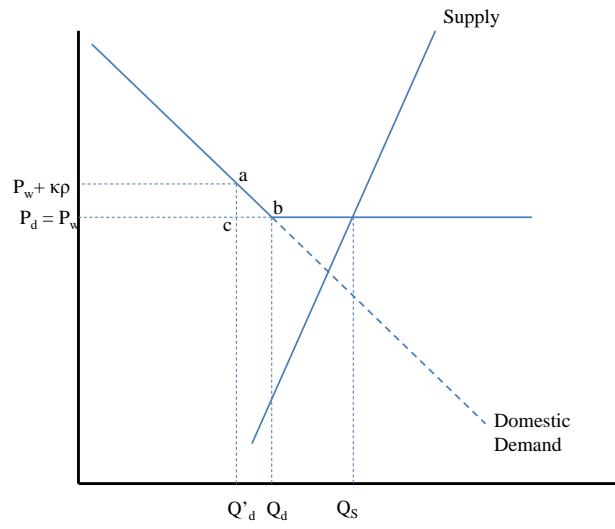


Figure 3a. Mandate impacts on gasoline

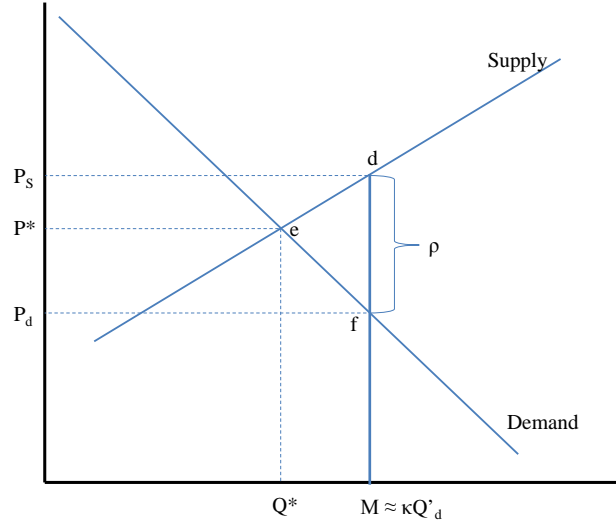


Figure 3b. Mandate impacts on ethanol