Mandating green: On the design of renewable fuel policies and cost containment mechanisms

October 2015

A Research Report from the National Center for Sustainable Transportation

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EXECUTIVE SUMMARY

The transportation sector is responsible for over a quarter of US greenhouse gas emissions, the majority of which are the result of fossil fuel combustion. Politicians and regulatory agencies at both federal and state levels have passed or considered a suite of policies aimed at decreasing emissions in the sector. Proposals include using carbon taxes, fuel economy standards for new vehicles, renewable fuel mandates, and including transportation sector emissions under regional or federal cap and trade programs.

Of these proposed policies, whenever unpriced emissions are the sole market failure, a carbon tax or cap and trade program is more likely to achieve the first-best, while fuel mandates are unable to replicate the first-best solution. However, rather than establish a carbon tax or cap and trade program to reduce emissions in the sector, policy-makers have favored renewable fuel mandates, likely due at least in part to political economy reasons. The most prominent fuel mandates in the US currently are the federal Renewable Fuel Standard (RFS), a renewable fuel share mandate; and California's Low Carbon Fuel Standard (LCFS), a carbon intensity standard. In addition, several other states have considered implementing similar policies.

The market effects of carbon intensity standards and renewable fuel share mandates have been studied by a number of authors. In addition, a growing literature compares the relative performance of fuel mandates to more traditional policy instruments such as carbon taxes; studies unintended consequences of the policies and their relative efficiency when markets are imperfectly competitive or open to trade; and examines ways policymakers can increase the efficiency fuel mandates through strategic policy choices.

In this paper, we formalize, expand upon, and synthesize the prior literature by developing a model of fuel mandates under perfect competition that incorporates both a renewable fuel share mandate and a carbon intensity standard. We summarize the effects of the policies on important market outcomes including equilibrium fuel prices and quantities. We also derive analytically and numerically the second-best optimal RFS and LCFS.

When a policy is second-best, adding a second policy lever can improve efficiency. In particular, we study the effects and potential efficiency gains from measures aimed at constraining the policies' compliance costs. We study two cost containment mechanisms that have either been implemented or proposed in practice: (1) a credit window whereby regulated parties may purchase compliance credits from a regulator for a predetermined price; and (2) a renewable fuel multiplier where the regulator allows parties to inflate their accounting of renewable fuels towards their compliance obligations.

Cost containment mechanisms have typically been studied as tools to decrease compliance cost uncertainty under market based regulations. In this paper we show that cost containment mechanisms can also be used to increase the efficiency of quantity-based mechanisms even in settings with no uncertainty.

We show that whenever the marginal cost of renewable fuels is high relative to fossil fuels, cost containment mechanisms have the benefit of both constraining compliance costs and reducing deadweight loss. In addition, when both a fuel mandate and cost containment mechanism are set optimally, the efficiency of fuel mandates can increase substantially over optimally setting fuel mandates alone. In a limiting case, an LCFS with a credit window offering can achieve the first-best outcome. Using a numerical model of the US gasoline market, we show that the efficiency gains from strategically including a credit window offering with a fuel mandate are sizable; however, optimally setting a renewable fuel multiplier yields only modest welfare gains.

Our results have implications beyond the context of fuel mandates. We demonstrate that the efficiency of a politically favored, second-best policy can be substantially increased through cost containment provisions. Given that quantity-based mechanisms are typically preferred to price instruments in environmental regulations, we show that cost containment mechanisms can be viewed beyond their traditional role of limiting price volatility. Specifically, they may also be used as an instrument to increase the economic efficiency of a policy.

Mandating green: On the design of renewable fuel policies and cost containment mechanisms*

Gabriel E. Lade[†] and C.-Y. Cynthia Lin Lawell[‡]

October 2015

Abstract

Policymakers typically favor renewable fuel mandates over taxes and cap and trade programs to reduce greenhouse gas emissions from the transportation sector. Because of delays in the development of commercially viable renewable fuels and important constraints on their use and distribution, fuel mandates are susceptible to sudden increases in compliance costs as policies become more stringent. We study the effects and efficiency of two fuel mandates, a renewable share mandate and a carbon intensity standard, as well as the effects of two cost containment provisions, a credit window price and a renewable fuel multiplier. We show using a numerical model of the US fuel market that when the mandates are set optimally, they can lead to modest efficiency gains over business as usual; however, when combined optimally with a credit window price, the efficiency of both mandates increases substantially. In contrast, optimally combining a mandate with a renewable fuel multiplier that indirectly relaxes the standard results in only modest efficiency gains over the optimal mandates alone.

JEL Codes: H23, Q42, Q54, Q58

Keywords: Renewable fuels, second-best policies, share mandates, intensity standards, cost containment mechanisms

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1 Introduction

The transportation sector is responsible for over a quarter of US greenhouse gas emissions, the majority of which are the result of fossil fuel combustion (EPA, 2015). Politicians and regulatory agencies at both federal and state levels have passed or considered a suite of policies aimed at decreasing emissions in the sector. Proposals include using carbon taxes, fuel economy standards for new vehicles, renewable fuel mandates, and including transportation sector emissions under regional or federal cap and trade programs (Knittel, 2012; Lade and Lin, 2015).

Of these proposed policies, whenever unpriced emissions are the sole market failure, a carbon tax or cap and trade program is more likely to achieve the first-best (Pigou, 1920; Coase, 1960), while fuel mandates are unable to replicate the first-best solution (Helfand, 1992; Holland et al., 2009; Lapan and Moschini, 2012). However, rather than establish a carbon tax or cap and trade program to reduce emissions in the sector, policy-makers have favored renewable fuel mandates,[1] likely due at least in part to political economy reasons (Knittel, 2013; Metcalf, 2009). The most prominent fuel mandates in the US currently are the federal Renewable Fuel Standard (RFS), a renewable fuel share mandate; and California's Low Carbon Fuel Standard (LCFS), a carbon intensity standard. In addition, several other states have considered implementing similar policies.[2]

The market effects of carbon intensity standards and renewable fuel share mandates have been studied by a number of authors (de Gorter and Just, 2009; Holland et al., 2009; Lapan and Moschini, 2012). In addition, a growing literature compares the relative performance of fuel mandates to more traditional policy instruments such as carbon taxes (Holland et al., 2013, 2014; Chen et al., 2014); studies unintended consequences of the policies and their relative efficiency when markets are imperfectly competitive (Holland, 2012) or open to trade (Rajagopal et al., 2011); and examines ways policymakers can increase the efficiency fuel mandates through strategic policy choices (Lemoine, 2013).[3]

In this paper, we formalize, expand upon, and synthesize the prior literature by developing a model of fuel mandates under perfect competition that incorporates both a renewable fuel share mandate and a carbon intensity standard. We summarize the effects of the policies on important market outcomes including

[1] An exception is California's cap and trade program. Beginning in 2015, refiners in California hold an obligation under the program for carbon emissions from the combustion of all fossil fuels sold in the state. The most aggressive policy aimed at reducing carbon emissions in the state, however, remains the Low Carbon Fuel Standard, a carbon intensity standard.

[2] Oregon's legislature passed a bill in 2009 authorizing the state's Environmental Quality Commission to adopt an LCFS (Langston et al., 2011). In 2009, Washington state's governor issued Executive Order 09-05, directing the state's Department of Ecology to study whether adopting an LCFS would meet the state's greenhouse gas reduction goals (Pont et al., 2014).

[3] In addition, because the feedstocks used for the production of corn-based ethanol can also be used for food, there is a related literature on the effects of ethanol policies on the relationship between food and fuel markets (Runge and Senauer, 2007; Rajagopal et al., 2007; Wright, 2014; Poudel et al., 2012; Abbott et al., 2008, 2009, 2011; de Gorter et al., 2013).

equilibrium fuel prices and quantities. We also derive analytically and numerically the second-best optimal RFS and LCFS.

When a policy is second-best, adding a second policy lever can improve efficiency. In particular, we study the effects and potential efficiency gains from measures aimed at constraining the policies' compliance costs. We study two cost containment mechanisms that have either been implemented or proposed in practice: (1) a credit window whereby regulated parties may purchase compliance credits from a regulator for a predetermined price; and (2) a renewable fuel multiplier where the regulator allows parties to inflate their accounting of renewable fuels towards their compliance obligations.

Cost containment mechanisms have typically been studied as tools to decrease compliance cost uncertainty under market based regulations (Newell et al., 2005; Nemet, 2010). In this paper we show that cost containment mechanisms can also be used to increase the efficiency of quantity-based mechanisms even in settings with no uncertainty.

We show that whenever the marginal cost of renewable fuels is high relative to fossil fuels, cost containment mechanisms have the benefit of both constraining compliance costs and reducing deadweight loss. In addition, when both a fuel mandate and cost containment mechanism are set optimally, the efficiency of fuel mandates can increase substantially over optimally setting fuel mandates alone. In a limiting case, an LCFS with a credit window offering can achieve the first-best outcome. Using a numerical model of the US gasoline market, we show that the efficiency gains from strategically including a credit window offering with a fuel mandate are sizable; however, optimally setting a renewable fuel multiplier yields only modest welfare gains.

Our results have implications beyond the context of fuel mandates. We demonstrate that the efficiency of a politically favored, second-best policy can be substantially increased through cost containment provisions. Given that quantity-based mechanisms are typically preferred to price instruments in environmental regulations, we show that cost containment mechanisms can be viewed beyond their traditional role of limiting price volatility. Specifically, they may also be used as an instrument to increase the economic efficiency of a policy.

The paper proceeds as follows. Section 2 provides a brief background on the Renewable Fuel and Low Carbon Fuel Standards, and discusses cost containment provisions that have either been considered or implemented under each policy. Section 3 presents a model of a regulated fuel industry and derives the effect of the policies and cost containment mechanisms on important market outcomes, as well as derives the second-best policies with and without cost containment mechanisms in place. Section 4 presents our numerical model of the US gasoline market, expanding upon the model in Section 3 along several important dimensions. Section 5 concludes.

2 Renewable Fuel Mandates

2.1 The Renewable Fuel Standard

The Renewable Fuel Standard (RFS) was created by the Energy Policy Act of 2005 and expanded by the Energy Independence and Security Act of 2007, creating the RFS2. The RFS2 is administered by the Environmental Protection Agency (EPA) and sets ambitious targets for renewable fuel consumption in the US, with the goal of expanding consumption to 36 billion gallons (bgal) a year by 2022. The RFS2 requires that a certain portion of the total mandate must come from specific sources. To do this, policy specifies nested mandates for: (1) cellulosic biofuel; (2) biodiesel; and (3) advanced biofuel.

2.2 Low Carbon Fuel Standards

California's Low Carbon Fuel Standard (LCFS) was created by Executive Order S-01-07 in 2007 by former Governor Arnold Schwarzenegger and went into effect in 2011. The standard is a key measure in achieving statewide reductions in greenhouse gas emissions required under California's Assembly Bill 32, the Global Warming Solutions Act of 2006. The standard is administered by the California Air Resources Board (ARB) and mandates a 10% reduction in the average carbon intensity of fuels sold in the state by 2020.

The LCFS is agnostic as to the fuels that can be used to meet the standard so long as all production pathways are approved by the ARB and assigned a carbon intensity (CI) value.[4] For example, in addition to biofuel producers, providers of electricity for plug-in vehicles and hydrogen fuel producers may generate credits under the LCFS (California ARB, 2015).

British Columbia also currently has an LCFS in place that has many similarities to California's regulation (British Columbia Ministry of Energy and Mines, 2014). Low carbon fuel standards have also been proposed in Oregon (Oregon Department of Environmental Quality, 2014), Washington (Pont et al., 2014), and the European Union (European Commission, 2014). Outside the fuel sector, a low carbon fuel standard, or rate-based standard, is one of the two policy instruments states can use to comply with the EPA's Clean Power Plan Rule, which sets state specific goals for reducing the carbon intensity of states' electricity generation (EPA, 2014).

[4] CI values represent the ARB's estimate of the carbon equivalent emissions rate of a given fuel's lifecycle production process.

2.3 Tradeable credits and compliance

Both the RFS and LCFS are enforced using tradeable compliance credits. Obligated parties, predominantly upstream gasoline and diesel refiners, generate deficits while qualifying renewable fuel producers generate credits. In order to maintain compliance, obligated parties must account for their deficits by purchasing or generating an equal number of credits by the end of each compliance period.

Under the RFS, compliance credits are known as Renewable Identification Numbers (RINs). Every gallon of approved renewable fuel produced in or imported into the United States from a registered source is associated with a RIN. Whenever a gallon of renewable fuel is blended into the US fuel supply, the RIN is 'detached' from the fuel and is available to be sold. Parties comply with the RFS2 by turning in a quantity of RINs equal to their prorated requirement under the mandate, and can obtain RINs by either physically blending renewable fuel or by purchasing detached RINs generated by other parties. RINs are differentiated by vintage year and fuel type in order to enforce banking restrictions and ensure the mandate for each biofuel category is met.

Under an LCFS, credits and deficits are denominated in tons CO_2 equivalence (CO_2e) and calculated using the spread between the fuels' assigned carbon intensity (CI) value and the standard. For example, every gallon of gasoline sold generates a deficit equal to the difference between gasoline's CI and the standard. Analogously, every gallon of a fuel produced that has a lower CI than the standard generates a credit surplus equal to the difference between the standard and its CI. Thus, credits (deficits) are generated only for the amount of emissions below (in excess of) the standard. Obligated parties maintain compliance by purchasing credits from low carbon intensive fuel producers, producing or blending renewable fuels themselves, reducing their production, and/or lowering the carbon intensity of their own fuel by changing their production pathways.

2.4 Implementation challenges and cost containment mechanisms

The success of both the RFS2 and LCFS in coming years faces a number of challenges. The two most notable are: (1) the 'blend wall'; and (2) the slow development of commercial scale low carbon fuel production.

The blend wall refers to the notion that consumption of ethanol beyond 10% of US gasoline supply is costly. Ethanol has historically been blended with gasoline at two levels: 10% ethanol, referred to as E10; and 85% ethanol, referred to as E85. Vehicle owners must have flex fuel vehicles (FFVs) in order to fuel with E85, and gasoline station owners must invest in special fueling infrastructure in order for a station to offer the fuel. While many FFVs have been produced in the US, they are not located in regions with the highest density of E85 stations due to unintended consequences from incentives for FFVs under US fuel economy standards (Anderson, 2012; Pouliot and Babcock, 2014). As a result, increasing biofuel consumption beyond the blend wall in the near term requires either expanding E85 consumption or increasing biodiesel consumption where blending constraints are less binding. Both options are costly due to a combination of high production costs and binding capacity constraints.

To date, the predominant fuel used to meet both mandates is ethanol derived from corn (EPA, 2013a; Yeh et al., 2013). The success of both the RFS2 and LCFS in coming years depends on the development of advanced alternative fuels such as cellulosic biofuel. As of early 2015, cellulosic production was far below the original RFS2 mandates (EIA, 2012b). In addition, Yeh et al. (2013) found that Califorina's fuel mix in 2013 would only allow the industry to maintain compliance with the LCFS through the end of 2013.[5]

Given these challenges, both the EPA and the California ARB have considered or enacted various cost containment provisions. For example, from 2010-2011 the EPA allowed parties to purchase cellulosic RIN credits through an open credit window in lieu of blending cellulosic fuel. In addition, in November 2013, the EPA proposed a substantial rollback of the RFS mandates for 2014 and beyond in response to high RIN prices (EPA, 2013b). In California, the Air Resources Board released a white paper in May 2013 discussing a number of mechanisms to contain compliance costs including establishing a credit window or a low carbon credit multiplier (California ARB, 2014). In March 2014, the Board began a re-adoption process of the policy, and one of the key provisions under consideration is the inclusion of a cost containment mechanism (California ARB, 2013).

3 Model

To best focus on and present the intuition for why cost containment mechanisms can increase the efficiency of quantity-based mechanisms even in settings with no uncertainty, we develop a streamlined model with no uncertainty, a single compliance period, and a single biofuel mandate, and one that incorporates both a renewable fuel share mandate and a carbon intensity standard.[6] Consider a competitive industry that produces fuel of total quantity Q. Assume the industry uses two inputs: (1) a conventional input, q^c; and (2) a renewable input, q^r.[7] Assume the inputs are denominated in such a way that they are perfect substitutes in production with $Q = q^c + q^r$. For example, if consumers value the energy content of fuel, the units could be denominated in gasoline gallon equivalence (GGE) or in common energy units such as mega-joules (MJ).[8] Suppose each input is associated with an emission factor ϕ^j for $j = c, r$ and that aggregate

[5]Before the LCFS reached this critical level, several court rulings led to the LCFS being frozen at 1.5% while the California ARB re-adopts the policy (California ARB, 2013).

[6]In Lade et al. (2015), we relax these assumptions and develop a dynamic model of compliance with the RFS2 under uncertainty to better understanding market clearing credit prices.

[7]The assumption of two fuels is made for notational ease. While the qualitative results are not affected in the multi-fuel case (Lade and Lin, 2013), not all the analytic results presented in this section generalize to the multi-fuel case. We examine the multi-fuel case in our numerical model in Section 4.

[8]A gallon of ethanol has around 70% of the energy content as a gallon of gasoline. A gallon of neat biomass-based diesel has around 95% of the energy content of conventional diesel fuel.

emissions are associated with damages captured by the function $D(\phi^c q^c + \phi^r q^r)$, where the marginal damages $\phi^i \partial D/\partial q^i = \phi^i \partial D/\partial q$ for $i = c, r$ are equal for the two fuels.

We begin by studying the effects of each fuel mandate on key market outcomes. We then study the effect of the two cost containment mechanisms: (i) a credit window offering that caps compliance costs; and (ii) a renewable fuel multiplier that increases the accounting of renewable fuel credits under the policy constraints. The multiplier indirectly relaxes the policy constraints, but does not cap compliance costs. Both mechanisms have either been implemented or proposed in practice. In addition, most cost containment mechanisms that have been considered by policymakers can be shown to be a special case or variant of the two considered mechanisms. For example, a fixed noncompliance penalty has similar effects as a credit window option. Likewise, decreasing the stringency of the policy has similar effects as implementing a renewable fuel multiplier. Last, we study the second-best levels of the fuel mandates and cost containment mechanisms.

3.1 Market effects of fuel mandates

We study two mandates: (1) a renewable share mandate similar to the federal RFS;[9] and (2) an energy-based carbon intensity standard similar to California's LCFS. We model market equilibrium using a representative firm. Suppose consumers have decreasing, weakly concave inverse demand for fuel given by $P(Q)$. Assuming aggregate increasing, convex cost curves $C^c(q^c)$ and $C^r(q^r)$ for conventional and renewable fuel, respectively, the solution to the representative firm's problem replicates the competitive market equilibrium.

An RFS requires the share of renewable fuel to be greater than a specified volume obligation. We write the constraint as $q^r \geq \alpha q^c$, where α is renewable share mandate set by the regulator. We specify the LCFS as an energy-based carbon intensity standard, writing the policy constraint as $\frac{\phi^c q^c + \phi^r q^r}{q^c + q^r} \leq \sigma$, where σ is the low carbon fuel standard. For notational ease, we rewrite both policies as $\varphi(q^c, q^r; \theta) \geq 0$ as:

$$\begin{aligned} &\text{[RFS:]} && \varphi(q^c, q^r; \theta) = q^r - \alpha q^c \geq 0 \\ &\text{[LCFS:]} && \varphi(q^c, q^r; \theta) = (\sigma - \phi^c) q^c + (\sigma - \phi^r) q^r \geq 0, \end{aligned}$$

where θ are the policy parameters with $\theta = \alpha$ under the RFS and $\theta = \sigma$ under the LCFS.

Under a renewable fuel mandate, the representative firm's problem can be written as:

$$\max_{q^c \geq 0; q^r \geq 0} P(q^c + q^r) - C^c(q^c) - C^r(q^r) + \lambda \left[\varphi(q^c, q^r; \theta) \right],$$

where λ is the Lagrange multiplier on the mandate constraint, with $\lambda \geq 0$ if the policy binds. The Karush-Kuhn-Tucker optimality conditions are:

$$[q^c:] \quad P - \frac{\partial C^c}{\partial q^c} + \lambda \frac{\partial \varphi(\cdot)}{\partial q^c} \leq 0 \tag{1}$$

[9]Given our assumption of a single renewable fuel, we do not model the RFS using a nested mandate structure. Thus, our model is most applicable to studying the RFS or the overall biofuel mandate under the RFS2.

$$[q^r :] \quad P - \frac{\partial C^r}{\partial q^r} + \lambda \frac{\partial \varphi(\cdot)}{\partial q^r} \leq 0 \tag{2}$$

$$\lambda[\varphi(q^c, q^r; \theta)] = 0.$$

Conditions (1) and (2) hold with equality for interior solutions, and the third condition states that either the policy binds with equality or the constraint is slack and $\lambda = 0$. For the RFS, the partial derivatives of the policy function are given by $\frac{\partial \varphi(\cdot)}{\partial q^c} = -\alpha < 0$ and $\frac{\partial \varphi(\cdot)}{\partial q^r} = 1 > 0$. For the LCFS, the partial derivatives of the policy function are given by $\frac{\partial \varphi(\cdot)}{\partial q^c} = (\sigma - \phi^c) < 0$ and $\frac{\partial \varphi(\cdot)}{\partial q^r} = (\sigma - \phi^r) > 0$.

The conditions summarize findings in prior research on the two policies (de Gorter and Just, 2009; Holland et al., 2009; Lapan and Moschini, 2012). Conditions (1) and (2) state that the policies implicitly tax conventional fuels and subsidize renewable fuels. The level of the tax and subsidy is endogenous, where the Lagrange multiplier on the policy constraint adjusts to the point where the mandate is just met whenever the policy binds. Lemma 1 states the effect of the policies on fuel prices.[10]

Lemma 1: *Under a binding RFS and LCFS, the equilibrium price is a weighted average of the marginal costs of each fuel where the weights correspond to the share requirement under each respective mandate.*

Lemma 1 illustrates the similarity of the two fuel mandates.[11] The distinguishing factor between the policies is how the implicit or explicit share mandate on renewable fuels is constructed. Under the RFS, the share mandate is set directly by α, while for an LCFS the share mandate is determined by the relative difference of the carbon intensity assignment of both the conventional and renewable fuel.

Before proceeding, it is helpful to establish the effect of credit trading programs and the interpretation of λ from the optimality conditions under each policy. Lemma 2 summarizes the role of credit trading and establishes our interpretation of λ.

Lemma 2: *Under a fuel mandate with a credit trading system:*

i Firms' marginal compliance costs are equalized as long as the credit trading is competitive and frictionless;

ii The equilibrium credit price is equal to λ, the aggregate firm's Lagrange Multiplier on the policy constraint;

iii The marginal value of relaxing each constraint is equal to $-\lambda q^c$ under the RFS and λQ under the LCFS.

---

[10]All proofs are presented in Appendix A.

[11]Moreover, for the special case when $\alpha = -(\sigma - \phi^c)/(\sigma - \phi^r)$, the policy functions $\varphi(q^c, q^r; \theta)$ for both the RFS and the LCFS are identical.

Lemma 2 states that whenever the market for compliance credits is competitive, the representative firm's Lagrange multiplier can be interpreted as the equilibrium compliance credit price. In addition, the value can be used to construct direct measures of the policies' costs. Note that the signs of in (iii) are different. This is because increasing α, the RFS mandate, increases the policy stringency while increasing σ, the LCFS mandate, relaxes the policy stringency.

We now turn to key comparative statics. Proposition 1 summarizes the comparative statics of an equilibrium under a binding fuel mandate with respect to the policy parameters.

Proposition 1: Market effects of fuel mandates

i Under both mandates, increasing the stringency of the policy parameter θ reduces the volume q^c of conventional fuel.

ii Under an RFS, increasing α increases the volume q^r of renewable fuel if $\frac{1}{\xi^c} - \frac{1}{\eta^d} > \alpha \frac{\lambda}{P}$, where ξ^c is the price elasticity of supply for the conventional input and η^d is the elasticity of demand.[12] *Under an LCFS, decreasing σ increases the volume q^r of renewable fuel if $\frac{1}{\xi^c} - \frac{1}{\eta^d} > (\phi^c - \sigma) \frac{\lambda}{P}$.*

iii Fuel price P increases if total fuel quantity Q decreases, and decreases if total fuel quantity Q increases.

Increasing the stringency of both policies decreases q^c and increases q^r so long as $\frac{1}{\xi^c} - \frac{1}{\eta^d}$ is larger than a term proportional to the ratio of the compliance credit price and the fuel price, $\frac{\lambda}{P}$. Thus, if the supply of conventional fuel and/or the demand for fuel are relatively inelastic, increasing the stringency of either policy will increase q^r. Intuitively, if consumers do not decrease consumption or conventional suppliers do not reduce their supply as the policies become more stringent, the only means to maintain compliance is to increase the supply of renewable fuel.[13] If, however, consumers reduce fuel consumption and/or fossil fuel producers reduce production in response to the policies, q^r need not increase to maintain compliance with the policy.

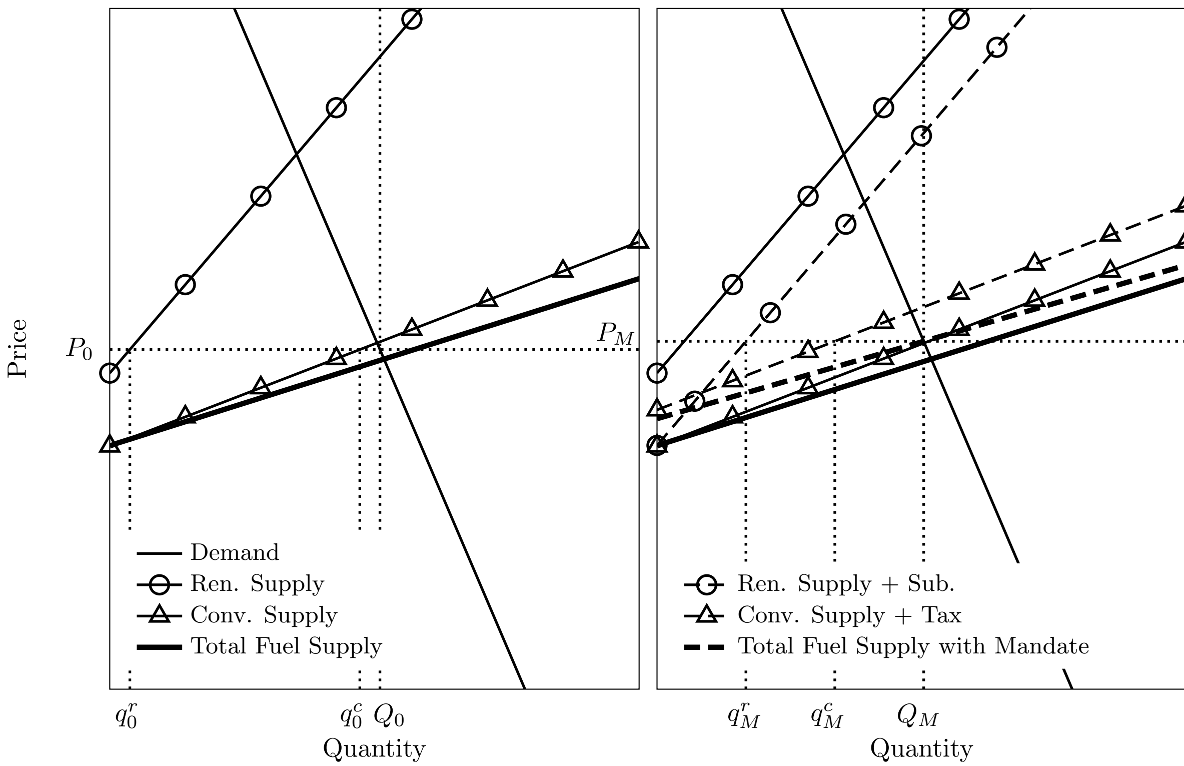
The effect of the mandates on fuel prices depends on total fuel supply response. It can be shown that a necessary condition for the policy to increase P is $\xi^c > \xi^r$, i.e., prices increase as the policies become more stringent if the supply elasticity of the conventional fuel is greater than the renewable supply elasticity. Fischer (2010) derives analogous results for the effect of Renewable Portfolio Standards on wholesale electricity prices.

Figure 1 illustrates the effects of both policies. The left graph illustrates the initial equilibrium, and the right graph illustrates the equilibrium under a fuel mandate. In both graphs, the downward sloping line is the fuel demand curve; the line with triangles is the conventional fuel supply curve; the line with circles is

[12] If elasticities are not constant, then ξ^c and η^d represent local elasticities.

[13] In the extreme case where fuel demand or conventional supply is perfectly inelastic, both policies unambiguously increase renewable fuels.

Figure 1: Market Effects of Fuel Mandates*



Notes: The left graph illustrates the initial equilibrium, and the right graph illustrates the equilibrium under a fuel mandate. The downward sloping line is the fuel demand curve, the line with triangles is the conventional fuel supply curve, the line with circles is the renewable fuel supply curve, and the bold upward sloping line is the total fuel supply curve. The right graph illustrates the equilibrium under a binding fuel mandate, with the solid lines representing the initial supply curves and the dashed lines representing the supply curves net of the implicit subsidy and tax under a fuel mandate.

the renewable fuel supply curve; and the bold upward sloping line is the total fuel supply curve, equal to the horizontal sum of the renewable and conventional supply curves.

In the left graph, the total and conventional fuel supply curves are the same until the price reaches the intercept of the renewable fuel supply curve. The initial market clearing price and total fuel quantity P_0 and Q_0 are found where the total fuel supply curve intersects the demand curve. The supply of each fuel, q_0^c and q_0^r, is given by the corresponding quantity where the equilibrium price intersects the individual supply curves.

The right graph illustrates the equilibrium under a binding fuel mandate, with the solid lines representing the initial supply curves and the dashed lines representing the supply curves net of the implicit subsidy and tax under a fuel mandate. Under both policies, the renewable supply curve shifts down and the conventional supply curve shifts up until the market clearing price and quantities are such that the equilibrium quantities comply with the mandate. The equilibrium price and quantity P_M and Q_M are found where the new dashed total fuel supply curve, equal to the sum of the shifted conventional and renewable supply curves intersects the demand curve. In our example, the resulting equilibrium results in a higher production of renewable fuel q^r_M and a lower production of conventional fuel q^c_M. Because total fuel consumption Q_M declines under the fuel mandate in our example, the policy results in slightly higher fuel prices P_M over the no policy equilibrium.

3.2 Cost containment mechanisms

Now suppose the regulator wishes to limit compliance costs under a fuel mandate. We study two mechanisms: (1) a credit window for compliance credits offered at a predetermined price; and (2) a multiplier for renewable fuels. The former gives firms an alternative compliance option, while the latter indirectly relaxes the policy constraint.

First consider the credit window offering. Let $c > 0$ denote the number of credits bought from the regulator through the window and $\bar{p}^{\text{cred}}$ be the credit window price set by the regulator. The policy constraints with a credit window are given by:

$$\begin{aligned} &[\text{RFS:}] && \varphi(q^c, q^r, c; \theta) = q^r + c - \alpha q^c \geq 0 \\ &[\text{LCFS:}] && \varphi(q^c, q^r, c; \theta) = (\sigma - \phi^c) q^c + (\sigma - \phi^r) q^r + c \geq 0. \end{aligned}$$

The representative firm's problem is given by:

$$\mathcal{L} = \max_{q^c, q^r, c \geq 0} P(q^c + q^r) - C^c(q^c) - C^r(q^r) - \bar{p}^{\text{cred}} c + \lambda \left[\varphi_i(q^c, q^r, c; \theta) \right],$$

with corresponding Karush-Kuhn-Tucker conditions:

$$[q^c :] \quad P - \tfrac{\partial C^c}{\partial q^c} + \lambda \tfrac{\partial \varphi(\cdot)}{\partial q^c} \leq 0 \tag{3}$$

$$[q^r :] \quad P - \tfrac{\partial C^r}{\partial q^r} + \lambda \tfrac{\partial \varphi(\cdot)}{\partial q^r} \leq 0 \tag{4}$$

$$[c :] \quad \lambda - \bar{p}^{\text{cred}} \leq 0 \tag{5}$$

$$\lambda[\varphi(q^c, q^r; \theta)] = 0.$$

The conditions state that if a regulator establishes a credit window, if marginal compliance costs are below the credit price, firms will not purchase credits from the window and marginal compliance costs will be determined as in the no policy case. If, however, marginal compliance costs reach or exceed the credit price, firms will purchase from the window and compliance credit prices will equal $\bar{p}^{\text{cred}}$. Hence, the open credit window creates a ceiling on marginal compliance costs. Proposition 2 summarizes the comparative statics with respect to the credit price $\bar{p}^{\text{cred}}$ when firms purchase from the credit window.

Proposition 2: *Suppose firms purchase from the credit window such that $\lambda = \bar{p}^{cred}$. Under both fuel mandates as the emergency credit price $\bar{p}^{cred}$ increases:*

i The volume of conventional fuel q^c decreases and the volume of renewable fuel q^r increases;

ii The quantity of compliance credits c decreases; and

iii The fuel price increases if Q decreases and decreases if Q increases.

Proposition 2 states that so long as the ceiling on credit prices is binding, an increase in $\bar{p}^{\text{cred}}$ decreases q^c, increases q^r, and decreases c.

Next consider the multiplier for renewable fuel. We specify the multiplier as $\gamma \geq 1$ such that every gallon of renewable fuel generates γq^r credits. The policy constraints with a multiplier are given by:

$$\text{[RFS:]} \qquad \varphi(q^c, q^r; \theta) = \gamma q^r - \alpha q^c \geq 0$$
$$\text{[LCFS:]} \quad \varphi(q^c, q^r; \theta) = (\sigma - \phi^c)q^c + (\sigma - \phi^r)\gamma q^r \geq 0.$$

The representative firm's problem is equivalent to the problem from Section 3.1; however, the optimality conditions incorporate γ into the policy constraint so that $\frac{\partial \varphi(\cdot)}{\partial q^c} = -\alpha$ and $\frac{\partial \varphi(\cdot)}{\partial q^r} = \gamma$ for the RFS; and $\frac{\partial \varphi(\cdot)}{\partial q^c} = (\sigma - \phi^c)$ and $\frac{\partial \varphi(\cdot)}{\partial q^r} = (\sigma - \phi^r)\gamma$ for the LCFS. Proposition 3 summarizes the comparative statics for each policy with respect to the renewable fuel multiplier.

Proposition 3: *Instituting a renewable fuel multiplier $\gamma > 1$ under a binding mandate is equivalent to decreasing the stringency of the fuel mandate, i.e., decreasing α or increasing σ.*

Proposition 3 highlights the similarity between increasing the renewable fuel multiplier and reducing the stringency of each fuel mandate. Increasing the renewable fuel multiplier increases q^c and decreases marginal compliance costs λ. As in Proposition 1, increasing γ decreases q^r if the supply of conventional fuel and/or demand for fuel are inelastic. If either of these hold, increasing γ decreases q^r in equilibrium.

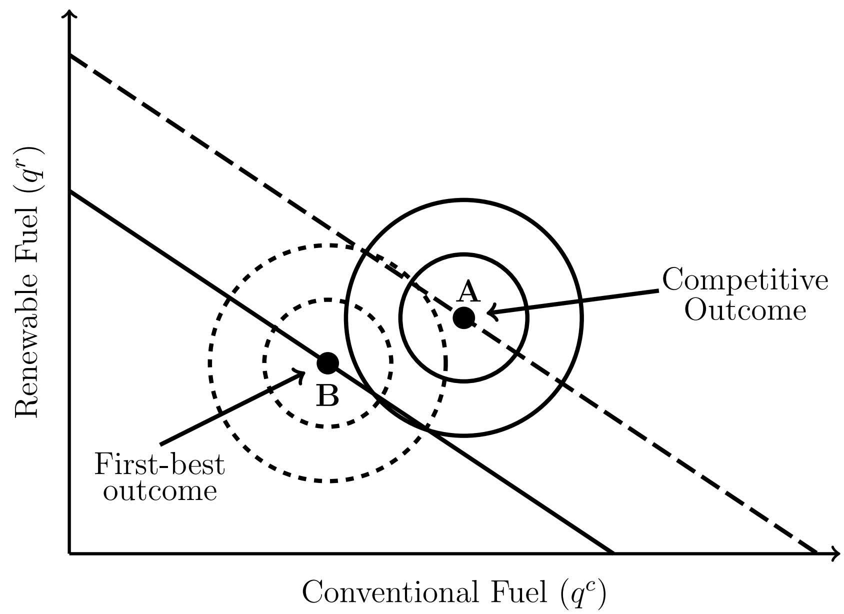
3.3 Second-best policies

Now consider the second-best fuel mandates with and without cost containment provisions. Whenever unpriced emissions are the sole market failure, fuel mandates are unable to replicate the first-best solution (Helfand, 1992; Holland et al., 2009; Lapan and Moschini, 2012). This is due to the implicit subsidy effect of the policies for renewable fuels.

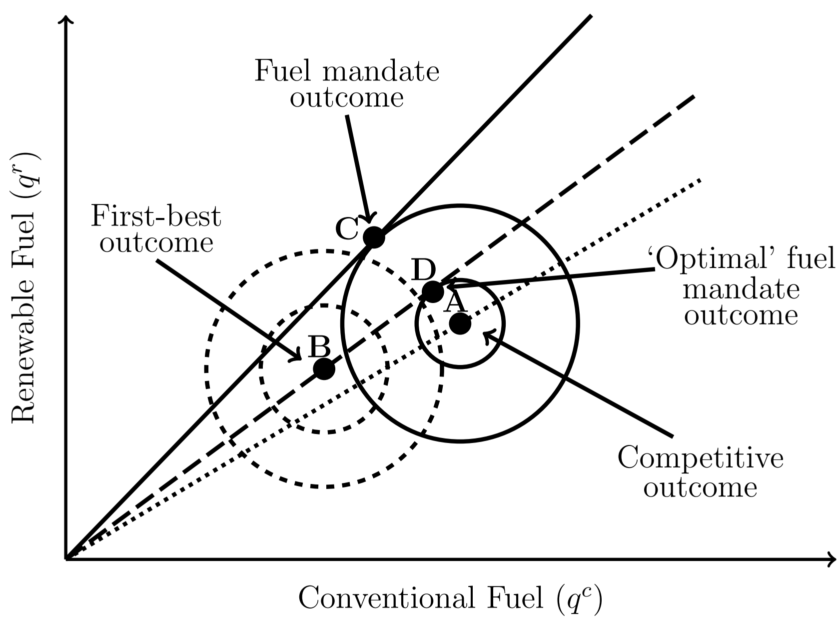
Figure 2 illustrates the inefficiency of the mandates graphically. The solid circles represent iso-welfare curves when pollution damages are excluded. The dashed circles are iso-welfare curves when pollution externalities are internalized.[14] In the absence of any policy, the competitive market maximizes consumer and producer surplus at point A, which differs from the social optimum, point B.

[14]Specifically, the solid circles represent level curves of the function $U(Q) - C^c(q^c) - C^r(q^r)$, and the dashed circles represent level curves of the function $U(Q) - C^c(q^c) - C^r(q^r) - D(q^c, q^r)$.

Figure 2: First-best, competitive outcome, and fuel mandates



(a)



(b)

*Notes: Solid circles are iso-welfare curves less damages and the dotted circles are iso-social welfare curves. Lines parallel to the origin are iso-emission lines with slope $(-\phi^c/\phi^r)$. The rays from the origin represent fuel mandates.

In order to align the competitive and first-best outcome, a regulator can either tax emissions or institute a cap and trade program, illustrated in Figure 2(a). Iso-emissions curves are graphed as perpendicular lines to the origin with slope $(-\phi^c/\phi^r)$. The dashed perpendicular line corresponds to emissions under the no policy outcome. If the government institutes a cap and trade program setting the cap at the first-best emission level, represented by the solid line, the competitive market outcome will correspond to the social optimum.

Now consider the efficiency of fuel mandates, illustrated in Figure 2(b). We represent both policies as rays from the origin, where the slope of the ray corresponding to the share of renewable fuel required by the policy. A binding share mandate must pass to the left of the initial share of renewable fuels given by the dashed ray passing through point A. Consider the effect of a binding mandate given by the solid ray. Under the fuel mandate, firms maximize profits at C, resulting in higher renewable and conventional fuel production and higher emissions than the efficient outcome B.

To illustrate that fuel mandates cannot achieve the first-best outcome, suppose the regulator knows the share of renewable fuels or the carbon intensity of fuels under the first-best outcome and sets the mandate at this level, represented by the dotted line through point B. Despite being set at the optimal share, the market maximizes profits at D, away from the first-best outcome. This is due to the subsidy the policies provide for renewable fuel, which reduces the price impact of the policy.

Despite the economic inefficiency of fuel mandates, a regulator may seek to optimally set the policy. Given a fuel mandate, θ, and an optimizing regulator, the regulator's problem can be written as:

$$\max_{0\leq\alpha\leq 1} \int_0^Q P(x)dx - C^c(q^c) - C^r(q^r) - D(\phi^c q^c + \phi^r q^r).$$

Proposition 4 characterizes the second-best RFS and LCFS, generalizing the results for a second-best LCFS in Holland et al. (2009).

Proposition 4: *Consider an interior, second-best RFS and LCFS. Under both policies, if increasing the policy stringency increases the volume q^r of renewable fuel,*[15] *the implicit tax on conventional fuel is lower than marginal damages at the optimum. If, however, increasing the policy stringency decreases the volume q^r of renewable fuel, the implicit tax on conventional fuels should be set higher than its marginal damages.*

Proposition 4 states that a second-best fuel mandate should be set at a level where the implicit tax on conventional fuel is less than its marginal damages so long as increasing the policy stringency increases the use of renewable fuel. The US government currently uses a social cost of carbon of \$39/ton CO_2 in its regulatory impact analyses (IAWG, 2013). Thus, our result implies that an optimal RFS and LCFS should be set at a level such that the implicit tax on conventional fuel is less than \$39/ton. Note that the implicit tax is not equal to the price to compliance credits, but is the price of credits scaled by α and $(\phi^c - \sigma)$ under an RFS and LCFS, respectively.

[15]Conditions under which increasing the stringency of the RFS and LCFS increases the volume of renewable fuel are given by Proposition 1.

3.4 Improving the second-best through cost containment

Policymakers may be motivated to include a cost containment mechanism in a fuel mandate for a number of reasons. When market outcomes are uncertain, a policy that places a ceiling on compliance costs can act to eliminate small probability, high compliance cost events (Nemet, 2010), and potentially increase the policy's efficiency (Newell et al., 2005). In this section, we show that cost containment mechanisms can increase a mandate's efficiency even in the absence of uncertainty.

Suppose a regulator operates in an environment where enacting a fuel mandate is preferred to instituting a carbon price. Furthermore, suppose the regulator is not able to change the policy stringency, perhaps due to a legislative mandate, but that the regulator has the ability to set the level of a cost containment mechanism. The propositions below derive optimal cost containment mechanisms conditional on a given policy level θ. We first consider the conditionally optimal compliance credit window price in Proposition 5.

Proposition 5: *An optimal binding credit window price conditional on policy θ for each mandate ensures that the implicit tax on conventional fuel is less than its marginal damages.*

Proposition 5 illustrates that the optimal credit window price, conditional on a given policy level α or σ, shares many of the same features as the optimal policy levels. From Proposition 2 we know that the volume q^c of conventional fuel decreases and the volume q^r of renewable fuel increases as the credit window price $\bar{p}^{\text{cred}}$ increases. Thus, the optimal credit window price under an RFS increases in conventional emissions and decreases in renewable emissions. Similar results hold for an optimal credit window price under an LCFS.

The intuition for Proposition 5 is as follows. Combining a mandate policy with a binding credit window makes the policy look like a tax but with greater equilibrium use of low-emission fuels, and therefore lower benefits. Thus, the optimal binding credit window price conditional on the mandate policy should ensure that the implicit tax on conventional fuel is less stringent than the optimal tax.

Importantly, the credit window gives the regulator an additional tool that can be used to increase the efficiency of a fuel mandate, particularly if the mandate is set at inefficient levels. For example, suppose prior to enacting the policy, a policymaker believes the marginal cost of the renewable fuel is $\frac{\partial C_L^r}{\partial q^r}$. The anticipated market clearing compliance credit price is λ_L. Knowing an efficient policy requires the implicit tax on conventional fuels to be below marginal damages, the policymakers chooses θ optimally and $\left(-\lambda_L \frac{\partial \varphi(\cdot)}{\partial q^c}\right) < \frac{\partial D}{\partial q^c}$.

Suppose, however, that ex post marginal costs are $\frac{\partial C_H^r}{\partial q^r} > \frac{\partial C_L^r}{\partial q^r}$. Compliance credit prices adjust endogenously, and compliance credit prices are given by $\lambda_H > \lambda_L$. Suppose credit prices adjust such that $\left(-\lambda_H \frac{\partial \varphi(\cdot)}{\partial q^c}\right) > \frac{\partial D}{\partial q^c}$. Clearly the policy is inefficient. By establishing a credit window, however, the regulator can correct this. Assuming the initial standard was set second-best optimally given the anticipated λ_L, the regulator could set $\bar{p} = \lambda_L$ to achieve the ex-ante policy goal.

Inspecting the optimality conditions under an LCFS with a credit window price reveals a key feature unique to the LCFS, summarized in Corollary 1.

Corollary 1: *An LCFS with a credit window price is able to achieve the first-best outcome, while an RFS with a credit window price is unable to achieve the first-best.*

Corollary 1 raises an important distinction between the RFS and the LCFS. Because the LCFS differentiates fuels based on their carbon intensity factors, the policy has the potential to achieve more efficient outcomes than the RFS. If the regulator sets both the policy stringency and the compliance credit price optimally, the optimal policy calls for setting a standard equal to zero and the credit window price equal to marginal damages. In contrast, an RFS with a credit window is never able to achieve the first-best because the policy always implicitly subsidizes renewable fuels.[16]

Now consider the multiplier for renewable fuel. Proposition 6 summarizes when a renewable fuel multiplier is optimal and improves welfare conditional on the mandate policy θ.

Proposition 6: *If increasing the multiplier γ increases (decreases) the volume q^r of renewable fuel,*[17] *the optimal multiplier conditional on policy θ is set such that the implicit tax on conventional fuel is greater (less) than its marginal damages.*

Whenever increasing the renewable fuel multiplier decreases the volume of renewable fuel, similar results apply as in Propositions 4 and 5, and γ should be set such that the implicit tax on conventional fuels is less than its marginal damages. If increasing the renewable fuel multiplier increases q^r, increasing γ unambiguously increases emissions. As a result, γ should be set such that the implicit tax on conventional fuels is greater than marginal damages.

Corollary 2 highlights that the inefficiencies associated with both fuel mandates persists even with a renewable fuel multiplier.

Corollary 2: *Neither the RFS nor the LCFS with a renewable fuel multiplier can achieve the first-best outcome.*

Thus, it is not feasible for a fuel mandate with a renewable fuel multiplier to achieve the first-best outcome.

[16]The same would remain true for a nested mandate structure. An example of a nested mandated structure is the RFS2, for which cellulosic biofuel and biodiesel count toward the advanced biofuel mandate, and all biofuels count twoard the overall renewable fuel mandate. While the nested mandate levels and credit window prices may be adjusted, yielding efficiency gains beyond using only an overall mandate, the lowest-tiered mandate will always serve as an implicit subsidy for the lowest tiered renewable fuel, preventing the policy from achieving the first-best as under an LCFS.

[17]Conditions under which increasing γ decreases q^r are given by Propositions 1 and 3.

4 Simulation of the US fuel market

We develop a numerical model of the US gasoline market to better understand the relative performance and market effects of the various fuel mandates and cost containment provisions. We assume firms produce three fuels: (1) gasoline; (2) conventional corn ethanol; and (3) cellulosic ethanol. We assume consumers demand energy, and specify demand in gasoline gallon equivalence (GGE). All demand and supply functions are constant elasticity. More details on the simulation parameters are presented in Appendix B.

We calibrate the model so that the supply of gasoline and conventional ethanol and fuel prices are similar to those in 2010. Using a similar model, Lade and Lin (2013) found that market outcomes under an LCFS were sensitive to the assumed availability of cellulosic ethanol. To account for this, we consider two scenarios: (i) a high cellulosic scenario; and (ii) a low cellulosic scenario. The former assumes both higher initialized supply of cellulosic ethanol, 3 billion gallons versus 500 million gallons; and a higher supply elasticity, 3 versus 0.5. Both the high and low cellulosic scenarios assume production is higher than installed capacity as of 2015, and thus are meant to represent 'medium-run' scenarios, and supply elasticities for gasoline and conventional ethanol are set accordingly.

We assume carbon damages are \$100/ton CO_2e. The most recent estimates of the average social cost of carbon issued by the Interagency Working Group on the Social Cost of Carbon based on a 3% discount rate is \$39/ton CO_2; however, estimates based on the same discount rate range from nearly zero to nearly \$120/ton CO_2 (IAWG, 2013). Our damages fall in the range of these estimates, and results are not sensitive to the assumed damages.

The RFS requires that the total volume of renewable fuel, equal to the sum of cellulosic and conventional ethanol, is greater than a renewable volume obligation given by αq^c. The LCFS requires that the average carbon intensity of fuel is less than the standard. We specify fuels' carbon intensity (CI) factors so that they are similar to those used by the California ARB. We normalize the CI factors so that the initial carbon intensity is equal to 1 in the business-as-usual (BAU), or no policy, equilibrium. Thus, an LCFS equal to 0.9 is readily interpreted as requiring a 10% reduction in the average CI of fuel.

From Corollary 1, we know setting the LCFS equal to zero and the credit price equal to marginal damages will achieve the first-best outcomes. Given that such a policy is unlikely to be passed, we constrain both fuel mandates to be 'technologically' feasible. Specifically, we constrain the LCFS to be between the initial carbon intensity of fuels, 1, and the carbon intensity of cellulosic ethanol, 0.2131. Thus, the most ambitious LCFS the government can pass in our model is an LCFS that requires a 78.69% reduction in the carbon intensity of fuel such that the only fuel that meets the standard is cellulosic ethanol. For the RFS, we constrain the policy to be between the initial share of biofuels and a 100% biofuel mandate.

Our simulation differs from the model studied in Section 3 in a number of ways. Because we assume three fuels, the equivalence between the RFS and LCFS does not generally hold.[18] Nonetheless, the policies continue to have similar market effects in the multiple fuel case. In addition, we assume the regulator institutes a multiplier for cellulosic ethanol instead of for all renewable fuel.[19] In this case, increasing the multiplier is no longer equivalent to relaxing the policy constraint; however, it has qualitatively similar effects.

4.1 Second-best policies

We solve for market clearing prices and quantities under all policy and cost containment combinations to compare welfare outcomes across the various scenarios. We solve for the second-best policies using a grid search over the policy parameters to find the welfare maximizing level. For the policies with a cost containment mechanism, we search over both the policy parameter and the level of the cost containment mechanism. Table 1 summarizes the optimal policies under both the high and low cellulosic scenarios.

Recall that all policies are second-best by nature. Therefore, the difference between the social welfare under each of the policies and the welfare under the first-best scenario is equal to the deadweight loss (DWL) of the policy. As such, DWL measures are also presented.

In both the low and high cellulosic scenarios, the largest DWL occurs under BAU. An optimal, second-best RFS and LCFS lead to small welfare gains over BAU on the order of \$200 million/year in the low cellulosic ethanol scenario. In the high cellulosic scenario, the LCFS and RFS increase welfare over BAU by approximately \$660 million and \$420 million per year, respectively. In all scenarios, losses relative to the first-best allocation remain over \$5 billion/year when implementing an optimal fuel mandates alone.

Welfare gains are modest when a regulator sets both the policy and the cellulosic multiplier optimally over optimally setting the policy alone. In the low cellulosic scenario, the optimal policy levels are slightly higher for both the RFS and LCFS, and the optimal multipliers are approximately 4 and 8, respectively. Because little cellulosic fuel is available, welfare improvements over the optimal RFS and LCFS alone are small, less than \$50 million/year. In the high cellulosic scenario, an optimal policy and multiplier leads to larger welfare gains. Under an RFS, the gains over the optimal RFS are on the order of \$50 million/year. Under an LCFS, the optimal policy-multiplier increases welfare by over \$150 million/year over the optimal LCFS. For both policies, the DWL when the policy and the cellulosic multiplier are chosen optimally remain over \$5.5 billion/year.

[18] In a model with multiple renewable fuels, unless the carbon intensity assignments for the renewable fuels are the same, an RFS and an LCFS cannot be designed in a way such that they are functionally equivalent.

[19] This is motivated by the California ARB's proposed fuel multiplier.

Table 1: Optimal Second-Best Policies and Social Welfare Outcomes Relative to the First-Best*

Low Cellulosic Scenario

Policy		**Optimal Level**	**DWL ($ bil)**
BAU			$5.81
RFS	Mandated Share	12.78%	$5.63
RFS w/ Multiplier	Mandated Share	16.48%	$5.59
	Multiplier	8.64	
RFS w/ Credit Window	Mandated Share	100%	$4.56
	Credit Price	$0.18/gal	
LCFS	Mandated Reductions	0.90%	$5.62
LCFS w/ Multiplier	Mandated Reductions	1.90%	$5.59
	Multiplier	4.12	
LCFS w/ Credit Window	Mandated Reductions	78.69%	$0.16
	Credit Price	$1.35/gal	

High Cellulosic Scenario

Policy		**Optimal Level**	**DWL ($ bil)**
BAU			$6.32
RFS	Mandated Share	15.64%	$5.90
RFS w/ Multiplier	Mandated Share	32.14%	$5.49
	Multiplier	5.46	
RFS w/ Credit Window	Mandated Share	100%	$4.71
	Credit Price	$0.19/gal	
LCFS	Mandated Reductions	2.10%	$5.66
LCFS w/ Multiplier	Mandated Reductions	5.60%	$5.49
	Multiplier	2.49	
LCFS w/ Credit Window	Mandated Reductions	78.69%	$0.24
	Credit Price	$1.35/gal	

*Notes: BAU stands for 'business as usual' and corresponds to the 2010 no policy equilibrium. The LCFS is phrased in percent reductions from the 2010 carbon intensity. The RFS is phrased as percent biofuel mandated. DWL stands for 'deadweight loss' and represents the social welfare loss relative to the first-best outcome.

The largest welfare gains occur when policies are optimally paired with a credit window offering, particularly for the LCFS. In both scenarios and for both policies it is optimal to set the policies at their most stringent level and offer compliance credits at a low price. Consistent with our theoretic results, the credit window price is set such that the implicit tax on gasoline is less than marginal damages. In particular, given the simulation parameters marginal damages from gasoline are approximately \$1.20/gal. Under the high cellulosic scenario, the optimal implicit gasoline tax is approximately \$0.19/gal and \$1.12/gal from the RFS and the LCFS, respectively.

The RFS with a credit multiplier reduces DWL over the BAU case by over \$1 billion/year. The optimal LCFS with a credit window, however, reduces DWL to \$160 - \$240 million/year. Thus, while the LCFS and RFS have similar welfare effects in all other scenarios, when paired strategically with a credit window option an LCFS nearly eliminates DWL while the optimal RFS and credit window continues to be associated with a DWL of over \$4.5 bil/year.

4.2 Market effects of fuel mandates

Table 2 presents market outcomes relative to the first-best allocation for the high cellulosic scenario. Results for the low cellulosic scenario are similar. Every policy with the exception of the LCFS with a credit window have significantly lower fuel prices (≈\$1.10/gal lower) and higher consumer surplus than the first-best. The results illustrate a key feature of fuel mandates: the policies induce transfers between producers to achieve their objectives and therefore generally dampen the price impact of the policies compared to a carbon tax or emissions tax.

Total fuel consumption is higher than the first-best equilibrium across the policies. The composition of fuel, however, varies substantially. For the policies that more closely mirror a tax on gasoline (the RFS with credit window, and LCFS with credit window), gasoline supply is close to the first-best allocation. Because both policies continue to either under-tax or subsidize renewable fuel, however, they have higher total ethanol supply than the first-best.

Gasoline producers have the highest production under the BAU and LCFS multiplier scenarios. Conventional ethanol producers have the highest production under an LCFS and an RFS with a credit window, and cellulosic producers have the highest production under the LCFS with a credit window and RFS with a multiplier.

Emissions are around 120 million metric tons (MMT) or 8% higher under BAU than the first-best policy. While all policies reduce emissions relative to BAU, most reductions with the exception of an LCFS with credit window are modest. A second-best RFS reduces emissions the least, with emissions decreasing only around 9 MMT, or 0.5 percentage points, from BAU levels. An optimal RFS with a credit window reduces emissions the second most. The largest emission reductions occur under an optimal LCFS with credit window. In this case, emissions are only slightly higher than first-best emissions despite having quite a different fuel mix.

Table 2: High Cellulosic Relative Market Outcomes*

Outcomes	**BAU**	**RFS**	**RFS Credit**	**RFS Mult.**	**LCFS**	**LCFS Credit**	**LCFS Mult.**
Fuel Price ($/gal)	-$1.11	-$1.11	-$0.97	-$1.10	-$1.10	-$0.15	-$1.10
Consumer Surplus (bil $)	$150.45	$149.81	$86.56	$149.10	$149.43	$19.65	$149.10
Quantities (bgals)							
Fuel	8.10	8.20	7.32	8.63	8.27	0.76	8.62
Gasoline	11.29	7.96	4.69	7.694	7.23	-0.95	7.68
Conventional Ethanol	-1.35	2.82	5.32	1.19	2.99	2.13	1.21
Cellulosic Ethanol	-2.05	-1.41	-1.03	0.54	-0.55	0.75	0.54
Emissions (MMT)	120.59	111.30	90.39	101.55	105.86	5.24	101.54

*Notes: BAU stands for 'Business as Usual' and corresponds to the 2010 no policy equilibrium. MMT is 'million metric tons'. All variables are phrased in levels relative to the corresponding first-best outcome.

4.3 Efficiency gains from cost containment mechanisms

The previous sections compare the relative efficiency of the policies when all parameters are set optimally. In this section we study when, for given a policy, instituting a cost containment mechanism leads to efficiency gains in the spirit of the results derived in Section 3.4.

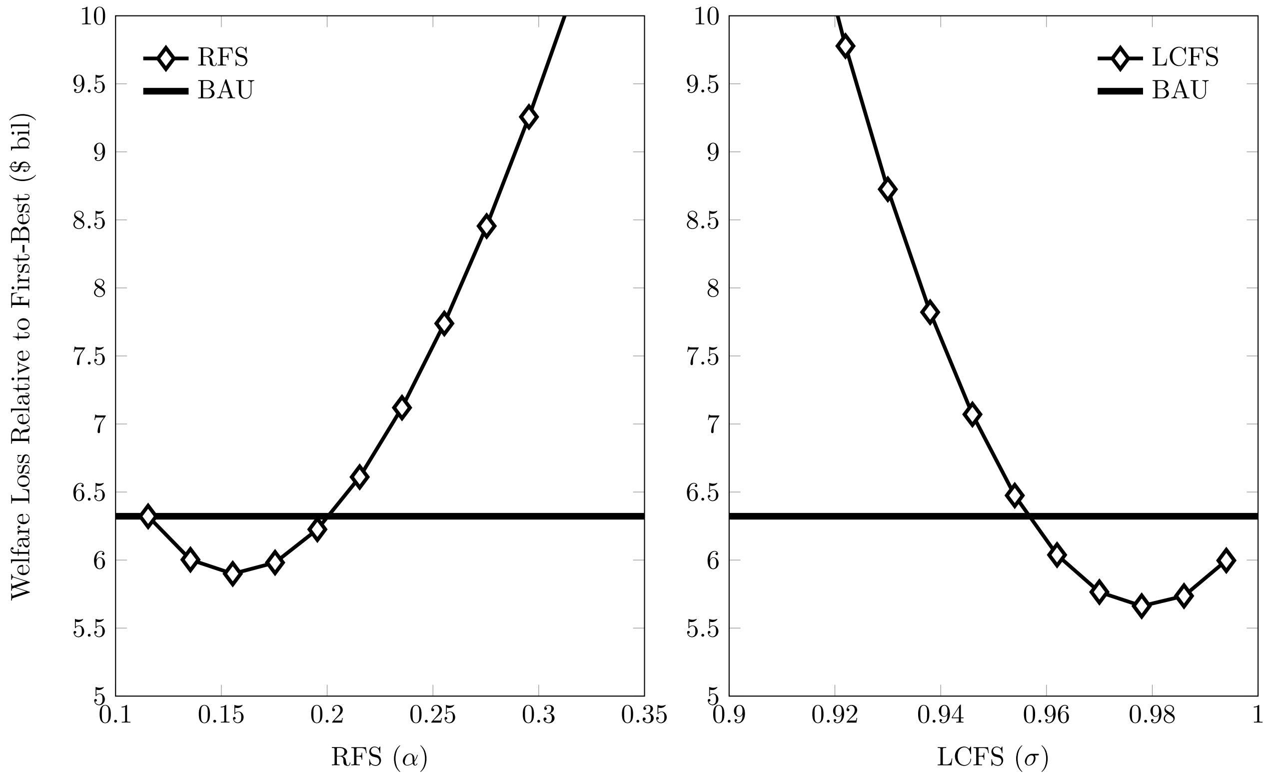
For reference, Figure 3 graphs the DWL in billion dollars on the y-axes against varying levels of the RFS and LCFS on the x-axes. The bold horizontal line corresponds to the DWL under BAU. Thus, whenever the DWL under an RFS or LCFS is higher than the DWL under BAU, the regulator would be better served by having no policy.

An optimizing regulator seeks to minimize the DWL from the policy. This corresponds to a 15% RFS or an LCFS that requires just over a 2% CI reduction.[20] DWL from the policies exceed BAU levels if the RFS mandate is higher than 20% or the LCFS requires more than a 5% average CI reduction. Losses increase sharply beyond these levels and exceed $10 bil/year as the RFS exceeds a 30% biofuel mandate or the LCFS requires more than a 8% average CI reduction.

Now consider a scenario where the policy level is fixed but the regulator has the ability to offer a credit window. Figure 4 graphs DWL on the y-axes and the price of either the RFS or LCFS compliance credit on the x-axes for three RFS and LCFS levels. As before, the bold horizontal line corresponds to the business

[20]Recall that the BAU average CI is 1 in our model. Thus the second best LCFS of $\sigma = 0.98$ corresponds to a policy requiring a $(1 - 0.98) \times 100$ % average CI reduction.

Figure 3: Deadweight Loss of Fuel Mandates

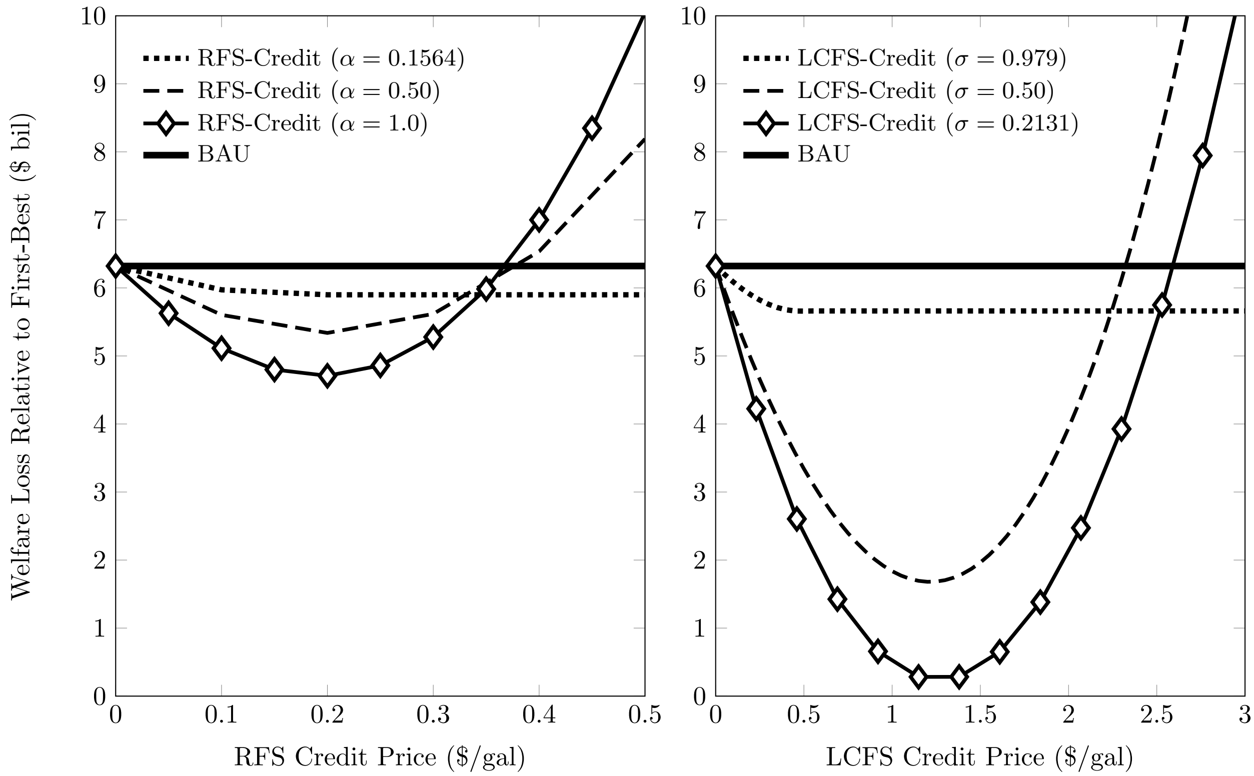


as usual DWL. Note that when credit prices are $0/gal, the policy is non-binding as parties simply collect free compliance credits.

Consider the RFS in the left graph of Figure 4. The dotted line corresponds to the second-best RFS with no cost containment provision ($\approx$ 15%), the dashed line corresponds to a more stringent biofuel mandate (50%), and the line with diamonds corresponds to the second-best RFS with credit window, a 100% mandate. For a 15% mandate, the DWL is unchanged whenever the credit price is greater than $0.10/gal because credit prices are so high that the window is non-binding and firms comply with the policy instead of purchasing credits form the window. In this case, losses are minimized when the credit price is high and firms comply with the policy. Thus, at low levels of the RFS, adding a credit window to an RFS does not generally increase welfare above BAU.

A credit window offering leads to larger efficiency gains when mandate levels are stringent. A 50% RFS with no cost containment mechanisms leads to a DWL exceeding $10 bil/year (Figure 3). With a credit window offering, setting the credit price optimally reduces DWL to $\approx$ $5 bil/year, which is lower than BAU losses. The optimal RFS-credit window corresponds to a 100% biofuel mandate and a credit price of $0.19/gal. Optimally setting both the RFS and credit window price reduces DWL to around $4.7 bil/year.

Figure 4: Deadweight Loss of Fuel Mandates with a Credit Window

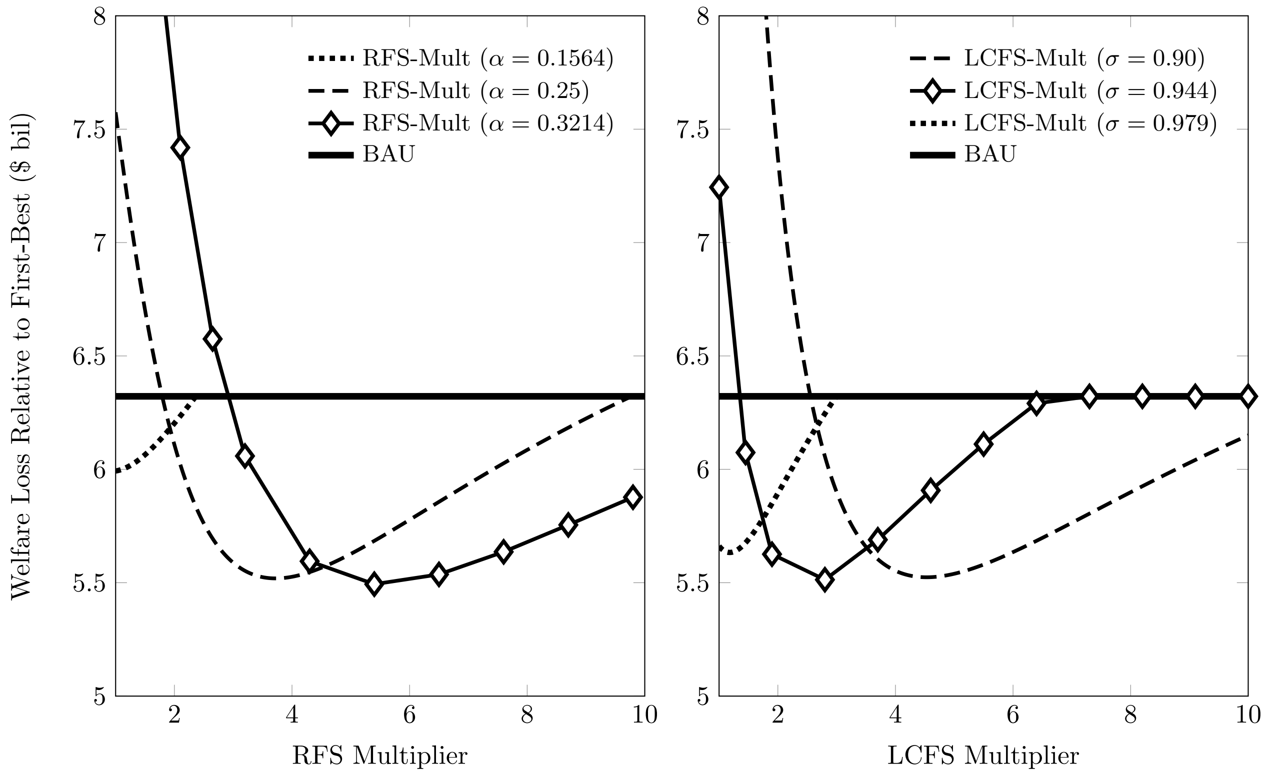


The right graph presents analogous results for three LCFS mandates. The dotted line corresponds to the second-best LCFS with a 2.10% CI reduction; the dashed lines correspond to an LCFS requiring a 50% CI reduction; and the line with diamonds corresponds to an LCFS requiring a 78.69% CI reduction. When the policy is set at low levels, the credit window does not lead to efficiency gains. Under a stringent LCFS, however, a setting credit prices at $1.35/gal leads to large efficiency gains. For a 10% CI reduction, an optimal credit window choice can reduce DWL to $2 bil/year, while setting the most stringent LCFS in combination with an optimally set credit window price nearly eliminates the DWL.

Figure 5 presents similar results for the RFS and LCFS with a cellulosic multiplier. In the left graph the dotted line corresponds to a 15% RFS mandate, the dashed line to a 25% mandate, and solid line with diamonds to a 32% mandate. In the right graph, the dotted and dashed lines correspond to an LCFS requiring a 2.10% and 10% CI reduction, respectively. The solid line with diamonds corresponds to an LCFS that requires a 5.6% CI reduction. As before, dashed lines are equal to second-best policies with no cost containment mechanisms and the lines with diamonds represent optimal policy mandates with a cellulosic multiplier. Whenever the multiplier is equal to 1, the policy constraint equals the initial constraint.

Whenever both policies are set at low levels, a cellulosic multiplier can lead to larger DWL than not having a multiplier. In both the left and right graphs, whenever the multiplier exceeds 4 the constraint

Figure 5: Deadweight Loss of Fuel Mandates with Cellulosic Multiplier



no longer binds and welfare losses correspond to the BAU scenario. When the policy is more stringent, instituting multiplier acts to relax the policy constraint and can reduce DWL. These gains, however, never reduce relative welfare losses below $5.5 bil/year.

5 Conclusion

Fuel mandates such as the RFS and LCFS are becoming increasingly popular tools for policymakers seeking to reduce carbon emissions in the energy sector. Because most renewable energy mandates rely on advances in new technologies, there is substantial compliance cost uncertainty associated with the policies. As a result, cost containment provisions, especially credit window prices, should play an important role in preventing short-run increases in compliance costs.

In this paper, we show that cost containment mechanisms can substantially increase the efficiency of fuel mandates even in the absence of uncertain compliance costs. We show there may be substantial welfare gains to setting a stringent policy with a low cap on compliance costs by establishing a compliance credit window. When both the fuel mandates and the credit window price are set optimally, the second-best policy and credit window price can substantially reduce the deadweight loss from the externality, and nearly eliminates deadweight loss under an LCFS with a credit window. Importantly, we show that the efficiency of an RFS is limited by its inability to differentiate fuels based on their relative emission intensities.

While the analysis here focuses on the transportation, particularly gasoline markets, our findings have implications for policies beyond this particular application. For example, similar renewable energy standards are commonplace in state and regional electricity markets. In general, our results hold for any market facing an intensity standard.

The work here can be extended along a number of interested avenues. For example, future research could explore: (i) the implications of a nested mandate structure within the context of the nested structure of the federal RFS; (ii) the implications of a regional LCFS nested within a federal RFS; (iii) the implications of cost and demand uncertainty; and (iv) the impact of federal CAFE standards on fuel policies such as the RFS and LCFS. In addition, the analysis could be extended to incorporate other market features and failures such as the presence of learning in the renewable energy cost structure.

The success of an intervention in compliance credit markets depends on the existence of a liquid market for credits. While the RIN credit market has been fairly developed since 2009, recent price spikes in 2013 have caused some participants to question whether the market has behaved efficiently. In addition, California's LCFS credit market has been characterized by low trade volumes and large swings in the value of the credits. If fuel mandate compliance credit markets have high transactions costs or poor price discovery, the results discussed here are not applicable. Further exploration of these issues, both analytically and empirically, would be beneficial to understanding the efficiency of these market-based polices.

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A Proofs

- **Proof of Lemma 1** The representative firm's optimality conditions for an interior solution under a binding fuel mandate are given by:

$$
\begin{aligned}
[q^c:] \quad & P = \tfrac{\partial C^c}{\partial q^c} - \lambda \tfrac{\partial \varphi(\cdot)}{\partial q^c} \\
[q^r:] \quad & P = \tfrac{\partial C^r}{\partial q^r} - \lambda \tfrac{\partial \varphi(\cdot)}{\partial q^r}.
\end{aligned}
$$

Given increasing and strictly convex cost functions, the two conditions characterize the unique equilibrium for both fuel mandates. Equating the two optimality conditions:

$$
\begin{aligned}
[\text{RFS:}] \quad & \lambda = \frac{\frac{\partial C^r}{\partial q^r} - \frac{\partial C^c}{\partial q^c}}{1+\alpha} \\
[\text{LCFS:}] \quad & \lambda = \frac{\frac{\partial C^r}{\partial q^r} - \frac{\partial C^c}{\partial q^c}}{\phi^c - \phi^r}.
\end{aligned}
$$

Substituting the expression for λ into either yields:

$$
[\text{RFS:}] \qquad P = \tfrac{1}{1+\alpha} \tfrac{\partial C^c}{\partial q^c} + \tfrac{\alpha}{1+\alpha} \tfrac{\partial C^r}{\partial q^r}
$$

$$
[\text{LCFS:}] \quad P = \tfrac{\sigma - \phi^r}{\phi^c - \phi^r} \tfrac{\partial C^c}{\partial q^c} + \tfrac{\phi^c - \sigma}{\phi^c - \phi^r} \tfrac{\partial C^r}{\partial q^r}.
$$

Thus, the final fuel price is equal to the weighted average of the marginal costs of each fuel, where the weights correspond to the share of each fuel required to meet the respective standard.

- **Proof of Lemma 2**

An individual firm's maximization problem is equivalent to the representative firm's problem, however, each firm has the additional option of purchasing compliance credits, x_i, from other firms. Thus, the firms' policy constraints are:

$$
\begin{aligned}
[\text{RFS:}] \quad & \varphi_i(q_i^c, q_i^r, x_i; \theta) = q_i^r + x_i - \alpha q_i^c \geq 0 \\
[\text{LCFS:}] \quad & \varphi_i(q_i^c, q_i^r, x_i; \theta) = (\sigma - \phi^c) q_i^c + (\sigma - \phi^r) q_i^r + x_i \geq 0.
\end{aligned}
$$

A firm purchases credits whenever $x_i > 0$ and sells credits whenever $x_i < 0$. Each firm's problem under a renewable fuel mandate is:

$$
\max_{q_i^c, q_i^r \geq 0; x_i^c} P(q_i^c + q_i^r) - C_i^c(q_i^c) - C_i^r(q_i^r) - p^{\text{cred}} x_i + \lambda_i \left[\varphi_i(q_i^c, q_i^r, x_i; \theta) \right],
$$

where p^{cred} is the market clearing compliance credit price. The optimality conditions are:

$$
\begin{aligned}
[q_i^c:] \quad & P - \tfrac{\partial C_i^c}{\partial q_i^c} + \lambda_i \tfrac{\partial \varphi_i(\cdot)}{\partial q_i^c} \leq 0 \\
[q_i^r:] \quad & P - \tfrac{\partial C_i^r}{\partial q_i^r} + \lambda_i \tfrac{\partial \varphi_i(\cdot)}{\partial q_i^r} \leq 0 \\
[x_i:] \quad & \lambda_i - p^{\text{cred}} = 0 \\
& \lambda_i \left[\varphi_i(q_i^c, q_i^r, x_i; \theta) \right] = 0.
\end{aligned}
$$

The third condition proves conjecture i and ii, and relies on the existence of a competitive, frictionless compliance credit market.

To see iii, consider the value function for the representative firm:

$$V(q^{c*}, q^{r*}) = P(q^{c*} + q^{r*}) - C^c(q^{c*}) - C^r(q^{r*}) + \lambda\left[\varphi(q^{c*}, q^{r*}, \theta)\right],$$

The Envelope Theorem implies the marginal value of increasing each mandate is $\frac{\partial V(q^c,q^r)}{\partial \alpha} = -\lambda q^c$ for the RFS and $\frac{\partial V(q^c,q^r)}{\partial \sigma} = \lambda Q$ for the LCFS. The difference in signs is due to the different interpretation of each policy variable. For the RFS, as α increases the mandated share of renewable fuel increases and the policy becomes more stringent. For the LCFS, as σ increases, the average carbon intensity requirement on fuels increases and the policy becomes less stringent.

- **Proof of Proposition 1:**

Taking the total differential of equations (1), (2), and the policy constraint yields:

$$\underbrace{\begin{bmatrix} \frac{\partial P}{\partial Q} - \frac{\partial^2 C^c}{\partial q^c \partial q^c} & \frac{\partial P}{\partial Q} & \frac{\partial \varphi(\cdot)}{\partial q^c} \\ \frac{\partial P}{\partial Q} & \frac{\partial P}{\partial Q} - \frac{\partial^2 C^r}{\partial q^r \partial q^r} & \frac{\partial \varphi(\cdot)}{\partial q^r} \\ \frac{\partial \varphi(\cdot)}{\partial q^c} & \frac{\partial \varphi(\cdot)}{\partial q^r} & 0 \end{bmatrix}}_{=H} \begin{bmatrix} dq^c \\ dq^r \\ d\lambda \end{bmatrix} = \underbrace{\begin{bmatrix} -\lambda \frac{\partial^2 \varphi(\cdot)}{\partial q^c \partial \theta} \\ -\lambda \frac{\partial^2 \varphi(\cdot)}{\partial q^r \partial \theta} \\ -\frac{\partial \varphi(\cdot)}{\partial \theta} \end{bmatrix}}_{=D} d\theta.$$

Let η^d denote the price elasticity of demand for fuel and ξ^i denote the price elasticity of supply for $i = c, r$. Substituting $\frac{\partial P}{\partial Q} = \frac{1}{\eta^d}\frac{P}{Q}$, and $\frac{\partial^2 C^i}{\partial q^i \partial q^i} = \frac{1}{\xi^i}\frac{P}{q^i}$ for $i = c, r$:

$$\underbrace{\begin{bmatrix} \frac{1}{\eta^d}\frac{P}{Q} - \frac{1}{\xi^c}\frac{p}{q^c} & \frac{1}{\eta^d}\frac{P}{Q} & \frac{\partial \varphi(\cdot)}{\partial q^c} \\ \frac{1}{\eta^d}\frac{P}{Q} & \frac{1}{\eta^d}\frac{P}{Q} - \frac{1}{\xi^r}\frac{P}{q^r} & \frac{\partial \varphi(\cdot)}{\partial q^r} \\ \frac{\partial \varphi(\cdot)}{\partial q^c} & \frac{\partial \varphi(\cdot)}{\partial q^r} & 0 \end{bmatrix}}_{=H} \begin{bmatrix} dq^c \\ dq^r \\ d\lambda \end{bmatrix} = \underbrace{\begin{bmatrix} -\lambda \frac{\partial^2 \varphi(\cdot)}{\partial q^c \partial \theta} \\ -\lambda \frac{\partial^2 \varphi(\cdot)}{\partial q^r \partial \theta} \\ -\frac{\partial \varphi(\cdot)}{\partial \theta} \end{bmatrix}}_{=D} d\theta.$$

The matrix H is the bordered Hessian and is negative semi-definite by concavity of the objective function. We can solve for $\frac{dx}{d\theta}$ for $x \in \{q^c, q^r\}$ using Cramer's rule:

$$\frac{dx}{d\theta} = \frac{\det(H^i)}{\det(H)},$$

where H is the bordered Hessian and $H^i(\cdot)$ is the matrix H with the ith column replaced with column D. Note that $\det(H) > 0$ for both policies.[21] Thus, the signs of the effects on each variable are determined by $\operatorname{sign}\left(\det(H^i)\right)$.

Solving for the RFS yields:

$$\frac{dq^c}{d\alpha} = \left(\frac{P}{\eta^d} - \frac{P}{\xi^r} - \lambda\right)\det(H)^{-1} < 0$$

$$\frac{dq^r}{d\alpha} = \left(\frac{P}{\xi^c} - \frac{P}{\eta^d} - \alpha\lambda\right)\det(H)^{-1}.$$

[21] To confirm this, note that $\det(H) = \frac{1}{\xi^c}\frac{P}{q^c} - \frac{1}{\eta^d}\frac{P}{Q} + \alpha^2\left(\frac{1}{\xi^r}\frac{P}{q^r} - \frac{1}{\eta^d}\frac{P}{Q}\right) - 2\alpha\frac{1}{\eta^d}\frac{P}{Q} > 0$ for the RFS and $\det(H) = (\sigma - \phi^c)^2\left(\frac{1}{\xi^r}\frac{P}{q^r} - \frac{1}{\eta^d}\frac{P}{Q}\right) + (\sigma - \phi^r)^2\left(\frac{1}{\xi^c}\frac{P}{q^c} - \frac{1}{\eta^d}\frac{P}{Q}\right) + 2(\sigma - \phi^c)(\sigma - \phi^r)\frac{1}{\eta^d}\frac{P}{Q} > 0$ for the LCFS.

Considering the price effect:

$$\frac{dP}{d\alpha} = \frac{\partial P}{\partial Q}\left(\frac{dq^c}{d\alpha} + \frac{dq^r}{d\alpha}\right)$$
$$= \frac{1}{\eta^d}\frac{P}{Q}\frac{dQ}{d\alpha}.$$

Solving for the LCFS yields:

$$\frac{dq^c}{d\sigma} = \left((\phi^c - \phi^r)\left(\frac{P}{\xi^r} - \frac{P}{\eta^d}\right) + (\sigma - \phi^r)(\phi^c - \phi^r)\lambda\right)\det(H)^{-1} > 0$$
$$\frac{dq^r}{d\sigma} = \left((\phi^c - \phi^r)\left(\frac{P}{\eta^d} - \frac{P}{\xi^c}\right) + (\phi^c - \sigma)(\phi^c - \phi^r)\lambda\right)\det(H)^{-1}.$$

with fuel price effects:

$$\frac{dP}{d\sigma} = \frac{1}{\eta^d}\frac{P}{Q}\frac{dQ}{d\sigma}.$$

- **Proof of Proposition 2:**

  Taking the total differential of equations (1), (2), and the policy constraint as previously yields:

$$\underbrace{\begin{bmatrix} \frac{1}{\eta^d}\frac{P}{Q} - \frac{1}{\xi^c}\frac{P}{q^c} & \frac{1}{\eta^d}\frac{P}{Q} & 0 \\ \frac{1}{\eta^d}\frac{P}{Q} & \frac{1}{\eta^d}\frac{P}{Q} - \frac{1}{\xi^r}\frac{P}{q^r} & 0 \\ \frac{\partial\varphi(\cdot)}{\partial q^c} & \frac{\partial\varphi(\cdot)}{\partial q^r} & 1 \end{bmatrix}}_{=H} \begin{bmatrix} dq^c \\ dq^r \\ dc \end{bmatrix} = \underbrace{\begin{bmatrix} -\frac{\partial\varphi(\cdot)}{\partial q^c} \\ -\frac{\partial\varphi(\cdot)}{\partial q^r} \\ 0 \end{bmatrix}}_{=D} d\overline{p}^{\text{cred}}.$$

  We can derive the comparative statics using Cramer's rule. For the RFS, this yields:

$$\frac{dq^c}{d\overline{p}^{\text{cred}}} = \left(\frac{1}{\eta^d}\frac{P}{Q} + \alpha\left(\frac{1}{\eta^d}\frac{P}{Q} - \frac{1}{\xi^r}\frac{P}{q^r}\right)\right)\det(H)^{-1} < 0$$
$$\frac{dq^r}{d\overline{p}^{\text{cred}}} = \left(\frac{1}{\eta^c}\frac{P}{q^c} - (1+\alpha)\frac{1}{\eta^d}\frac{P}{Q}\right)\det(H)^{-1} > 0$$
$$\frac{dc}{d\overline{p}^{\text{cred}}} = \left(\alpha^2\left(\frac{1}{\eta^d}\frac{P}{Q} - \frac{1}{\xi^r}\frac{P}{q^r}\right) + \frac{1}{\eta^d}\frac{P}{Q} - \frac{1}{\xi^c}\frac{P}{q^c} + 2\alpha\frac{1}{\eta^d}\frac{P}{Q}\right)\det(H)^{-1} < 0.$$

  Price effects are the same as Proposition 1.

  Next consider the LCFS:

$$\frac{dq^c}{d\overline{p}^{\text{cred}}} = \left((\phi^c - \sigma)\left(\frac{1}{\eta^d}\frac{P}{Q} - \frac{1}{\xi^r}\frac{P}{q^r}\right) + (\sigma - \phi^r)\frac{1}{\eta^d}\frac{P}{Q}\right)\det(H)^{-1} < 0$$
$$\frac{dq^r}{d\overline{p}^{\text{cred}}} = \left((\sigma - \phi^r)\left(\frac{1}{\xi^c}\frac{P}{q^c} - \frac{1}{\eta^d}\frac{P}{Q}\right) - (\phi^c - \sigma)\frac{1}{\eta^d}\frac{P}{Q}\right)\det(H)^{-1} > 0$$
$$\frac{dc}{d\overline{p}^{\text{cred}}} = \left((\phi^c - \sigma)^2\left(\frac{1}{\eta^d}\frac{P}{Q} - \frac{1}{\xi^r}\frac{P}{q^r}\right) + (\sigma - \phi^r)^2\left(\frac{1}{\eta^d}\frac{P}{Q} - \frac{1}{\xi^c}\frac{P}{q^c}\right) + 2(\phi^c - \sigma)(\sigma - \phi^c)\frac{1}{\eta^d}\frac{P}{Q}\right)\det(H)^{-1} < 0.$$

- **Proof of Proposition 3:**

  Note that we can write the renewable fuel multiplier under the RFS as

$$\frac{\gamma q^r}{q^c} = \frac{(1+\nu)q^r}{q^c} \geq \alpha,$$

  where $\gamma = 1+\nu$. Rearranging yields:

$$\frac{q^r}{q^c} \geq \left(\alpha - \nu\frac{q^r}{q^c}\right).$$

  Increasing the multiplier for $\gamma > 1$ is equivalent to reducing α by $\nu\frac{q^r}{q^c}$. A similar argument follows for the LCFS.

- **Proof of Proposition 4:**

  Let $\theta = \{\alpha, \sigma\}$ denote the policy. The government's problem is given by:

$$\max_{0\leq\alpha\leq 1} \int_0^Q P(x)dx - C^c(q^c) - C^r(q^r) - D(\phi^c q^c + \phi^r q^r).$$

  The optimality conditions for a interior solution are given by:

$$\left(P - \frac{\partial C^c}{\partial q^c} - \phi^c\frac{\partial D}{\partial q}\right)\frac{dq^c}{d\theta} + \left(P - \frac{\partial C^r}{\partial q^r} - \phi^r\frac{\partial D}{\partial q}\right)\frac{dq^r}{d\theta} = 0.$$

  First consider the RFS. Substituting the firm's optimality conditions for an RFS:

$$\underbrace{[\alpha\lambda - \phi^c\frac{\partial D}{\partial q}]}_{?}\underbrace{\frac{dq^c}{d\alpha}}_{<0} = \underbrace{[\lambda + \phi^r\frac{\partial D}{\partial q}]}_{>0}\underbrace{\frac{dq^r}{d\alpha}}_{?}.$$

  If $\frac{dq^r}{d\alpha} > 0$ the condition is satisfied only if $\alpha\lambda < \phi^c\frac{\partial D}{\partial q}$ and the opposite holds if $\frac{dq^r}{d\alpha} < 0$.
  The optimality condition for an LCFS is given by:

$$\underbrace{\left[(\phi^c - \sigma)\lambda - \phi^c\frac{\partial D}{\partial q}\right]}_{?}\underbrace{\frac{dq^c}{d\sigma}}_{>0} = \underbrace{\left[(\sigma - \phi^r)\lambda + \phi^r\frac{\partial D}{\partial q}\right]}_{>0}\underbrace{\frac{dq^r}{d\sigma}}_{?}.$$

  If $\frac{dq^r}{d\alpha} > 0$ the condition is satisfied so long as $(\phi^c - \sigma)\lambda < \phi^c\frac{\partial D}{\partial q}$, while the opposite holds if $\frac{dq^r}{d\alpha} < 0$.

- **Proof of Proposition 5:**

  The regulator's problem is given by:

$$\max_{\bar{p}^{\text{cred}}|\theta} \int_0^Q P(x|\theta)dx - C^c(q^c|\theta) - C^r(q^r|\theta) - D(\phi^c q^c + \phi^r q^r).$$

  The optimality condition for an interior solution are given by:

$$\left(P(Q) - \frac{\partial C^c}{\partial q^c} - \phi^c\frac{\partial D}{\partial q}\right)\frac{dq^c}{d\bar{p}^{\text{cred}}} + \left(P(Q) - \frac{\partial C^r}{\partial q^r} - \phi^r\frac{\partial D}{\partial q}\right)\frac{dq^r}{d\bar{p}^{\text{cred}}} = 0.$$

First consider an RFS.

$$\underbrace{[\alpha\bar{p}^{\text{cred}} - \phi^c\frac{\partial D}{\partial q}]}_{?}\underbrace{\frac{dq^c}{d\bar{p}^{\text{cred}}}}_{<0} = \underbrace{[\bar{p}^{\text{cred}} + \phi^r\frac{\partial D}{\partial q}]}_{>0}\underbrace{\frac{dq^r}{d\alpha}}_{>0}.$$

Thus, a necessary condition is $\phi^c\frac{\partial D}{\partial q} > \alpha\lambda$ in the optimum.

Using similar arguments as before, it can be shown that a necessary condition for a conditionally optimal credit price is equal to $\phi^c\frac{\partial D}{\partial q^c} > (\phi^c - \sigma)\lambda$ in an optimal solution.

- **Proof of Corollary 1:**

The conditions for an interior first-best policy are:

$$p = \frac{\partial C^i}{\partial q^i} + \phi^i\frac{\partial D}{\partial q}$$

for $i = c, r$. Comparing this with the firm's optimality conditions under an RFS, no combination of α and $\bar{p}$ is able to replicate the first-best optimality conditions. Under an LCFS, however, setting $\sigma = 0$ and $\bar{p} = \frac{\partial D}{\partial q}$ replicates the first-best optimality conditions.

- **Proof of Proposition 6:**

The regulator's problem is given by:

$$\max_{\gamma|\theta}\int_0^Q P(x|\theta)dx - C^c(q^c|\theta) - C^r(q^r|\theta) - D(\phi^c q^c + \phi^r q^r).$$

The optimality condition for an interior solution under an RFS are:

$$\underbrace{\left(\alpha\lambda - \phi^c\frac{\partial D}{\partial q}\right)}_{?}\underbrace{\frac{dq^c}{d\gamma}}_{>0} = \underbrace{\left(\gamma\lambda + \phi^r\frac{\partial D}{\partial q}\right)}_{>0}\underbrace{\frac{dq^r}{d\gamma}}_{?}.$$

If $\frac{dq^r}{d\gamma} < 0$, it must be the case that $\alpha\lambda < \frac{\partial D}{\partial q^c}$. If $\frac{dq^r}{d\gamma} > 0$, then it must be the case that $\alpha\lambda > \frac{\partial D}{\partial q^c}$.

The optimality condition for an interior solution under an LCFS are:

$$\underbrace{\left((\phi^c - \sigma)\lambda - \frac{\partial D}{\partial q^c}\right)}_{?}\underbrace{\frac{dq^c}{d\gamma}}_{>0} = \underbrace{\left((\sigma - \phi^r)\gamma\lambda + \frac{\partial D}{\partial q^r}\right)}_{>0}\underbrace{\frac{dq^r}{d\gamma}}_{?} > 0.$$

If $\frac{dq^r}{d\gamma} < 0$, it must be the case that $\lambda(\phi^c - \sigma) < \frac{\partial D}{\partial q^c}$. If $\frac{dq^r}{d\gamma} > 0$, then it must be the case that $\lambda(\phi^c - \sigma) > \frac{\partial D}{\partial q^c}$.

- **Proof of Corollary 2:**

The conditions for an interior first-best policy are:

$$p = \frac{\partial C^i}{\partial q^i} + \frac{\partial D}{\partial q^i}$$

for $i = c, r$. Comparing this with the firm's optimality conditions under an RFS and LCFS, no combination of θ and γ is able to replicate the first-best optimality conditions.

B Simulation Details

Table B.1 presents the parameters used for the simulation model. All supply and demand curves are assumed to have constant elasticity. The elasticity of demand is set to reflect recent estimates in the literature (Hughes et al., 2012; Coyle et al., 2012). Baseline fuel prices as well as gasoline and ethanol production levels are set to be similar to those observed in 2010 (EIA, 2012a).

Supply elasticities for gasoline and conventional ethanol are set to reflect medium to long-run elasticities. Estimates of fuel supply elasticities reflect short run inelastic supply with highly elastic long-run supply (Dahl and Duggan, 1996; Coyle et al., 2012; Luchansky and Monks, 2009; Lee and Sumner, 2010). Most fuel mandates phase in over time, and do not reach steady state mandate levels for a decade or more. Given the static nature of the model, we seek to capture the medium to long-run efficient policies and thus choose mid-range supply elasticities to reflect this. Results are not sensitive to the assumed supply elasticities.

The supply elasticity and baseline values for cellulosic ethanol are set to reflect two scenarios, one in which cellulosic ethanol is more readily available with a higher supply elasticity and another with low initial production and in which supply is relatively capacity constrained. In the former, we set the initial production of cellulosic ethanol at 2 bgals with a supply elasticity of 3. In the latter, we assume initial production is 0.5 bgals with a supply elasticity of 0.5.

Carbon intensity values are set to be similar to the assigned values from the California Air Resources Board (ARB). Gasoline, ethanol and cellulosic ethanol are assigned a carbon carbon intensity value of 100, 85, and 30 gCO_2/MJ, respectively (California ARB, 2015).

The policy constraints are equivalent to those used in Section 3, with the exception that they include cellulosic ethanol in the constraints as well. Thus, the constraints with no cost containment mechanism are given by:

$$\text{[RFS:]} \qquad q^{\text{ETH}} + q^{\text{CEL}} - \alpha q^{\text{GAS}} \geq 0$$

$$\text{[LCFS:]} \qquad (\sigma - \phi^{\text{GAS}})q^{\text{GAS}} + (\sigma - \phi^{\text{ETH}})q^{\text{ETH}} + (\sigma - \phi^{\text{CEL}})q^{\text{CEL}} \geq 0,$$

where α is the RFS constraint, σ is the LCFS constraint, 'GAS' denotes gasoline, 'ETH' denotes corn ethanol, and 'CEL' denotes cellulosic ethanol.

We allow the RFS to range from the initial share of biofuel, S_0 in Table B.1, to 100% biofuel. The initial share varies depending on the assumed availability of cellulosic ethanol.

We normalize the LCFS constraint so that the carbon intensity of fuel in the no policy equilibrium is equal to 1. This value varies depending on the initial availability of cellulosic ethanol. In setting the constraint this way, $(1 - \sigma) * 100$ represents the percentage reduction in the carbon intensity of fuels relative to the baseline carbon intensity required by the policy. In addition, the Lagrange Multiplier on the policy constraint is denominated in \$/gal under the normalization, allowing for easy comparison with the RFS shadow value. We allow the constraint to range from the 1 to the carbon intensity of cellulosic ethanol. Thus, the policymaker cannot set an infeasible policy level, and the strictest policy that can be set would require all fuel to be derived from cellulosic ethanol.

The credit window price ranges from free to \$5/gal. Free credits are equivalent to a non-binding policy. Whenever compliance credits are available, the policy constraints are given by:

$$\begin{aligned} &[\text{RFS:}] && q^{\text{ETH}} + q^{\text{CEL}} + c - \alpha q^{\text{GAS}} \geq 0 \\ &[\text{LCFS:}] && (\sigma - \phi^{\text{GAS}})q^{\text{GAS}} + (\sigma - \phi^{\text{ETH}})q^{\text{ETH}} + (\sigma - \phi^{\text{CEL}})q^{\text{CEL}} + c \geq 0. \end{aligned}$$

We have explored allowing for higher credit prices, and credit prices above \$5/gal always results in lower welfare for both policies.

We allow the cellulosic ethanol multiplier, γ, to range between 1 and 10. Results do not change using higher values of the multiplier. The policy constraints with a cellulosic ethanol multiplier are given by:

$$\begin{aligned} &[\text{RFS:}] && q^{\text{ETH}} + \gamma q^{\text{CEL}} - \alpha q^{\text{GAS}} \geq 0 \\ &[\text{LCFS:}] && (\sigma - \phi^{\text{GAS}})q^{\text{GAS}} + (\sigma - \phi^{\text{ETH}})q^{\text{ETH}} + (\sigma - \phi^{\text{CEL}})\gamma q^{\text{CEL}} \geq 0. \end{aligned}$$

For a given policy, we solve for market clearing prices and quantities using the simulation model developed in Lade and Lin (2013). We solve for the optimal policy and cost containment levels using a fine grid search to solve for the social welfare maximizing policies.

Table B.1: Numerical Simulation Parameters*

Market Parameters	
Fuel Demand Elasticity	0.2
Gas Supply Elasticity	3
Conventional Ethanol Supply Elasticity	3
Cellulosic Ethanol Elasticity	{0.5, 3}
Marginal Damages ($/ton CO_2)	100
Gasoline Carbon Intensity (gCO_2/MJ)	100
Conventional Ethanol Carbon Intensity (gCO_2/MJ)	85
Cellulosic Ethanol Carbon Intensity (gCO_2/MJ)	30
Baseline Fuel Price ($/gal)	2.835
Baseline Gasoline Production (bgal)	130
Baseline Conventional Ethanol Production (bgal)	13
Baseline Cellulosic Ethanol Production (bgal)	{0.5, 2}
Policy Parameters	
LCFS Constraint (gCO_2/MJ)	[30,100]
RFS Constraint (%)	[S_0, 100]
Credit Window Price ($/gal)	[0,5]
Cellulosic Multiplier	[1,10]

*Notes: S_0 is the initial share of biofuel, which differs across the low and high cellulosic scenario.