The Design of Renewable Fuel Policies and Cost Containment Mechanisms*

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

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Abstract

Renewable fuel mandates are popular policy mechanisms to reduce greenhouse gas emissions from transportation fuels. We study the effects and efficiency of two policies, a renewable share mandate and a carbon intensity standard, with and without a cost containment mechanism. Using both a theory model of a regulated fuel industry and a numerical model of the U.S. fuel market, we show that an optimally set mandate leads to only modest welfare gains over business as usual. However, the efficiency of both policies substantially increases when combined optimally with a cost containment mechanism.

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†Corresponding author. Department of Economics and the Center for Agricultural and Rural Development, Iowa State University; gelade@iastate.edu.

‡Department of Agricultural and Resource Economics, University of California at Davis; cclin@primal.ucdavis.edu.

1 Introduction

The transportation sector is responsible for over a quarter of U.S. greenhouse gas emissions, the majority of which result from fossil fuel combustion. Politicians and regulatory agencies in the U.S. have passed or considered a suite of policies to decrease emissions in the sector, including carbon taxes, fuel economy standards, renewable fuel mandates, and regional or federal emissions trading programs. If unpriced emissions are the sole market failure, a carbon tax or emissions trading program can achieve the first-best market allocation (Pigou, 1920; Coase, 1960), while renewable fuel mandates are strictly second-best (Helfand, 1992; Holland et al., 2009; Lapan and Moschini, 2012). Despite this, policymakers typically favor renewable fuel mandates to reduce transportation fuel emissions.[1]

The most prominent fuel mandates in the U.S. 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. To comply with renewable fuel mandates, both upstream firms and downstream consumers must invest in new technologies. For example, the RFS requires 36 billion gallons (bgals) of ethanol to be blended into the U.S. fuel supply each year by 2022, of which 16 billion gallons must be biofuel derived from cellulosic feedstocks. Meeting these targets will require tremendous investments in the research and development, commercialization, and production of cellulosic biofuels. In addition, consumers must purchase millions of vehicles capable of using high-ethanol blend fuels.

Delays in the development and deployment of new technologies when binding mandates exist for their use may lead to situations with high short-run compliance costs. The problem compounds if compliance credits are bankable, in which case the anticipation of high future compliance costs may lead to significant increases in credit prices in the present. This situation has already borne out under the RFS. In 2013, the fuel industry anticipated that the statutory mandates would become increasingly difficult to meet beyond 2014. This caused RFS compliance credit prices to increase from \$0.10/gal to \$1.40/gal over the course of only a few months. The large and sudden increase in compliance costs set off a prolonged period of regulatory uncertainty and delay as the EPA considered how to best address these challenges, and eventually led to the Agency relaxing the mandates (Lade et al., 2017).

In this paper, we study the market effects of and efficiency gains from including cost containment mechanisms in renewable fuel mandates. To this end, we formalize, expand upon, and synthesize the previous literature studying renewable fuel mandates by developing a model of mandates under perfect competition that incorporates both a renewable share mandate and a carbon intensity standard, both with and without a cost containment mechanism. The extant literature has traditionally considered cost containment mechanisms as tools for increasing program efficiency and decreasing compliance cost uncertainty (Newell et al.,

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

2005; Nemet, 2010; Fell et al., 2012; Fell, 2016). In contrast, we show that cost containment mechanisms may substantially increase the efficiency of a policy even in settings with no uncertainty. In particular, 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 limiting deadweight loss. If both the mandate and cost containment mechanism are set optimally, the efficiency of the policy increases substantially over optimally setting the fuel mandates alone. In a limiting case, an LCFS with an optimal cost containment mechanism can achieve the first-best outcome. Using a numerical model of the U.S. gasoline market, we show that the efficiency gains from strategically including a credit window offering with a fuel mandate are economically significant.

This work builds on an extensive literature studying fuel mandates, environmental policy design, and cost containment mechanisms. A number of authors have studied the market effects of carbon intensity standards and renewable fuel mandates (de Gorter and Just, 2009; Holland et al., 2009; Lapan and Moschini, 2012). Others have built on this work, comparing the relative performance of fuel mandates to more traditional policy instruments such as carbon taxes (Holland et al., 2013, 2014; Chen et al., 2014); studying 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 examining ways policymakers can increase the efficiency fuel mandates through strategic policy choices (Lemoine, 2016).[2]

Our work also builds on the literature studying the effects and efficiency of hybrid price-quantity policies. Roberts and Spence (1976) first proposed pairing a fixed non-compliance penalty and abatement subsidy with a tradeable credit policy to bound compliance costs and reduce the expected social cost of a policy when costs and benefits are uncertain. A large literature has subsequently studied similar proposals, primarily in the context of emission trading programs (e.g., Pizer (2002); Newell et al. (2005); Burtraw et al. (2010); Fell and Morgenstern (2010)). In addition, it has been shown in the previous literature that a rate-based standard can achieve the first-best if it is coupled with an emissions tax (Holland et al., 2009) or a consumption tax (Holland, 2012); we build on this work by analyzing if one can improve the efficiency of renewable fuel mandates, including volumetric standards, by coupling the mandate with a cost containment mechanism.

Renewable energy mandates for new technologies exist in contexts other than the transportation fuel sector as well. Many states have ambitious renewable portfolio standards that require significant investments in renewable electricity generation. Thus, to the extent that similar capacity constraints exist in these contexts, the findings here have implications for the efficient design of renewable energy policies more broadly.

The paper proceeds as follows. Section 2.1 provides a brief background on the Renewable Fuel Standard and the Low Carbon Fuel Standard, 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, analyzes

[2]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).

the effects of renewable fuel mandates and a cost containment mechanism on important market outcomes, and derives the second-best policies with and without cost containment. Section 4 presents our numerical model, expanding upon the model in Section 3 along several important dimensions. Section 5 concludes.

2 Renewable Fuel Mandates

We begin by discussing the regulatory background for both the Renewable Fuel Standard and various Low Carbon Fuel Standards. We also discuss important design elements of each policy, focusing on the use and importance of tradeable compliance credits. We then discuss a number of important implementation challenges facing each policy.

2.1 Regulatory Background and Design

The Renewable Fuel Standard (RFS) was created by the Energy Policy Act of 2005 and expanded under the Energy Independence and Security Act of 2007, creating the RFS2. The policy is administered by the Environmental Protection Agency (EPA) and sets ambitious targets for renewable fuel consumption in the U.S., with the goal of expanding biofuel use to 36 billion gallons (bgal) per year by 2022, approximately a 25% biofuel-blending mandate. The RFS2 specifies sub-mandates for certain biofuels including: (1) cellulosic biofuel; (2) biomass-based diesel; and (3) advanced biofuel.[3] For example, the 2016 mandates require that 18.11 bgals of biofuel be blended into the U.S. fuel supply, of which 3.61 bgals must be advanced biofuel. Of the advanced biofuel mandate, 1.9 bgals must be biodiesel and 230 mgals must be cellulosic biofuel.

Executive Order S-01-07 created California's Low Carbon Fuel Standard (LCFS) in 2007, and the policy has been in effect since 2011. The standard is administered by the California Air Resources Board (ARB) and requires a 10% reduction in the average carbon intensity of fuels sold in the state by 2020. Unlike the RFS, the LCFS is agnostic as to the fuels that can be used to meet the standard so long as the ARB approves all production pathways and assigns fuels a carbon intensity (CI) value.[4] For example, providers of electricity for plug-in vehicles and hydrogen fuel producers may generate credits under the LCFS (California ARB, 2015). While California's LCFS is the largest intensity standard for transportation fuels, British Columbia and Oregon have similar policies in place, and Washington and the European Union have proposed instituting low carbon fuel standards (British Columbia Ministry of Energy and Mines, 2014; Oregon Department of Environmental Quality, 2016; Pont et al., 2014; European Commission, 2014).

[3] Cellulosic biofuels are fuels produced from non-edible biomass such as corn stover or switchgrass. Biomass-based diesel is produced mostly from animal fats or vegetable oils such as soybean oil. Biofuels qualify as 'advanced' if their lifecycle greenhouse gas production emissions are below a threshold set by the EPA.

[4] Carbon intensity (CI) values represent the ARB's estimate of the carbon equivalent emissions rate of a given fuel's life-cycle production process.

Both the RFS and LCFS are enforced using tradeable compliance credits. Obligated parties, primarily upstream gasoline and diesel refiners, generate deficits in proportion to their fuel sales while qualifying renewable fuel producers generate credits. 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 U.S. fuel supply, the RIN is 'detached' from the fuel and able to be sold to obligated parties. RINs are differentiated by vintage year and fuel type to enforce banking restrictions and ensure the mandate for each biofuel category is met.

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 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 fuel producers, producing or blending renewable fuels themselves, or lowering the carbon intensity of their fuel by changing their production pathways.

2.2 Implementation challenges and cost containment mechanisms

The future success of both policies faces a number of challenges. The two most notable issues 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 blending ethanol beyond a 10% rate in gasoline is costly. Ethanol has historically been blended at two levels: E10, fuel containing 10% ethanol; and E85, fuel containing 65%-85% ethanol. Vehicle owners must own flex-fuel vehicles (FFVs) to fuel with E85, and gasoline station owners must invest in fueling infrastructure to offer the fuel. While many FFVs have been produced in the U.S., they are not located in regions with the highest density of E85 stations due to unintended consequences from incentives for FFVs under U.S. fuel economy standards (Anderson and Sallee, 2011; Pouliot and Babcock, 2014). Increasing biofuel consumption beyond the blend wall in the near term requires either expanding E85 use 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.

Before 2013, the primary biofuel used to for compliance towards both the RFS and LCFS was ethanol derived from corn (Environmental Protection Agency, 2013a; Yeh et al., 2013). However, the success of both the RFS2 and LCFS in coming years depends crucially on the development of advanced alternative fuels such as cellulosic biofuel. As of early 2015, cellulosic production was far below the original RFS2 mandates (Energy Information Agency, 2012b). In addition, Yeh et al. (2013) found that California's fuel mix in 2013 would only allow the industry to maintain compliance with the LCFS through the end of 2013 and that meeting future LCFS targets would become increasingly difficult without a significant expansion in the use of advanced, low-carbon fuels.[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 instead 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 (Environmental Protection Agency, 2013b). In California, the Air Resources Board released a white paper in May 2013 discussing mechanisms to contain compliance costs including establishing a credit window or a low carbon credit multiplier (California ARB, 2014).[6] In March 2014, the Board began a re-adoption process of the policy, and one of the key provisions under consideration was the inclusion of a cost containment mechanism (California ARB, 2013).

3 Model

To present the intuition for why cost containment mechanisms can increase the efficiency of renewable fuel mandates, we develop a model of a mandate with no uncertainty, a single compliance period, and a single biofuel mandate. 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 with $Q = q^c + q^r$. For example, if consumers value the energy content of fuel, the units could be denominated in gasoline gallon equivalent (GGE) units.[8] Suppose each input is associated with an emission factor ϕ^j for $j = c, r$. The damages from aggregate emissions are captured by the damage function $D(\phi^c q^c + \phi^r q^r)$, where the marginal damage $D'(\cdot)$ from a

[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-adopted the policy (California ARB, 2013). The court order was subsequently lifted in 2015, and the ARB re-adopted the policy with a new compliance schedule.

[6] Lade and Lin (2013) compare the effectiveness of each of the ARB's proposals in constraining compliance costs under the LCFS. A low carbon credit multiplier acts in a similar manner as simply relaxing the policy constraint, and is therefore not considered here.

[7] The assumption of two inputs 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] Denominating in gasoline gallon equivalent (GGE) units may be needed if consumers value the energy content of fuel, since a gallon of renewable fuel typically does not contain as much energy as a gallon of gasoline or diesel. A gallon of ethanol has around 70% of the energy content of a gallon of gasoline, while a gallon of biomass-based diesel has around 95% of the energy content of conventional diesel.

unit of emissions is the same for the two fuels. We write the biofuel mandate as $\varphi(q^c, q^r; \theta)$ in order to accommodate both a renewable fuel share mandate and a carbon intensity standard.

We begin by studying the effects of each fuel mandate on important market outcomes. We then examine the market effects of a cost containment mechanism that caps compliance costs. In particular, we consider a scenario in which the regulator offers a credit window from which firms can purchase compliance credits at a fixed cost. Last, we consider 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 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 $P(Q)$. In addition, assume the fuel industry has increasing, convex production costs $C^c(q^c)$ and $C^r(q^r)$ for conventional and renewable fuel, respectively.

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 mandates 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:

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

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

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

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

[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 the overall biofuel mandate under the RFS.

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 $\frac{\partial\varphi(\cdot)}{\partial q^r} = (\sigma - \phi^r) > 0$.

When the market for compliance credits is competitive, the representative firm's Lagrange multiplier λ is the equilibrium compliance credit price.[10] The equilibrium compliance credit price λ can be used to construct direct measures of the policies' costs. To see this, note that the value function for the representative firm is given by:

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

The Envelope Theorem implies that the marginal value to the representative firm 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.

Equations (1) and (2) summarize the previous research studying the two mandates (de Gorter and Just, 2009; Holland et al., 2009; Lapan and Moschini, 2012). The conditions state that the mandates implicitly tax conventional fuels and subsidize renewable fuels. The implicit tax on conventional fuel is $-\lambda\frac{\partial\varphi(\cdot)}{\partial q^c}$ and the implicit subsidy for renewable fuel is $\lambda\frac{\partial\varphi(\cdot)}{\partial q^r}$. The level of the tax and subsidy is endogenous, where the compliance credit price λ adjusts to the point where the mandate is just met whenever the policy binds.

The compliance credit price under either policy is driven by the differences in marginal cost between the renewable and conventional fuel. To see this, combine the two optimality conditions (1) and (2) for each mandate to yield:

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

The conditions state that λ equals the weighted difference between the renewable and conventional fuel marginal costs. Thus, all else equal a high spread between marginal costs of renewable and conventional fuels will lead to high compliance costs under either policy.

Equilibrium fuel prices under each mandate equal a weighted average of the marginal costs of each fuel, where the weights correspond to the share requirement under each respective mandate. To see this, substitute each solution for λ above into either equation (1) or (2) to obtain:

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

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

[10]The proof follows Montgomery (1972), showing that when firms can trade compliance credits, have perfect information, and face no trading costs marginal compliance costs are equalized to λ across all firms.

The equations illustrate the similarity of the two fuel mandates.[11] The distinguishing factor between the policies is how the share mandate is constructed. The RFS share mandate is explicitly set by α, while the LCFS share mandate is implicitly determined by the fuels' relative carbon intensity factors.

Proposition 1 summarizes important comparative statics with respect to the policy parameters under a binding fuel mandate.[12]

Proposition 1: Market effects of fuel mandates

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

ii Under an RFS, increasing α increases production of renewable fuel q^r 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.[13] Under an LCFS, decreasing σ increases production of renewable fuel q^r if $\frac{1}{\xi^c} - \frac{1}{\eta^d} > (\phi^c - \sigma)\frac{\lambda}{P}$.

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 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. If, however, consumers reduce fuel consumption or fossil fuel producers reduce production in response to increases in the stringency of the policies, q^r does not necessarily need to increase to maintain compliance. 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 fuel price P is $\xi^c > \xi^r$, i.e., fuel prices increase as the policies become more stringent if the supply elasticity of the conventional fuel is greater than the renewable supply elasticity.[14]

Figure 1 illustrates the effects of both policies. The left figure graphs the no policy equilibrium, and the right figure graphs equilibrium under a fuel mandate. In both graphs, the downward sloping line is the fuel demand curve; the upward sloping line with triangles is the conventional fuel supply curve; the upward sloping line with circles is 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 figure, 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 P_0 and total fuel quantity Q_0 are found where the total fuel supply curve intersects the demand curve. The supply of conventional and renewable fuel, q_0^c and q_0^r, respectively, is given by the corresponding quantity where the equilibrium price intersects the individual supply functions.

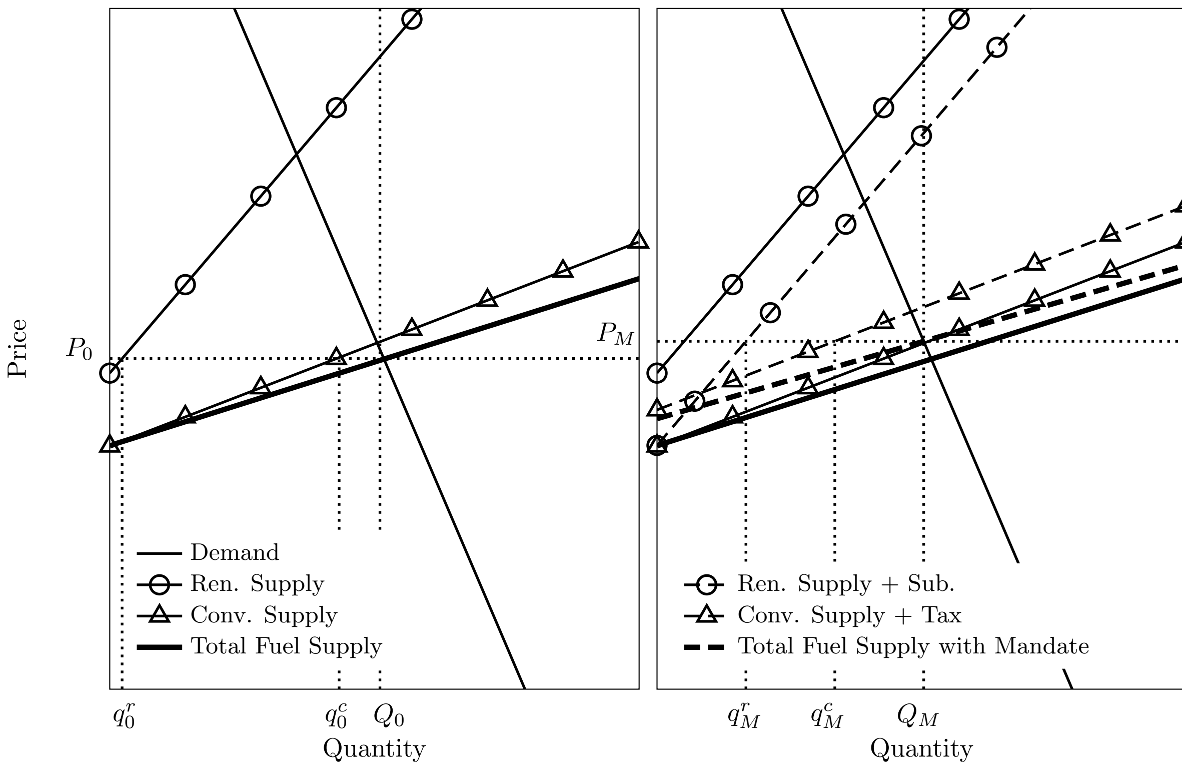
[11] Moreover, for the special case when $\alpha = -(\sigma - \phi^c)/(\sigma - \phi^r)$, the policy functions $\varphi(q^c, q^r; \theta)$ for both the RFS and the LCFS are identical.

[12] All proofs are presented in Appendix A.

[13] Note that ξ^c and η^d represent local elasticities.

[14] Fischer (2010) derives analogous results for the effect of Renewable Portfolio Standards on wholesale electricity prices.

Figure 1: Market Effects of Fuel Mandates*



Notes: The left figure illustrates the no policy equilibrium, and the right graphs the equilibrium under a fuel mandate. The downward sloping line is the fuel demand curve, the upward sloping line with triangles is the conventional fuel supply curve, the upward sloping 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 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 fuel mandate's implicit subsidy and tax. 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 P_M and quantity 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 greater production of renewable fuel q_M^r and a lower production of conventional fuel q_M^c. Because total fuel consumption Q_M declines, the policy results in higher fuel prices P_M over the no policy equilibrium.

3.2 Cost containment

Now suppose the regulator wishes to limit compliance costs. We model the cost containment mechanism as the regulator offering a credit window for compliance credits. 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. The new policy constraints are:

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

The representative firm's problem is:

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

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 when a regulator offers 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 before. If 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 q^c of conventional fuel decreases and the volume q^r of renewable fuel increases; and

ii The quantity c of compliance credits decreases

3.3 Second-best policies

Now consider the second-best fuel mandates with and without a cost containment mechanism. 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).[15] Despite the inefficiency of fuel mandates, a regulator may seek to set the fuel mandate policy optimally. The optimizing regulator's optimal mandate policy parameter θ choice problem can be written as:

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

[15] A more detailed treatment of the second-best nature of fuel mandates relative to a first-best cap and trade program is provided in Appendix B.

The first-order optimality conditions for a interior solution are given by:

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

For simplicity, assume a unique solution exists to the optimal fuel policy and that second-order conditions are satisfied. Consider the optimal RFS. Substituting the firm's optimality conditions for the RFS and making use of Proposition 1, the optimality condition can be written as:

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

If $\frac{dq^r}{d\alpha} > 0$ the condition is satisfied only if $\alpha\lambda < \phi^c D'(\cdot)$ and the opposite holds if $\frac{dq^r}{d\alpha} < 0$.

Similarly, we can write the optimality condition for the LCFS as:

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

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

The conditions state 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 if increasing the policy stringency increases the use of renewable fuel. The U.S. government currently uses a social cost of carbon around \$45/ton CO_2 for emissions with a 3% discount rate (IAWG, 2013). Thus, our results imply that an optimal RFS and LCFS in 2025 should be set such that the implicit tax on gasoline and diesel is less than \$45/ton.

3.4 Improving the second-best through cost containment

Policymakers may want to include a cost containment mechanism in a fuel mandate several reasons. When market outcomes are uncertain, a policy that places a ceiling on compliance costs can eliminate low probability, high compliance cost events and increase the policy's efficiency (Newell et al., 2005; Nemet, 2010). 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, for example due to political economy reasons. Furthermore, suppose the regulator is not able to change the policy stringency, perhaps due to a legislative mandate, but has the ability to set the level of a cost containment mechanism. Thus, 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:

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

As before, suppose a solution exists. Substituting the firm's optimality conditions and making use of Proposition 2, we obtain the following conditions for the optimal credit window price, conditional on a given policy level α or σ:

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

$$\underbrace{[(\phi^c - \sigma)\bar{p}^{\text{cred}} - \phi^c D'(\cdot)]}_{?}\underbrace{\frac{dq^c}{d\bar{p}^{\text{cred}}}}_{>0} = \underbrace{[(\sigma - \phi^r)\bar{p}^{\text{cred}} + \phi^r D'(\cdot)]}_{>0}\underbrace{\frac{dq^r}{d\bar{p}^{\text{cred}}}}_{>}.$$

for the RFS and LCFS, respectively. Thus, a necessary condition is for an optimum is that $\phi^c D'(\cdot) > \alpha\bar{p}^{\text{cred}}$ for the RFS and $\phi^c D'(\cdot) > (\phi^c - \sigma)\bar{p}^{\text{cred}}$ for the LCFS.

The conditions illustrate 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. In addition, the credit window gives the regulator an additional tool that can be used to increase the efficiency of a fuel mandate. For example, suppose that before enacting the mandate a policymaker believes the marginal cost of the renewable fuel will be $\frac{\partial C_L^r}{\partial q^r}$. The anticipated market clearing 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 $\lambda_H > \lambda_L$. 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 $\bar{p}^{\text{cred}} = \lambda_L$ to achieve the ex-ante policy goal.

With a cost containment mechanism as an additional policy lever, a regulator may wish to optimally choose both the mandate policy θ and the credit window price simultaneously. Inspecting the optimality conditions under an LCFS with a credit window reveals a key feature of an LCFS. First, note that the conditions for an interior first-best policy are:

$$P = \frac{\partial C^i}{\partial q^i} + \phi^i D'(\cdot)$$

for $i = c, r$. Comparing this condition with the firm's optimality conditions (3) and (4) under a mandate and a credit window price, no combination of the mandate α and credit window price $\bar{p}^{\text{cred}}$ can replicate the first-best optimality conditions under an RFS. Under an LCFS, however, setting the mandate to $\sigma = 0$ and the credit window price to $\bar{p}^{\text{cred}} = D'(\cdot)$ replicates the first-best optimality conditions.

This raises an important distinction between the RFS and the LCFS. Because the LCFS differentiates fuels based on their carbon intensity factors, the policy can 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]

It has been shown in the previous literature that a rate-based standard can achieve the first-best if it is coupled with an emissions tax (Holland et al., 2009) or a consumption tax (Holland, 2012); our result that one can achieve the first-best under an LCFS by setting the mandate to $\sigma = 0$ and the credit window price to $\bar{p}^{\text{cred}} = D'(\cdot)$ is an extension of these previous results. We further innovate upon the previous literature by also analyzing if one can improve the efficiency of volumetric standards such as the RFS by coupling the mandate with cost containment mechanisms. Even though one cannot achieve the first-best under the RFS even when combined with a credit window price, the analytic conditions we derive above for the optimal credit window price, conditional on a given policy level, show that it is possible to improve the efficiency of an RFS by coupling it with a credit window price. In our numerical model below, we solve for the optimal combinations of policy level and cost containment mechanism, and analyze the efficiency gains from choosing both the policy level and cost containment level optimally.

4 Simulation of the U.S. fuel market

We develop a numerical model of the U.S. gasoline market to better understand the relative performance and market effects of the fuel mandates and cost containment mechanism. We assume that consumers demand energy in GGE units and that firms produce three fuels: (1) gasoline, (2) corn ethanol, and (3) cellulosic ethanol. We calibrate the model so that the supply of gasoline and corn ethanol and fuel prices are similar to those in 2010. Table 1 presents the parameters used for the simulation model. All supply and demand functions 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), and baseline fuel prices as well as gasoline and ethanol production are set to reflect their 2010 levels (Energy Information Agency, 2012a).

Fuel supply elasticities in the literature typically reflect either short-run or very long-run elasticities (Dahl and Duggan, 1996; Coyle et al., 2012; Luchansky and Monks, 2009; Lee and Sumner, 2010). Most

[16] The same would remain true for a nested renewable share mandate structure. An example of a nested renewable share mandate structure is the RFS2, for which cellulosic biofuel and biodiesel count toward the advanced biofuel mandate, and all biofuels count toward 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 renewable share mandate policy from achieving the first-best.

Table 1: Numerical Simulation Parameters*

Market Parameters	
Fuel Demand Elasticity	0.2
Gas Supply Elasticity	3
Corn Ethanol Supply Elasticity	3
Cellulosic Ethanol Elasticity	{0.5, 3}
Marginal Damages ($/ton CO_2)	100
Gasoline Carbon Intensity (gCO_2/MJ)	100
Corn Ethanol Carbon Intensity (gCO_2/MJ)	85
Cellulosic Ethanol Carbon Intensity (gCO_2/MJ)	30
Baseline Fuel Price ($/gal)	2.835
Baseline Gasoline Production (bgal)	130
Baseline Corn 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]

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

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. The supply elasticity and initialized values of cellulosic ethanol production are set to reflect two scenarios, one in which cellulosic ethanol is more readily available with a higher supply elasticity and another with small 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 an elasticity of 3. In the latter, we assume initial production is 0.5 bgals with an elasticity of 0.5.

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 around $45/ton CO_2; however, estimates based on the same discount rate range from nearly zero to over $130/ton CO_2 (IAWG, 2013). We choose a relatively higher value to illustrate the qualitative features of optimal mandates better under various scenarios. Results are qualitatively the same for lower values; however, optimal mandate levels are less stringent. The carbon intensity values of each fuel are set to be similar to those used by the California Air Resources Board (ARB), with gasoline, corn ethanol, and cellulosic ethanol CIs set to 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. The constraints are given by:

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

where α is the RFS constraint, σ is the LCFS constraint, 'GAS' denotes gasoline, 'ETH' denotes corn ethanol, and 'CEL' denotes cellulosic ethanol. We normalize the LCFS constraint so that the carbon intensity of fuel in the no policy equilibrium equals 1. Thus, $(1 - \sigma) * 100$ 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.

From our discussion above, we know setting σ equal to zero and the credit price equal to marginal damages will achieve the first-best outcome. Given that such a policy is infeasible politically, we constrain both fuel mandates to be 'technologically' feasible. Specifically, we allow the RFS to range from the initial share of biofuel, S_0 in Table 1, to 100%. We allow the LCFS constraint to range from the 1 to the carbon intensity of cellulosic ethanol. Thus, the most stringent the LCFS can be set is to require that all fuel be cellulosic ethanol.

Whenever compliance credits are available, the policy constraints are given by:

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

The credit window price ranges from free to \$5/gal.

4.1 Second-best fuel mandates

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 2 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.

In both the low and high cellulosic scenarios, the largest DWL occurs under 'business as usual' (BAU), which corresponds to the 2010 no policy equilibrium. An optimally set RFS leads to small welfare gains over BAU, on the order of \$200 (\$420) million/year in the low (high) cellulosic ethanol scenario. Similarly, an optimally set LCFS decreases DWL relative to BAU by \$190 (\$660) million/year in the low (high) cellulosic

Table 2: 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/ Credit Window	Mandated Share Credit Price	100% $0.18/gal	$4.56
LCFS	Mandated Reductions	0.90%	$5.62
LCFS w/ Credit Window	Mandated Reductions Credit Price	78.69% $1.35/gal	$0.16
High Cellulosic Scenario			
Policy		**Optimal Level**	**DWL ($ bil)**
BAU			$6.32
RFS	Mandated Share	15.64%	$5.90
RFS w/ Credit Window	Mandated Share Credit Price	100% $0.19/gal	$4.71
LCFS	Mandated Reductions	2.10%	$5.66
LCFS w/ Credit Window	Mandated Reductions Credit Price	78.69% $1.35/gal	$0.24

*Notes: BAU is 'business as usual' and corresponds to the 2010 no policy equilibrium. The LCFS is specified as percentage reduction from the 2010 baseline carbon intensity. The RFS is specified as the percentage biofuel mandated. DWL is 'deadweight loss' and represents the social welfare loss relative to the first-best outcome.

scenario. In all scenarios, fuel mandates with no cost containment mechanism have a DWL exceeding $5 billion/year relative to the first best allocation.

The largest welfare gains occur when policies are paired optimally with a credit window, particularly for the LCFS. In both scenarios and for both policies, it is optimal to set the policies at their most stringent feasible level and offer compliance credits at a low price. Consistent with the results of our theory model, the optimal 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

Table 3: High Cellulosic Relative Market Outcomes*

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

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

for the RFS and the LCFS, respectively. The optimal LCFS with a credit window reduces DWL to $160 - $240 million/year. Thus, while the LCFS and RFS have similar welfare effects in all other scenarios, an LCFS nearly eliminates DWL when it is paired with an optimal credit window while the RFS with an optimal credit window has a DWL over $4.5 bil/year.

4.2 Market effects of fuel mandates

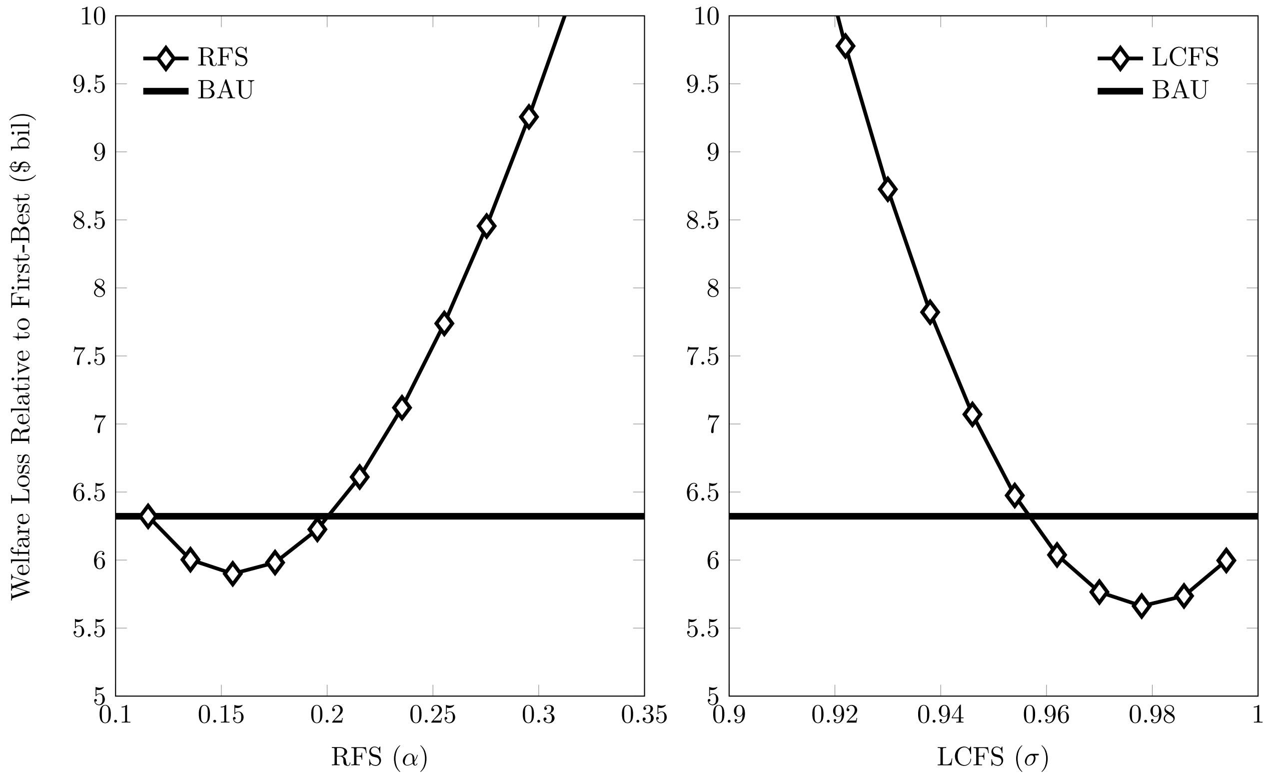
Table 3 compares key market outcomes relative to their corresponding first-best outcomes for the high cellulosic scenario.[17] Every policy except the LCFS with a credit window has significantly lower fuel prices (≈$1.10/gal lower) and higher consumer surplus than the first-best. The results illustrate a key feature of fuel mandates: by inducing transfers between firms rather than taxing all emissions, the policies have a much smaller price impact than a first-best policy.

Total fuel consumption is higher than the first-best equilibrium across all scenarios. 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 BAU. Corn ethanol producers have the highest production under the optimal RFS with a credit window, and cellulosic producers have the highest production

[17] Results for the low cellulosic scenario are similar and available upon request.

Figure 2: Deadweight Loss of Fuel Mandates



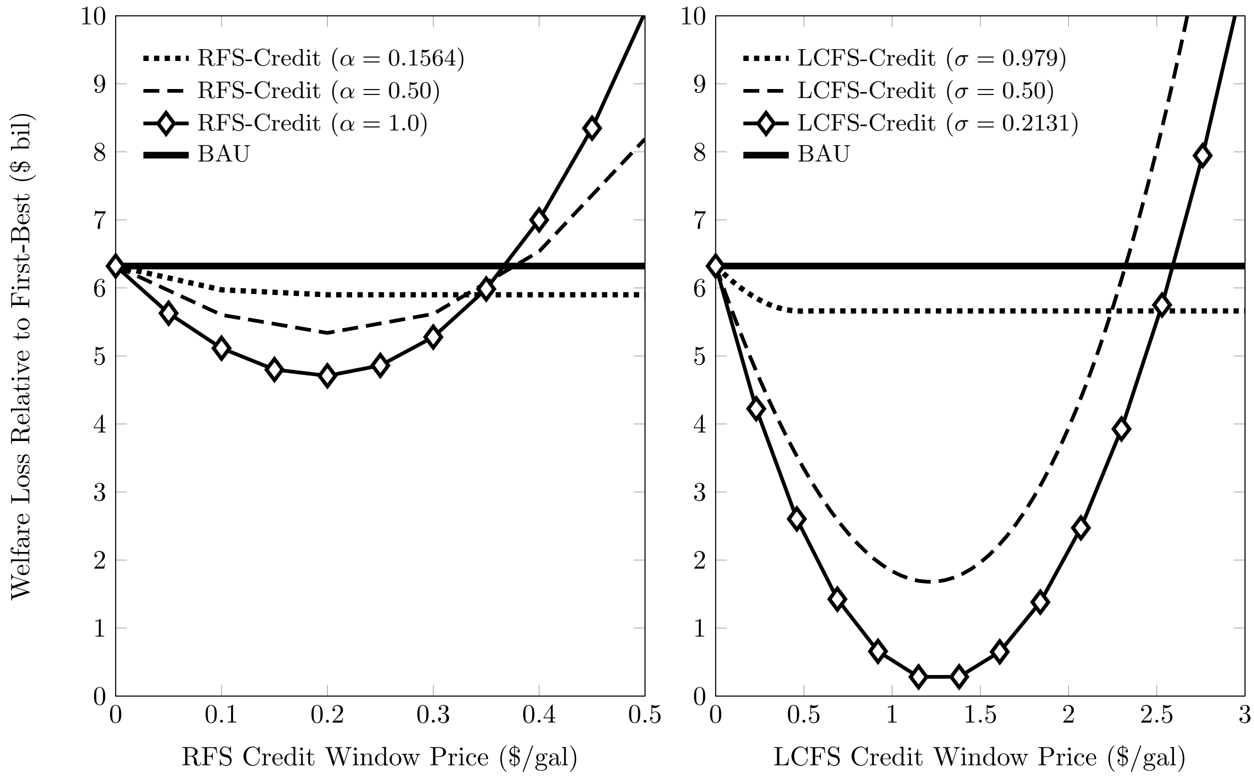
under the optimal LCFS with a credit window. Emissions under BAU are 8% higher than under the first-best policy. While all policies reduce emissions relative to BAU, most reductions are modest. A second-best RFS reduces emissions the least, with emissions decreasing only 0.5% from BAU. An optimal RFS with a credit window reduces emissions the second most. The largest emission reductions occur under an optimal LCFS with a credit window. In this case, emissions are only slightly higher than first-best emissions despite having quite a different fuel mix.

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 policy, instituting a cost containment mechanism leads to efficiency gains in the spirit of the analytical results derived in Section 3.4.

For reference, Figure 2 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. The optimal policies correspond to around a 15% RFS or an LCFS that requires just

Figure 3: Deadweight Loss of Fuel Mandates with a Credit Window



over a 2% CI reduction.[18] 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 with a fixed policy stringency where the regulator can offer a credit window. Figure 3 graphs DWL on the y-axes and the price of either the RFS or LCFS compliance credit window on the x-axes for three RFS and LCFS levels. As before, the bold horizontal line corresponds to business as usual DWL. Note that when credit window prices are $0/gal, the policy is non-binding as parties collect free compliance credits. Thus, when credits are free, each policy has the same DWL as BAU.

Consider the RFS in the left graph of Figure 3. 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 window price is greater than $0.10/gal because credit window prices are so high that the window is non-binding and firms comply with the policy

[18]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.

instead of purchasing credits from the window. In this case, losses are minimized when the credit window 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 increase welfare above BAU.

A credit window leads to larger efficiency gains when mandates are stringent. A 50% RFS with no cost containment mechanisms leads to a DWL exceeding \$10 bil/year (Figure 2). With a credit window offering, setting the credit window price optimally reduces DWL to $\approx$ \$5 bil/year, lower than BAU losses. The optimal RFS-credit window corresponds to a 100% biofuel mandate and a credit window price of \$0.19/gal. Optimally setting both the RFS and credit window price reduces DWL to around \$4.7 bil/year.

The right graph presents similar 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, setting credit window 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.

5 Discussion and Conclusion

Renewable energy mandates such as the RFS and LCFS are 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, a binding mandate may lead to situations with exceedingly high short-run compliance costs. As a result, cost containment provisions can 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 renewable fuel mandates even in the absence of uncertain compliance costs. We show that 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 mandate and the credit window price are set optimally, the second-best policy and credit window price can substantially reduce 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.

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 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 policies.

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A Proofs

- **Proof of Proposition 1:**

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

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

  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 $i = c, r$:

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

  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 h. Note that $\det(H) > 0$ for both policies.[19] Thus, the signs of the effects are determined by $\text{sign}\left(\det(H^i)\right)$.

  Solving for the RFS yields:

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

  Considering the price effect:

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

  Solving for the LCFS yields:

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

[19] 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.

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 yields:

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

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

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

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

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

Next consider the LCFS:

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

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

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

B Fuel Mandates as Second-Best Policies

In this section, we consider a graphical analysis of the second-best nature of fuel mandates. The analysis is similar to that presented in Helfand (1992). Figure B.1 illustrates the inefficiency of the mandates graphically. The solid circles are iso-welfare curves that exclude pollution damages. The dashed circles are iso-welfare curves when pollution externalities are internalized.[20] 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.

To align the competitive and first-best outcome, a regulator can either tax emissions or institute a cap and trade program, illustrated in Figure B.1(a). Iso-emissions curves are the parallel downward-sloping lines and have slope $(-\phi^c/\phi^r)$. The dashed downward-sloping 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 downward-sloping line, the competitive market outcome will correspond to the social optimum.

Now consider the efficiency of fuel mandates, illustrated in Figure B.1(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.

More formally, with a cap and trade permit system, the first-order conditions for an interior solution are:

$$P - \frac{\partial C^i}{\partial q^i} = \tau \phi^i$$

for $i = c, r$, where τ is the permit price.

We can say that, for each fuel $i = c, r$, $P - \frac{\partial C^i}{\partial q^i}$ the marginal abatement cost per unit of output, while the marginal abatement cost MAC^i per unit of emissions is:

$$MAC^i = \left(P - \frac{\partial C^i}{\partial q^i} \right) / \phi^i \tag{6}$$

[20] 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 $U(Q) - C^c(q^c) - C^r(q^r) - D(q^c, q^r)$.

for $i = c, r$.

In a cap and trade permit system, the marginal abatement cost MAC^i per unit of emissions given by equation (6) equals the permit price τ for each fuel $i = c, r$. As a consequence, it is possible for a cap and trade permit system to achieve first-best. In particular, a cap and trade permit system is first-best when the permit price is equal to marginal damages: $\tau = D'(\cdot)$.

However, for fuel mandates, the marginal abatement cost MAC^i per unit of emissions does not equal the permit price. Formally, for fuel mandates, the analogous first-order conditions are:

$$[q^c :] \quad P - \frac{\partial C^c}{\partial q^c} = \lambda\alpha \tag{7}$$

$$[q^r :] \quad P - \frac{\partial C^r}{\partial q^r} = -\lambda \tag{8}$$

for the RFS, and:

$$[q^c :] \quad P - \frac{\partial C^c}{\partial q^c} = \lambda\left(\phi^c - \sigma\right) \tag{9}$$

$$[q^r :] \quad P - \frac{\partial C^r}{\partial q^r} = -\lambda\left(\sigma - \phi^r\right) \tag{10}$$

for the LCFS.

Once again we can say that, for each fuel $i = c, r$, $P - \frac{\partial C^i}{\partial q^i}$ gives the marginal abatement cost per unit of output, while the marginal abatement cost MAC^i per unit of emissions is given by equation (6). However, the fuel mandate permit price does not equal the marginal abatement cost per unit of emissions. Instead, from the first-order conditions in equations (7) and (8), the RFS permit price equals the following:

$$[q^c :] \quad P - \frac{\partial C^c}{\partial q^c}/\alpha = \lambda \tag{11}$$

$$[q^r :] \quad -\left(P - \frac{\partial C^r}{\partial q^r}\right) = \lambda. \tag{12}$$

Likewise, from the first-order conditions in equations (9) and (10), the LCFS permit price equals the following:

$$[q^c :] \quad \left(P - \frac{\partial C^c}{\partial q^c}\right)/\left(\phi^c - \sigma\right) = \lambda \tag{13}$$

$$[q^r :] \quad -\left(P - \frac{\partial C^r}{\partial q^r}\right)/\left(\sigma - \phi^r\right) = \lambda. \tag{14}$$

Substituting in the marginal abatement cost MAC^i per unit of emissions given by equation (6) into equations (11)-(14) for the fuel mandate permit price, we get:

$$[q^c:] \quad MAC^c\phi^c/\alpha = \lambda \tag{15}$$

$$[q^r:] \quad -MAC^r\phi^r = \lambda \tag{16}$$

for the RFS, and:

$$[q^c:] \quad MAC^c\phi^c/\left(\phi^c - \sigma\right) = \lambda \tag{17}$$

$$[q^r:] \quad -MAC^r\phi^r/\left(\sigma - \phi^r\right) = \lambda. \tag{18}$$

for the LCFS, or, equivalently:

$$[q^c:] \quad MAC^c = \lambda\alpha/\phi^c \tag{19}$$

$$[q^r:] \quad MAC^r = -\lambda/\phi^r \tag{20}$$

for the RFS, and:

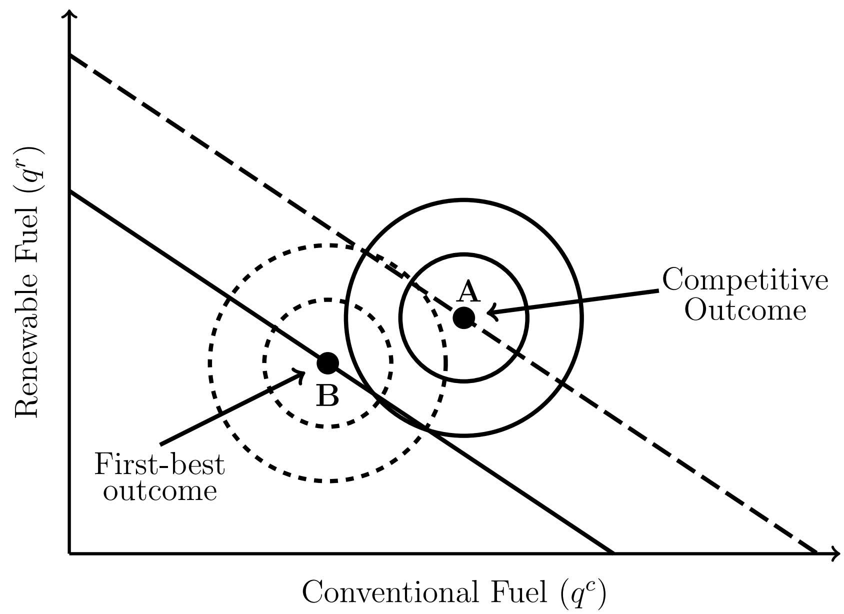
$$[q^c:] \quad MAC^c = \lambda\left(\phi^c - \sigma\right)/\phi^c \tag{21}$$

$$[q^r:] \quad MAC^r = -\lambda\left(\sigma - \phi^r\right)/\phi^r. \tag{22}$$

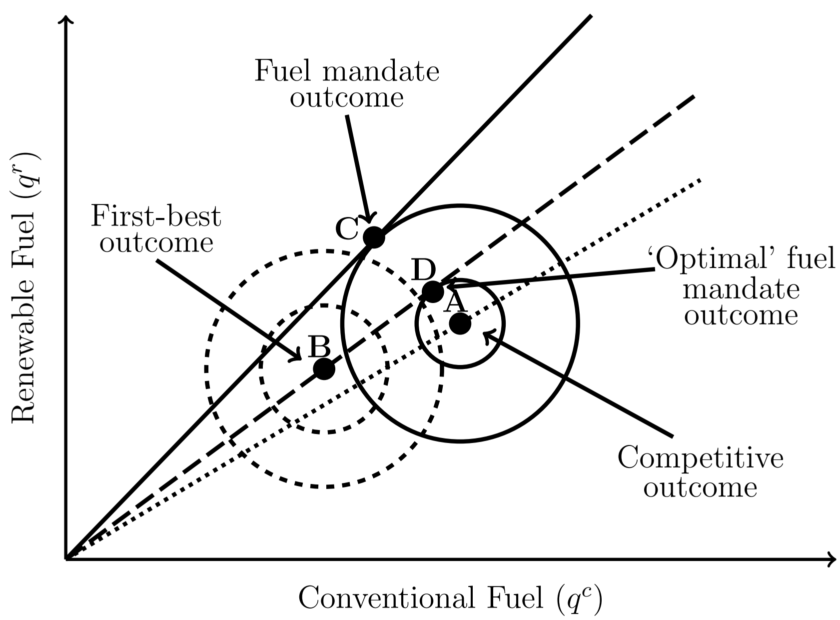
for the LCFS.

Thus, in contrast to a cap and trade program, for fuel mandates, the marginal abatement cost MAC^i per unit of emissions does not equal the permit price. As a consequence, mandates cannot achieve the first-best.

Figure B.1: 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. The parallel downward-sloping lines in (a) are iso-emission lines with slope $(-\phi^c/\phi^r)$. The rays from the origin in (b) represent fuel mandates.