The Design of Renewable Fuel Mandates and Cost Containment Mechanisms*

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Abstract

Policies to reduce greenhouse gas emissions from transportation fuels often take the form of renewable fuel mandates rather than taxes or cap-and-trade programs. Delays in the development and deployment of new technologies when binding mandates exist for their use may lead to situations with high compliance costs. We study the effects and efficiency of two mandates, a renewable share mandate and a carbon intensity standard, with and without a cost containment mechanism. Using both a theoretical model of a regulated fuel industry and a numerical model of the U.S. fuel market, we show that cost containment mechanisms can have the benefit of both constraining compliance costs and limiting deadweight loss. According to our numerical results, an optimally set mandate alone leads to only modest gains over business as usual welfare levels. The efficiency of both policies, especially carbon intensity standards, can increase substantially when combined with a cost containment mechanism.

JEL Codes: H23, Q42, Q54, Q58

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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 cap-and-trade 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, policies to reduce greenhouse gas emissions from transportation fuels often take the form of renewable fuel mandates rather than taxes or cap-and-trade programs, due at least in part to political economy reasons (Knittel, 2013; Metcalf, 2009b).

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 and incur compliance costs that may be particularly high in the short run. 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. Consumers must also 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 challenging to meet beyond 2014. Markets responded, and RFS compliance credit prices increased from \$0.10/gal to \$1.40/gal in just 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. The Agency eventually relaxed the mandates, reducing the incentive to invest in the technologies required to meet the future objectives of the RFS (Lade et al., 2018b).

This paper studies the market effects of and efficiency gains from including cost containment mechanisms in renewable fuel mandates. We formalize, expand upon, and synthesize the previous literature studying renewable fuel mandates by developing a model of mandates that incorporates both a renewable share mandate and a carbon intensity standard, both with and without a cost containment mechanism, in a unified framework. The particular cost containment mechanism we consider is a credit window for compliance credits whereby firms have the option to purchase compliance credits directly from the regulator at a given credit window price.

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). The existing literature has traditionally considered cost containment mechanisms as tools that may increase program efficiency by decreasing compliance cost uncertainty (Newell et al., 2005; Nemet, 2010; Fell et al., 2012; Fell, 2016). We show that cost containment mechanisms may substantially increase a policy's efficiency 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 constrain compliance costs and limit deadweight loss. If both the mandate and cost containment mechanisms are set optimally, the policy's efficiency 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. Further, we derive intuitive, easy-to-calculate upper bounds to guide policy in setting an efficient cost containment mechanism. Namely, the policy should ensure that the implicit fossil-fuel tax is below the first-best fossil fuel tax.

Our numerical model allows for two fuel markets – a gasoline and a diesel sector – and five fuels – gasoline, corn ethanol, cellulosic ethanol, diesel, and biodiesel – and reflects 2019 market conditions. We consider two scenarios. In the first scenario, biodiesel and cellulosic ethanol fuel are available at (approximately) their 2019 levels and have low fuel supply elasticities, reflecting current market conditions where it is expensive to expand production of either fuel. In the second scenario, biodiesel and cellulosic ethanol production are four times their 2019 levels and have higher fuel supply elasticities. Given our focus on medium- to long-run policies, we assume there are no relevant blending constraints in either scenario. Thus, the only relevant cost-driver in both scenarios is from the supply-side.

We show that cost containment mechanisms can lead to large efficiency gains when policies are set at levels similar to the long-run RFS and LCFS objectives. An optimally set credit window reduces deadweight loss by \$795 million/year with a 25% RFS, roughly the magnitude envisioned under the original RFS2 mandates. Potential gains are much larger, \$7.5 billion/year, for an LCFS with a 12% carbon intensity (CI) reduction, the levels set under the original LCFS. Further, we show that cost containment mechanisms can lead to substantive efficiency gains even at lower mandate levels. Our results highlight how, rather than relaxing or revisiting unrealistic mandate levels after they are unmet, strategically setting cost containment mechanisms can increase the policies' efficiency.

Our paper builds on an extensive literature studying fuel mandates, environmental policy design, and cost containment mechanisms. Many 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; Moschini et al., 2017; Just, 2017; Ghoddusi, 2017; Korting et al., 2019; Irwin et al., 2020; Afkhami and Ghoddusi, 2020). Others build on these studies, 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; Yeh et al., 2020), or subsidies for production, investment, or entry (Yi et al., 2021); studying unintended consequences of the policies and their relative efficiency when the mandates are anticipated (Okullo et al., 2021) or when markets are imperfectly competitive (Holland, 2012) or open to trade (Rajagopal et al., 2015); assessing the use of a single policy instrument to address multiple market failures (Landry and Bento, 2020); examining ways policymakers can increase the efficiency fuel mandates through strategic policy choices (Lemoine, 2017); and analyzing how well mandates perform as incentives for innovation (Clancy and Moschini, 2018) or for renewable natural gas adoption (Scheitrum, 2020).[1]

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 subsequently studied similar proposals, primarily in the context of emission trading programs (Weitzman, 1978; Wilcoxen and McKibbin, 1997; Pizer, 2002; Newell et al., 2005; Burtraw et al., 2010; Fell and Morgenstern, 2010). An emerging literature has considered hybrid taxes, taxes that adjust to achieve an emission target (Metcalf, 2009a; Aldy, 2017; Aldy et al., 2017; Hafstead et al., 2017; Hafstead and Williams III, 2020; Harris and Pizer, 2020). Burtraw et al. (2020) propose a price-responsive supply of emissions allowances, where the number of allowances supplied responds to market information about the costs of emissions reductions. Fischer et al. (2018) analyze the use of strategic technology policy as a supplement to renewable energy standards. Previous literature shows that a rate-based standard can achieve the first-best if 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.

Our research has several policy implications. First, our research has timely information for the federal Renewable Fuel Standard (RFS). The EPA is set to modify RFS2 mandates through 2022 (Bracmort, 2017) and consider mandates for 2023 and beyond (Lade et al., 2018a). Both processes will benefit from understanding the market effects and efficiency gains from including cost containment mechanisms.[2] Second, cost containment provisions such as price floors and ceilings are increasingly common. The re-adoption of the LCFS, approved in November 2015 and effective as of January 2016 (CARB, 2015b), includes a provision for holding a Credit Clearance Market (CCM) and an associated maximum credit price (CARB, 2020). Our

[1] 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; Filip et al., 2018).

[2] Although the RFS already has a cost containment mechanism similar to the one considered here (EPA, 2017), the current mechanism applies only to the mandate's cellulosic portion and has played only a limited role in containing compliance costs in the program.

work provides guidance on the optimal price ceilings for renewable fuel mandates.[3] Third, renewable energy mandates for new technologies exist in contexts other than the transportation fuel sector. Many states have ambitious renewable portfolio standards that require significant investments in renewable electricity generation. The findings here have implications for the efficient design of renewable energy policies more broadly to the extent that similar capacity constraints exist in these contexts.[4]

The paper proceeds as follows. Section 2 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 theory model of a regulated fuel industry, analyzes the effects of renewable fuel mandates and a cost containment mechanism on important market outcomes, derives the second-best policies with and without cost containment, and examines the potential efficiency gains from including cost containment mechanisms in renewable fuel mandates. Section 4 presents our numerical model, expanding upon the theory 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 the essential design elements of each policy, focusing on the use and importance of tradeable compliance credits. We then discuss several 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 (EISA) of 2007, creating the RFS2.[5] The EPA administers the

[3] While we focus on renewable fuel mandates, cost containment mechanisms are also prevalent in cap-and-trade policies. For example, California amended its cap-and-trade program to include a price ceiling (CARB, 2018). The revised Regional Greenhouse Gas Initiative (RGGI) model rule, which took into effect in 2014, added a cost containment reserve (CCR) to the cap-and-trade system (Ramseur, 2019). As part of its 2016 program review, RGGI considered a new provision, known as an emissions containment reserve (ECR), that would incorporate a minimum price for specified quantities of allowances under the cap and introduce steps into the allowance supply function (Burtraw et al., 2017). The revised European Union Emissions Trading System (EU ETS) also includes cost containment to mitigate excessive price fluctuations in the allowance market. The provision began in 2013 and applies if, for more than six consecutive months, the allowance price is more than three times the average price of allowances during the two preceding years on the European market (European Commission, 2020).

[4] Many renewable portfolio standards already include cost containment mechanisms, such as Alternative Compliance Payments in Massachusetts (Mass.gov, 2021), New Jersey (DSIRE, 2018), Ohio (PUCO, 2020), Maryland, and Delaware, among other states (Bird et al., 2011; Barbose, 2019).

[5] In addition to the federal RFS, state-level renewable share mandates have been implemented in Oregon, Washingon, Minnesota, Missouri, Louisiana, and Pennsylvania (Center for Climate and Energy Solutions, 2019).

policy, which set ambitious targets for renewable fuel consumption in the U.S., intending to expand biofuel use to 36 billion gallons (bgal) per year by 2022.[6] The RFS2 specifies sub-mandates for certain biofuels including: (1) cellulosic biofuel; (2) biomass-based diesel; and (3) advanced biofuel.[7] 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.[8] 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.[9] For example, providers of electricity for plug-in vehicles and hydrogen fuel producers may generate credits under the LCFS (CARB, 2015a).

Both the RFS and the 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. These 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.[10] LCFS credits and deficits are denominated in tons of CO_2 equivalent (CO_2e) and calculated using the spread between the fuels' assigned carbon intensity (CI) value and the standard.[11] Obligated parties maintain compliance by purchasing credits from low-carbon fuel producers,

[6] If met, the policy would require around 25% of motor gasoline to contain ethanol.

[7] 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 emissions are below a threshold set by the EPA.

[8] California's LFCS is an example of a carbon intensity standard since it requires that the average carbon intensity of fuels be below a specified standard. While California's LCFS is the largest carbon 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).

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

[10] RINs are differentiated by vintage year and fuel type to enforce banking restrictions and ensure the mandate for each biofuel category is met.

[11] 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 (above) the standard.

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 RFS and the LCFS face a number of challenges to their future success. The two most notable issues are: (1) the 'blend wall', and (2) the slow development of commercial-scale low-carbon fuel production (Lade et al., 2018a).

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.[12]

Before 2013, the primary biofuel used for compliance towards both the RFS and LCFS was ethanol derived from corn (EPA, 2013a; Yeh et al., 2013). The future success of the RFS2 and LCFS 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, 2012; Rapier, 2018; Padella et al., 2019). 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. Recent work highlights that these issues persist, and meeting 2030 targets with the maximum compliance credit price currently set by the ARB will be challenging (Bushnell et al., 2020).

Given these challenges, both the EPA and the California ARB have considered or enacted various cost containment provisions. Like the mechanism studies here, the EPA allows parties to purchase cellulosic waiver credits instead of blending cellulosic fuel. Nevertheless, the program is limited to just the cellulosic portion of the mandate and makes up only a tiny fraction of total compliance.[13] The EPA has instead

[12]Recent years have seen increased attention given to E15, fuel containing up to 15% ethanol. If widely adopted, E15 could 'break' the current blend wall since most gasoline-powered vehicles in use today can use the fuel. Nevertheless, for many reasons, its use has been very limited to date (Lade, 2019).

[13]Obligated parties purchased just under 12 million credits in 2017, the latest year for which the EPA has reported data of annual credits purchased. In that year, total cellulosic biofuel obligations were nearly 288 million gallons, and total renewable fuel obligations were 17.8 billion gallons. The highest reported amount of cellulosic waiver credits purchased was in 2016 when producers purchased just over 33 million credits (EPA, 2020, 2021).

managed compliance costs primarily through adjusting mandates. The EPA has repeatedly used its cellulosic biofuel waiver authority to reduce the cellulosic biofuel volume required, and, since 2014, to also reduce both the advanced biofuel and total renewable fuel volume required (Bracmort, 2020). 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 mechanisms to contain compliance costs including establishing a credit window or a low carbon credit multiplier (CARB, 2014).[14] 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 (CARB, 2013). Re-adoption was approved in November 2015 and became effective in January 2016 (CARB, 2015b), and included a provision for holding a Credit Clearance Market (CCM) and an associated maximum credit price (CARB, 2020).

3 Model of Mandates

We develop a stylized model of mandates to study and build intuition regarding the market effects of and efficiency gains from including cost containment mechanisms in renewable fuel mandates. Our model incorporates both a renewable share mandate and a carbon intensity standard, both with and without a cost containment mechanism, in a unified framework that expands on previous literature and synthesizes lessons and intuition across different renewable fuel mandates in a setting with no uncertainty.

We consider a two-fuel model of a mandate with no uncertainty, a single compliance period, and a single biofuel mandate. A competitive industry 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.[15] 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 fuel's energy content, the units could be denominated in gasoline gallon equivalent (GGE) units.[16] 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 unit of emissions is the same for the two fuels.

[14] 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 similarly to relaxing the policy constraint, and is therefore not considered here.

[15] 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. For example, a numerical equivalence exists between a renewable fuel share mandate and carbon intensity standard in the two-fuel case. The equivalence breaks down in the multi-fuel case. We examine the multi-fuel case in our numerical model in Section 4.

[16] 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. A gallon of biomass-based diesel has around 95% of the energy content of conventional diesel.

We model the market equilibrium using a representative firm. The fuel industry has increasing, convex production costs $C^c(q^c)$ and $C^r(q^r)$ for conventional and renewable fuel, respectively, and consumers have decreasing, weakly concave inverse demand for fuel $P(Q)$.

We study two mandates: (1) a renewable share mandate similar to the RFS;[17] and (2) an energy-based carbon intensity standard similar to California's LCFS. 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 the renewable share mandate set by the regulator. An LFCS requires that the average carbon intensity of fuels be below a specified standard. 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 carbon intensity standard set by the regulator.

For notational ease, we write the biofuel mandate as $\varphi(q^c, q^r; \theta) \geq 0$ to accommodate both a renewable fuel share mandate and a carbon intensity standard, where:

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

and 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:

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

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

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

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

When the market for compliance credits is competitive, the representative firm's Lagrange multiplier λ is the equilibrium compliance credit price.[18] The equilibrium compliance credit price λ can be used to construct

[17] 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.

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

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 interpretations 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.

3.1 The inefficiency of fuel mandates

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 tax and subsidy level is endogenous, where the compliance credit price λ adjusts to the point where the mandate is just met whenever the policy binds. Owing to their implicit subsidy on renewable fuels, 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).[19]

3.2 Second-best fuel mandates

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:

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

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 A.1 in Appendix A, the optimality condition can be written as the following:

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

[19] We analyze the effects of each fuel mandate on important market outcomes in Appendix A. Appendix B.1 provides a more rigorous analysis of why fuel mandates cannot achieve the first-best outcome. Appendix B.2 present a graphical analysis of the second-best nature of fuel mandates.

where beneath each term in brackets we have indicated the sign of the bracketed term for terms that can be signed and a question mark for terms whose signs are ambiguous. If $\frac{dq^r}{d\alpha} > 0$ the optimality 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 most recent estimates of the average social cost of carbon issued by the U.S. government's Interagency Working Group on Social Cost of Greenhouse Gases based on a 3% discount rate is around $46/ton CO_2 for 2025 (IAWG, 2016). 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 $46/ton.

3.3 Improving the second-best through cost containment

Suppose the regulator wishes to limit compliance costs. We model the cost containment mechanism as the regulator offering a credit window for compliance credits. Under a credit window, firms have the option to purchase compliance credits directly from the regulator at a given credit window price. The credits purchased from the regulator would not be associated with the production of any renewable fuel but would increase liquidity in the market.

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:

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

The representative firm's problem is:

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

with corresponding Karush-Kuhn-Tucker conditions:

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

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

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

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

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 are 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 the credit window price $\bar{p}^{\text{cred}}$. Hence, the open credit window creates a ceiling on marginal compliance costs.[20]

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 can 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 A.1 in Appendix A, we obtain the following conditions for the optimal credit window price, conditional on a given policy level α or σ:

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

for the RFS, and:

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

for the LCFS. 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. As before, the conditions state that the optimal credit window price, conditional on a given policy level α or σ, should be set at a level where the implicit tax on conventional fuel is less than its marginal damages. The credit window gives the regulator an additional

[20] We examine the market effects of a cost containment mechanism that caps compliance costs in Appendix A. Proposition A.2 in Appendix A summarizes the comparative statics for the credit window price $\bar{p}^{\text{cred}}$ when firms purchase from the credit window.

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 higher than the policymaker had anticipated and are given instead by $\frac{\partial C_H^r}{\partial q^r} > \frac{\partial C_L^r}{\partial q^r}$. Compliance credit prices adjust endogenously, and ex post compliance credit prices are $\lambda_H > \lambda_L$. Suppose ex post 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 ex ante, however, the regulator can correct this. Assuming the initial standard was set second-best optimally given the anticipated credit prices 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 reveals a key feature of an LCFS. With a LCFS, setting the LCFS mandate level to $\sigma = 0$ and the credit window price to $\bar{p}^{\text{cred}} = D'(\cdot)$ replicates the first-best optimality conditions in equation (B.1). In contrast, with a RFS, no combination of the RFS mandate level α and credit window price $\bar{p}^{\text{cred}}$ can replicate the first-best optimality conditions.[21] The result raises an important distinction between the RFS and the LCFS. By differentiating fuels based on their carbon intensity factors, an LCFS can achieve more efficient outcomes than the RFS.

Setting the mandate under an LCFS to $\sigma = 0$ and the credit window price to $\bar{p}^{\text{cred}} = D'(\cdot)$ transforms the LCFS to a carbon tax. Policymakers may be better able to overcome the political economy and other barriers to a carbon tax or cap-and-trade program and achieve the first-best by framing what is effectively a carbon tax as a renewable fuel mandate instead (Knittel, 2013; Metcalf, 2009b). In particular, if a carbon tax becomes politically feasible when it is instead framed as an LCFS with a mandate of $\sigma = 0$ and a credit window price of $\bar{p}^{\text{cred}} = D'(\cdot)$, then our results suggest a politically feasible means of implementing the first-best. Further, while setting $\sigma = 0$ may be infeasible if no 'zero-carbon' technologies exist, we show in Section 4 that setting the most aggressive 'technologically feasible' LCFS can substantially reduce the deadweight loss from an LCFS. Aggressive carbon policies such as those considered here are not out of the ordinary. Many communities across the U.S. have committed to 100% renewable, clean energy mandates in the last few years (Sierra Club, 2020). Relevant to this study, the original RFS2 mandated 16 bgals of cellulosic ethanol by 2022, before any commercial production was available. California also recently committed to an 80% GHG reduction target by 2050, and will presumably rely heavily on GHG reductions from transportation fuels through future LCFS rulemaking (EIA, 2018a).

[21] The same would remain true for a nested renewable share mandate structure. 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.

Previous literature shows 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 is an extension of these previous results. We further innovate upon the previous literature by analyzing if one can improve the efficiency of volumetric standards such as the RFS by coupling the mandate with cost containment mechanisms. While one cannot achieve the first-best under the RFS even when combined with a credit window price, the analytic conditions above 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. fuel market to better understand the relative performance and market effects of the fuel mandates and cost containment mechanism. Our numerical model examines the multi-fuel case and expands upon the theoretical model in Section 3 along several important dimensions. We allow for two consumer fuel markets, motor (ethanol-blended) gasoline and motor (biodiesel-blended) diesel. Gasoline consumers demand energy in gasoline gallon equivalent (GGE) units, and motor gasoline producers produce three motor gasoline fuels: (1) gasoline, (2) corn ethanol, and (3) cellulosic ethanol. Diesel demand is similarly specified in GGE units, and diesel fuel producers produce: (1) diesel, and (2) biodiesel.[22]

Table 1 presents the parameters used in the simulation model. We calibrate the model so that fuel prices and the supply of gasoline, diesel, and corn ethanol are similar to those in 2019. We explore the sensitivity of the model to assuming that low-carbon cellulosic ethanol and biodiesel are readily available versus available at around their 2019 production levels. 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; Dahl, 2012; Lin and Prince, 2013).

Fuel supply elasticities in the literature typically reflect either short-run or very long-run elasticities (Dahl and Duggan, 1996; Coyle et al., 2012; Marion and Muehlegger, 2011; 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 efficient medium- to long-run policies and therefore choose mid-range supply elasticities to reflect this.[23]

[22]Renewable diesel has become an important compliance fuel in California in recent years since renewable diesel is chemically very similar to diesel and therefore faces fewer blending constraints than biodiesel does (EIA, 2020). Nevertheless, the carbon intensities for biodiesel and renewable diesel are very similar, and we lack evidence that they have differential supply elasticities (EIA, 2018c). Given this, we aggregate biodiesel and renewable diesel in this exercise.

[23]Our focus on longer-term scenarios also motivates our choice not to model the blend wall for either motor gasoline or motor diesel fuel as others have recently done (e.g., Korting et al. (2019)).

Table 1: Numerical Simulation Parameters*

Parameter	Value	Source
Market Parameters		
Gasoline Demand Elasticity	-0.2	Hughes et al. (2012); Lin and Prince (2013)
Diesel Demand Elasticity	-0.1	Dahl (2012)
Gasoline Supply Elasticity	3	Dahl and Duggan (1996); Coyle et al. (2012)
Diesel Supply Elasticity	3	Dahl and Duggan (1996); Marion and Muehlegger (2011)
Corn Ethanol Supply Elasticity	3	Lee and Sumner (2010)
Cellulosic Ethanol Elasticity	{0.5, 3}	Assumption
Biodiesel Supply Elasticity	{0.5, 3}	Assumption
Marginal Damages (\$/ton CO_2)	100	IAWG (2016)
Gasoline Carbon Intensity (gCO_2/MJ)	100	CARB (2015a)
Diesel Carbon Intensity (gCO_2/MJ)	100	CARB (2015a)
Corn Ethanol Carbon Intensity (gCO_2/MJ)	85	CARB (2015a)
Cellulosic Ethanol Carbon Intensity (gCO_2/MJ)	30	CARB (2015a)
Biodiesel Carbon Intensity (gCO_2/MJ)	30	CARB (2015a)
Initial Gasoline Price (\$/gal)	2.60	EIA (2019b)
Initial Diesel Price (\$/gal)	3.06	EIA (2019b)
Initial Gasoline Production (bgal)	142.2	EIA (2019a)
Initial Diesel Production (bgal)	61.3	EIA (2019a)
Initial Corn Ethanol Production (bgal)	14.4	DOE AFDC (2020b)
Initial Cellulosic Ethanol Production (bgal)	{0.5, 2}	Assumption
Initial Biodiesel Ethanol Production (bgal)	{2.5, 10}	CARB (2019b); DOE AFDC (2020a)
Policy Parameters		
LCFS Constraint (gCO_2/MJ)	[30, 100]	Assumption
RFS Constraint (%)	[S_0, 100]	Assumption
Credit Window Price (\$/gal)	[0, 5]	Assumption

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

We simulate two different scenarios regarding cellulosic ethanol and biodiesel, the low carbon intensity advanced biofuels. In the 'low cellulosic/biodiesel' scenario, we set the initial cellulosic and biodiesel production levels at roughly their levels in 2019: 0.5 bgals and 2.5 bgals, respectively (CARB, 2019b; DOE AFDC, 2020a). The supply elasticities of both advanced biofuels are set to 0.5, reflecting current market conditions where it is expensive to expand production of either fuel.[24] In the 'high cellulosic/biodiesel' scenario, we set the initial cellulosic and biodiesel production levels at 2 bgals and 10 bgals, respectively, around four times their respective 2019 levels (CARB, 2019b; DOE AFDC, 2020a). The supply elasticities of both fuels are set to 3 (Irwin and Good, 2017). Given our focus on medium- to long-run policies, we assume there are no relevant blending constraints in either scenario. Thus, the only relevant cost-driver in both scenarios is from

[24]The 2019 RFS2 mandates for cellulosic ethanol were 418 mgals. Most RINs produced to satisfy the cellulosic mandate in that year were produced from biogas and other non-liquid cellulosic ethanol producers, however (EIA, 2018b). Thus, despite assuming low values for future cellulosic production, our assumptions here are likely quite generous for liquid cellulosic ethanol production.

the supply-side.

We assume carbon damages are \$100/ton CO_2e. While the most recent estimates of the average social cost of carbon issued by the Interagency Working Group on Social Cost of Greenhouse Gases based on a 3% discount rate is around \$42/ton CO_2 for 2020 and \$46/ton CO_2 for 2025, estimates based on the same discount rate range from nearly zero to over \$123/ton CO_2 for 2020, and over \$138/ton CO_2 for 2025 (IAWG, 2016). We choose a higher value to illustrate the qualitative features of optimal mandates better under various scenarios. Results are qualitatively the same for lower values for carbon damages, albeit with less stringent optimal mandate levels. The carbon intensity (CI) values of each fuel are set to be similar to those used by the California Air Resources Board (CARB, 2015a). Gasoline, corn ethanol, and cellulosic ethanol CIs are set to 100, 85, and 30 gCO_2/MJ, respectively. Diesel and biodiesel have assumed CIs of 100 and 30, respectively.

The policy constraints are equivalent to those used in Section 3, except that they now include multiple renewable and fossil fuels. In particular, the RFS requires the share of renewable fuel – which now includes corn ethanol, cellulosic ethanol, and biodiesel – to be greater than a specified volume obligation; the mandated share α is the RFS mandate level. The LFCS requires that the average carbon intensity of all fuels – which now include gasoline, corn ethanol, cellulosic ethanol, diesel, and biodiesel – be below a specified standard; the mandated carbon intensity standard σ is the LCFS mandate level. The constraints are given by:

$$[\text{RFS:}] \quad q^{\text{ETH}} + q^{\text{CEL}} + q^{\text{BD}} - \alpha\left(q^{\text{GAS}} + q^{\text{DIES}}\right) \geq 0$$

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

where α is the RFS mandate level, σ is the LCFS mandate level, 'GAS' denotes gasoline, 'DIES' denotes diesel, 'ETH' denotes corn ethanol, 'CEL' denotes cellulosic ethanol, and 'BD' denotes biodiesel. We normalize the LCFS mandate 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. The Lagrange multiplier on the LCFS policy constraint is denominated in \$/gal under the normalization, allowing for easy comparison with the Lagrange multiplier on the RFS policy constraint.

From our discussion above, we know setting the LCFS mandate 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, we constrain both fuel mandates to be 'technologically' feasible. Specifically, we allow the RFS mandate to range from the initial share of biofuel, S_0 in Table 1, to 100%. We allow the LCFS mandate to range from the 1 to the carbon intensity of cellulosic ethanol and biodiesel. Thus, the most stringent the LCFS can be set is to require that all motor gasoline be cellulosic ethanol and all motor diesel be biodiesel.

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

$$[\text{RFS:}] \quad q^{\text{ETH}} + q^{\text{CEL}} + q^{\text{BD}} + c - \alpha\left(q^{\text{GAS}} + q^{\text{DIES}}\right) \geq 0$$

$$[\text{LCFS:}] \quad (\sigma - \phi^{\text{GAS}})q^{\text{GAS}} + (\sigma - \phi^{\text{DIES}})q^{\text{DIES}} + (\sigma - \phi^{\text{ETH}})q^{\text{ETH}} + (\sigma - \phi^{\text{CEL}})q^{\text{CEL}} + (\sigma - \phi^{\text{BD}})q^{\text{BD}} + c \geq 0.$$

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 (i.e., the second-best RFS mandate level α and the second-best LCFS mandate level σ) 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 (RFS mandated share α or the LCFS mandated carbon intensity standard σ) and the level of the cost containment mechanism. Table 2 summarizes the optimal policies under both the high and low cellulosic/biodiesel scenarios. Recall that all policies are second-best by nature. Thus, the difference in social welfare between each scenario and the first-best social welfare is equal to the deadweight loss (DWL) of the policy.

In both the low cellulosic/biodiesel and high cellulosic/biodiesel scenarios, the largest DWL occurs under 'business as usual' (BAU), which corresponds to the 2019 'no policy' equilibrium. An optimally set RFS leads to small welfare gains over business as usual, on the order of \$0.24 (\$2.43) billion/year in the low (high) cellulosic/biodiesel scenario. Similarly, an optimally set LCFS decreases DWL relative to business as usual by \$0.21 (\$3.81) billion/year in the low (high) cellulosic/biodiesel scenario. In all scenarios, fuel mandates with no cost containment mechanism have a DWL exceeding \$8 billion/year relative to the first-best allocation.

The largest welfare gains occur when policies are paired optimally with a credit window. This is especially the case 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/biodiesel scenario, the optimal implicit gasoline tax is approximately \$0.26/gal and \$0.99/gal for the RFS and the LCFS, respectively.[25] The optimal LCFS with a credit window reduces DWL to \$210–\$350 million/year. Thus, while the LCFS and RFS have similar welfare effects in all other scenarios, consistent with our theory model, 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 \$6.4 bil/year.

[25] Recall that, with a credit window, the implicit gasoline tax is $\alpha \times \bar{p}^{\text{cred}}$ and $(\phi^c - \sigma)\bar{p}^{\text{cred}}$ for the RFS and LCFS, respectively.

Table 2: Optimal Policies and Social Welfare Outcomes Relative to the First-Best

Low Cellulosic/Biodiesel Scenario

Policy		**Optimal Level**	**Welfare Loss ($ bil)**
BAU			$8.42
LCFS	Mandated Reductions	0.70%	$8.21
LCFS w/ Credit Window	Mandated Reductions	79.50%	$0.21
	Credit Price	$1.41	
RFS	Mandated Share	10.14%	$8.18
RFS w/ Credit Window	Mandated Share	100%	$6.41
	Credit Price	$0.20	

High Cellulosic/Biodiesel Scenario

Policy		**Optimal Level**	**Welfare Loss ($ bil)**
BAU			$12.24
LCFS	Mandated Reductions	4.80%	$8.43
LCFS w/ Credit Window	Mandated Reductions	79.50%	$0.35
	Credit Price	$1.24	
RFS	Mandated Share	20.50%	$9.81
RFS w/ Credit Window	Mandated Share	100%	$7.32
	Credit Price	$0.26	

Notes: BAU is 'business as usual' and corresponds to the 2019 no policy equilibrium. The LCFS is specified as percentage reduction from the 2019 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.

4.2 Market effects of fuel mandates

Table 3 compares key market outcomes relative to their corresponding first-best outcomes for the high cellulosic/biodiesel scenario.[26] Every policy except the LCFS with a credit window has significantly lower fuel prices ($\approx$\$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.

[26] Results for the low cellulosic/biodiesel scenario are broadly similar.

Table 3: High Cellulosic/Biodiesel Relative Market Outcomes*

Outcomes	BAU	LCFS	LCFS Credit	RFS	RFS Credit
Motor Gasoline Price ($/gal)	-$1.11	-$1.10	-$0.18	-$1.09	-$0.92
Motor Diesel Price ($/gal)	-$1.03	-$0.98	-$0.16	-$1.02	-$0.85
Quantities (bgals)					
Gasoline	13.23	5.15	-$0.69	5.44	1.99
Corn Ethanol	-1.65	7.03	2.43	8.11	10.06
Cellulosic Ethanol	-2.29	0.63	0.71	-0.94	-0.66
Diesel	9.60	3.62	-0.59	6.35	4.74
Bioiesel	-8.08	-1.83	0.92	-4.65	-3.33
Motor Gasoline Consumer Surplus (bil $)	164.28	162.06	26.32	161.58	135.45
Motor Diesel Consumer Surplus (bil $)	80.40	76.50	12.44	79.52	66.38
Emission Damages (MMT)	239.57	153.51	5.95	186.79	143.11

Notes: BAU is 'business as usual' and corresponds to the 2019 no policy equilibrium. MMT is 'million metric tons'. All variables are in levels relative to the corresponding first-best outcome.

Total fuel consumption is higher than the first-best equilibrium across all scenarios. The composition of fuel, however, varies substantially. For the LCFS with a credit window, since it taxes gasoline and diesel at a level close to the first-best, gasoline and diesel supply is closer to the first-best allocation. Because both policies continue to either under-tax or subsidize renewable fuel, however, they typically lead to higher total corn ethanol supply than the first-best. Biodiesel is typically under-utilized relative to first-best. While all policies reduce emissions relative to business as usual, most reductions are modest. A second-best RFS reduces emissions the least, with emissions decreasing 20% from business as usual. The largest emission reductions occur under an optimal LCFS with a credit window. In this case, emissions are only slightly higher than the first-best emissions despite having a different fuel mix.

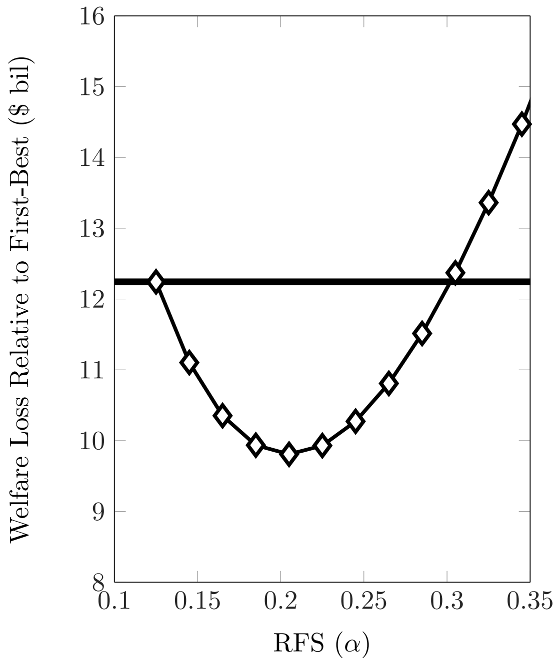
4.3 Efficiency gains from cost containment mechanisms

The previous sections compare the relative efficiency of the policies when all parameters are set optimally. We now study when, for a given policy, instituting a cost containment mechanism leads to efficiency gains.

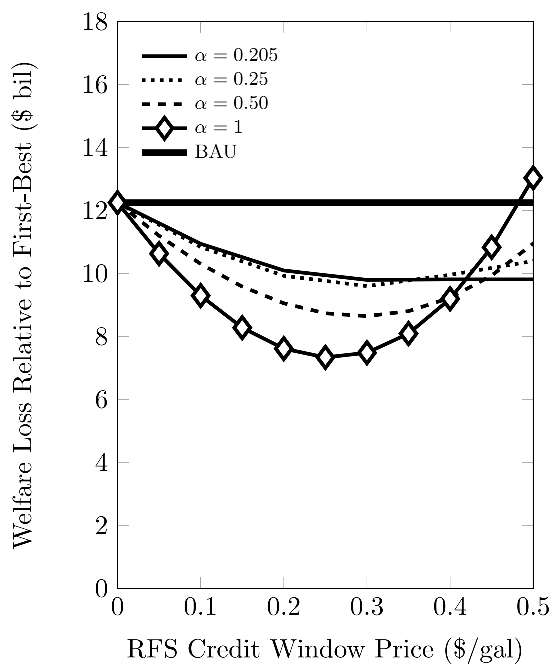
For reference, Figure 1 panel (a) graphs the DWL in billion dollars on the y-axes against varying levels of the RFS and LCFS on the x-axes. The bold horizontal line corresponds to the DWL under business as usual. Thus, whenever the DWL under an RFS or LCFS is higher than the DWL under business as usual, the regulator would be better served by having no policy. The optimal policies correspond to an RFS mandated share of around 20.50%, or an LCFS that requires just over a 4.80% CI reduction.[27] DWL from the policies exceed business as usual levels if the RFS mandate is higher than 30% or the LCFS requires more than a 9% average CI reduction. Welfare losses increase sharply beyond these levels.

[27]Recall that the business as usual average CI is 1 in our model. Thus the second-best LCFS of $\sigma = 0.952$ corresponds to a policy requiring a $(1 - 0.952) \times 100$ % average CI reduction.

Figure 1: Deadweight Loss of Fuel Mandates



(a) Fuel Mandates Alone



(b) Fuel Mandates with a Credit Window

Notes: Graphs plot the deadweight loss (DWL) in billion dollars on the y-axes against (a) varying levels of either the RFS or LCFS; and (b) varying prices of either the RFS or LCFS compliance credit window for different RFS mandated shares α or different LCFS mandated carbon intensity standards σ, respectively. In each graph, the bold horizontal line corresponds to the DWL under 'business as usual' (BAU), which corresponds to the 2019 no policy equilibrium.

Now consider a scenario with a fixed policy stringency where the regulator can offer a credit window. Figure 1(b) graphs DWL on the y-axes and the price of either the RFS or LCFS compliance credit window on the x-axes for four RFS and LCFS levels. As before, the bold horizontal line corresponds to the business as usual DWL.

When credit window prices are \$0/gal, the policy is non-binding as parties collect free compliance credits. Policies start with the same DWL as business as usual. As the credit price increases, the implicit tax and subsidy increase. The graphs in Figure 1(b) follow the same 'U-shape' seen in panel (a), reflecting initial welfare gains from effectively less stringent mandates followed by steep welfare losses as mandates become more stringent. The credit window always binds for the most stringent policies. For the less stringent policies – the RFS mandates at 20.5% and the LCFS mandates at a 4.8% and 12% CI reduction – the credit window eventually becomes non-binding. In these cases, the shadow price of complying with the mandates (as given by the Lagrange multiplier λ on the mandate constraint) is lower than the credit window price. This is visually evident where the welfare losses relative to first-best become straight lines.[28]

Consider the RFS in the left graph of Figure 1(b). The thin solid line corresponds to the second-best RFS with no cost containment provision ($\approx$ 20.5%); the short-dashed line corresponds to approximately the long-run EISA mandates ($\approx$ 25%); the long-dashed line corresponds to an even more ambitious mandate (50%); and the line with diamonds corresponds to the second-best RFS with credit window, a 100% mandate. For a 20.5% mandate, the credit window is non-binding above \$0.40/gal. The second-best RFS can be improved slightly ($\approx$ \$16 million/year) if the regulator sets a \$0.30/gal cap in RIN prices. If the regulator sets the mandate at the levels initially envisioned under EISA ($\approx$ 25%), the regulator can reduce DWL by \$795 million/year by offering around a \$0.30/gal credit price. Thus, even at lower levels commonly seen in regulations today, we see potentially large improvements by strategically pairing a cost containment mechanism with an RFS. A credit window leads to larger efficiency gains when mandates are very stringent. A 50% RFS with no cost containment mechanisms leads to a DWL exceeding \$25 bil/year. With a credit window offering, setting the credit window price optimally reduces DWL to $\approx$ \$8 bil/year, lower than business as usual losses. The optimal RFS-credit window corresponds to a 100% biofuel mandate and a credit window price of \$0.26/gal. Optimally setting both the RFS and credit window price reduces DWL to around \$7.3 bil/year.

The right graph in Figure 1(b) presents similar results for four LCFS mandates. The thin solid line corresponds to the second-best LCFS with a 4.8% CI reduction; the short-dashed line corresponds to an LCFS requiring a 12% CI reduction, approximately the long-run mandates under the original LCFS; the long-dashed line corresponds to a 50% CI reduction; and the line with diamonds corresponds to an LCFS requiring a 78% CI reduction. A binding credit window offering does not improve the second-best LCFS,

[28]Figure C.1 in Appendix C shows credit purchases in each scenario in panel (b). Credit window purchases decrease as credit window prices become higher, and reach zero when credit window prices exceed the policy constraint's shadow price.

i.e., DWL is lowest with a non-binding credit window price. However, a strategically set credit window can substantially reduce DWL of an even slightly more aggressive LCFS. When the policy sets a 12% CI reduction, approximately the long-run mandates under the original LCFS, setting a credit window price around $0.85/gal reduces the deadweight loss of the policy by almost $7.5 billion/year. Potential reductions are even larger for more stringent LCFS policies, consistent with our theoretical results. 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.

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 mandate level and the credit window price are set optimally, this second-best optimal combination of the mandate level and credit window price can substantially reduce deadweight loss from the emissions externality. Indeed, under the LCFS, when both the LCFS and the credit window price are set optimally, this second-best optimal combination nearly eliminates deadweight loss. Importantly, however, we show that the efficiency of an RFS – even with a second-best optimal combination of an RFS and a credit window price – is limited by its inability to differentiate fuels based on their relative emission intensities.

Aggressive low-carbon fuel mandates are becoming the norm, rather than the exception, in electricity and transportation fuel markets. Our results highlight how, rather than relaxing or revisiting unrealistic mandate levels after they are unmet, strategically setting cost containment mechanisms can substantially increase the policies' efficiency. Further, we derive intuitive, easy-to-calculate upper bounds to guide policy on how to set an efficient cost containment mechanism. Namely, the policy should ensure that the implicit fossil-fuel tax is below the first-best fossil fuel tax.

The cost containment mechanism considered here could produce substantial government revenues (Charles River Associates, 2018). This would represent a fundamental shift in regulators' administrative role in these programs since transfers that take place under renewable fuel mandates rarely involve regulators collecting revenues. While beyond the scope of this paper, these funds could have the added benefit of increasing funding for infrastructure programs or research and development for advanced biofuels, relaxing some of the very constraints that may lead to high compliance costs. Such programs have ready equivalents in cap-and-trade programs. For example, California uses proceeds from its cap-and-trade program to invest in programs that 'facilitate greenhouse gas (GHG) emission reductions and provide economic, environmental, and public health benefits' (CARB, 2019a). The success of an intervention in compliance credit markets also depends on the existence of a liquid market for credits. While the RIN credit market has been relatively developed since 2009, recent price spikes in 2013 have caused some participants to question whether the market has behaved efficiently. California's LCFS credit market has also been characterized by low trade volumes and large swings in the credit values. If compliance credit markets have high transaction costs or poor price discovery, the results discussed here are not applicable. Further exploration of these issues, both analytically and empirically, would help understand the efficiency of these policies.

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A Market Effects

A.1 Market effects of fuel mandates

We first study the effects of each fuel mandate on important market outcomes. The compliance credit price under both an RFS and an LCFS 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:

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

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:

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

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

The equations illustrate the similarity of the two fuel mandates.[29] 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 A.1 summarizes important comparative statics with respect to the policy parameters under a binding fuel mandate.

Proposition A.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.[30] Under an LCFS, decreasing σ increases production of renewable fuel q^r if $\frac{1}{\xi^c} - \frac{1}{\eta^d} > (\phi^c - \sigma)\frac{\lambda}{P}$.

[29]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.

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

- **Proof of Proposition A.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.[31] 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:

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

  Solving for the LCFS yields:

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

[31] 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:

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

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.[32]

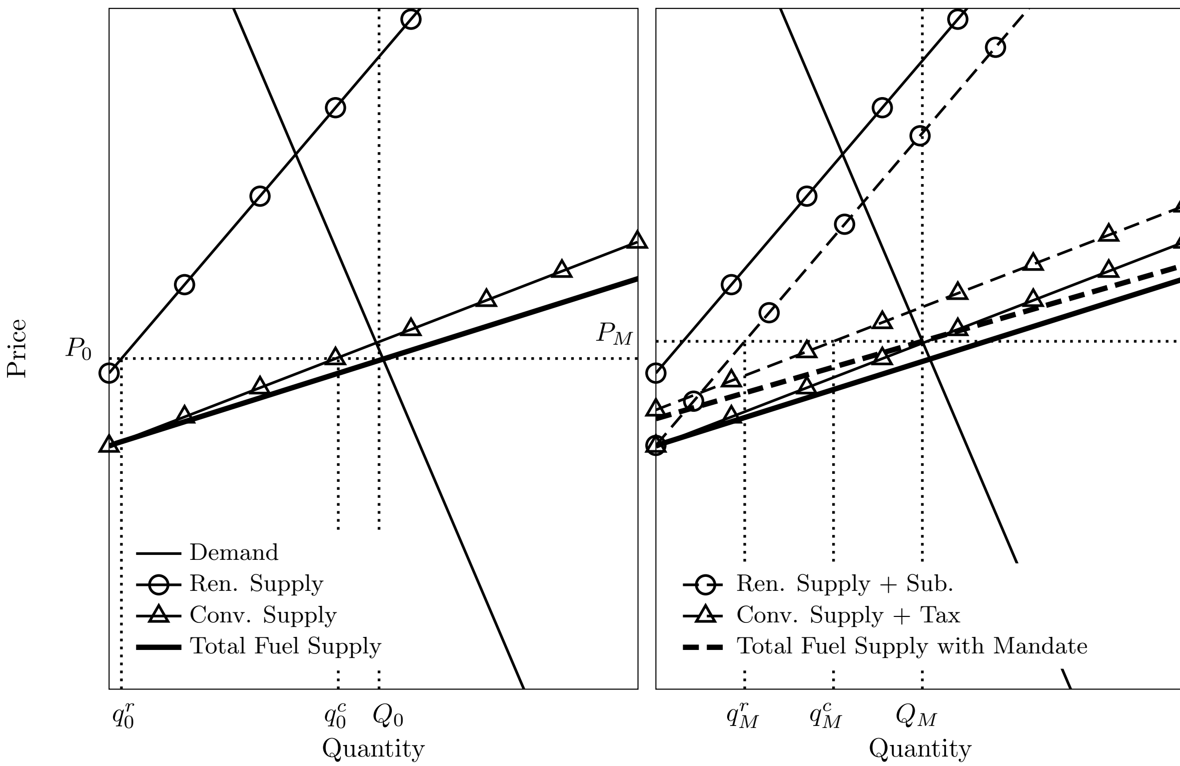
Figure A.1 illustrates the effects of both policies. The left figure graphs the no policy equilibrium, and the right figure graphs equilibrium under a fuel mandate. In both graphs, the downward sloping line is the fuel demand curve; the upward sloping line with triangles is the conventional fuel supply 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.

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 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.

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

Figure A.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.

A.2 Market effects of cost containment mechanism

We next examine the market effects of a cost containment mechanism that caps compliance costs. We model the cost containment mechanism as the regulator offering a credit window for compliance credits. Under a credit window, firms have the option to purchase compliance credits directly from the regulator at a given credit window price. The credits purchased from the regulator would not be associated with the production of any renewable fuel but would increase liquidity in the market.

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. Proposition A.2 summarizes the comparative statics for the credit window price $\bar{p}^{\text{cred}}$ when firms purchase from the credit window.

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

- **Proof of Proposition A.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 Intuition for Inefficiency of Mandates

B.1 Mandates and marginal abatement costs

For additional intuition for the second-best nature of fuel mandates relative to a first-best cap-and-trade program, we analyze how the marginal abatement cost per unit of emissions relates to the permit price under a cap-and-trade program. We then compare it to how the marginal abatement cost per unit of emissions relates to the credit price under a fuel mandate.

With a cap-and-trade permit system, the first-order condition for an interior solution for each fuel $i \in \{c, r\}$ is given by:

$$P - \frac{\partial C^i}{\partial q^i} = \tau \phi^i, \tag{B.1}$$

where τ is the permit price.

For each fuel $i \in \{c, r\}$, the marginal abatement cost per unit of output is given by $P - \frac{\partial C^i}{\partial q^i}$, while the marginal abatement cost MAC^i per unit of emissions is given by:

$$MAC^i = \left(P - \frac{\partial C^i}{\partial q^i} \right) / \phi^i. \tag{B.2}$$

In a cap-and-trade permit system, the marginal abatement cost MAC^i per unit of emissions given by equation (B.2) equals the permit price τ for each fuel i. As a consequence, a cap-and-trade permit system can achieve the first-best when the permit price equals marginal damages: $\tau = D'(\cdot)$. Under the first-best cap-and-trade permit system, the marginal abatement cost MAC^i per unit of emissions is equalized across both fuels i and set equal to marginal damages: $MAC^i = D'(\cdot)\ \forall i$.

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

$$[q^c :] \quad P - \tfrac{\partial C^c}{\partial q^c} = \lambda \alpha \tag{B.3}$$

$$[q^r :] \quad P - \tfrac{\partial C^r}{\partial q^r} = -\lambda \tag{B.4}$$

for the RFS, and:

$$[q^c :] \quad P - \tfrac{\partial C^c}{\partial q^c} = \lambda \left(\phi^c - \sigma \right) \tag{B.5}$$

$$[q^r :] \quad P - \tfrac{\partial C^r}{\partial q^r} = -\lambda \left(\sigma - \phi^r \right) \tag{B.6}$$

for the LCFS.

Once again, for each fuel $i \in \{c, r\}$, the marginal abatement cost per unit of output is given by $P - \frac{\partial C^i}{\partial q^i}$, while the marginal abatement cost MAC^i per unit of emissions is given by equation (B.2). The fuel mandate credit price λ does not equal the marginal abatement cost per unit of emissions, however. Instead, from the first-order conditions in equations (B.3) and (B.4), the RFS credit price λ is given by the following:

$$[q^c :] \quad \left(P - \frac{\partial C^c}{\partial q^c}\right)/\alpha = \lambda \tag{B.7}$$

$$[q^r :] \quad -\left(P - \frac{\partial C^r}{\partial q^r}\right) = \lambda. \tag{B.8}$$

Likewise, from the first-order conditions in equations (B.5) and (B.6), the LCFS credit price λ is given by the following:

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

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

Fuel mandates implicitly tax conventional fuels and subsidize renewable fuels. With the RFS, this is because a firm generates credits from the production of renewable fuel, even though the renewable fuel may have a non-zero emissions factor ϕ^r. With the LCFS, this is because a firm only requires (generates) credits based on how much the carbon intensity ϕ^i of the fuel $i = c, r$ exceeds (is lower than) the average carbon intensity σ mandated by the LCFS standard.

Substituting in the marginal abatement cost MAC^i per unit of emissions given by equation (B.2) into equations (B.7)-(B.10) for the fuel mandate credit price λ, we get:

$$[q^c :] \quad MAC^c = \lambda\alpha/\phi^c \tag{B.11}$$

$$[q^r :] \quad MAC^r = -\lambda/\phi^r \tag{B.12}$$

for the RFS, and:

$$[q^c :] \quad MAC^c = \lambda\left(\phi^c - \sigma\right)/\phi^c \tag{B.13}$$

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

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 credit price, and is not equalized across fuels i. As a consequence, mandates cannot achieve the first-best. The RFS provides an implicit subsidy for renewable fuels even if the renewable fuel may have a non-zero emissions factor ϕ^r, meaning the RFS does not give an incentive to reduce the emissions from these fuels. Similarly, for fuels with carbon intensities ϕ^r lower than the average carbon intensity σ mandated by the LCFS, the LCFS provides an implicit subsidy even if the carbon intensity of that fuel is non-zero, meaning the LCFS does not give an incentive to reduce the emissions from these fuels.

B.2 Graphical representation of second-best mandates

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.[33] In the absence of any policy, the competitive market maximizes the sum of 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.

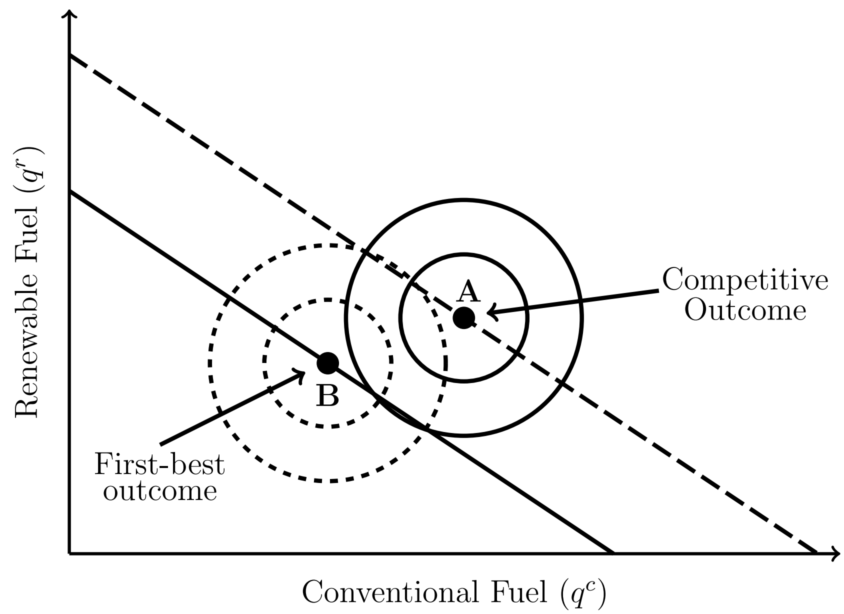
Now consider the efficiency of fuel mandates, illustrated in Figure B.1(b). We represent both policies as rays from the origin, where the slope of the ray corresponding to the share of renewable fuel required by the policy. A binding share mandate must pass to the left of the initial share of renewable 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.

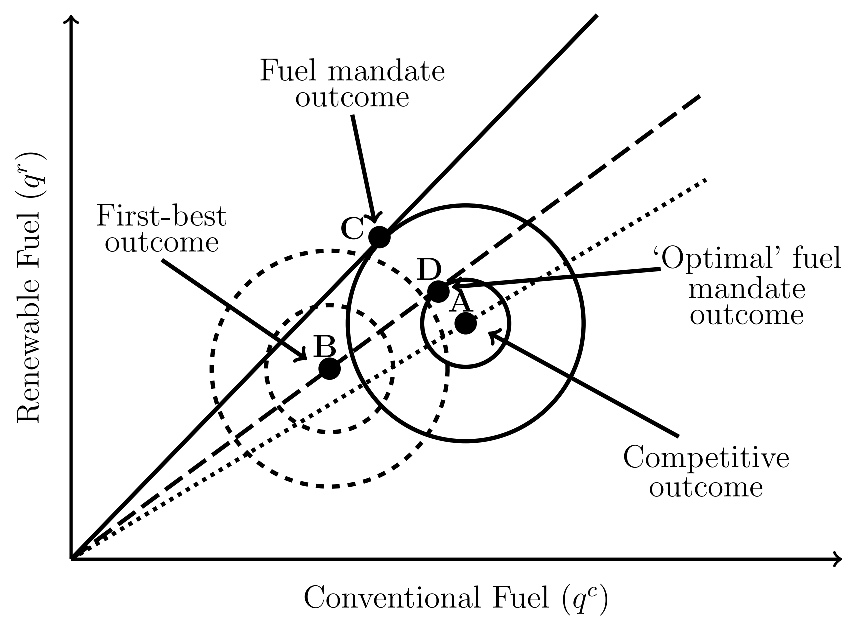
[33] Specifically, the solid circles represent level curves of the function $U(Q) - C^c(q^c) - C^r(q^r)$, and the dashed circles represent level curves of the function $U(Q) - C^c(q^c) - C^r(q^r) - D(\phi^c q^c + \phi^r q^r)$, where $U(Q)$ is the total benefit from fuel consumption. When the marginal utility of income is constant, the total benefit from fuel consumption Q is given by the area under the demand curve, which measures the gross consumer surplus. Weitzman (2003) shows that using the area under the demand curve in place of firm revenue yields the same outcome as a perfectly competitive market (Lin and Wagner, 2007; Lin, 2009; Lin et al., 2009; Lin Lawell, 2021).

Thus, owing to their implicit subsidy on renewable fuels, 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).

Figure B.1: First-best, competitive outcome, and fuel mandates



(a)

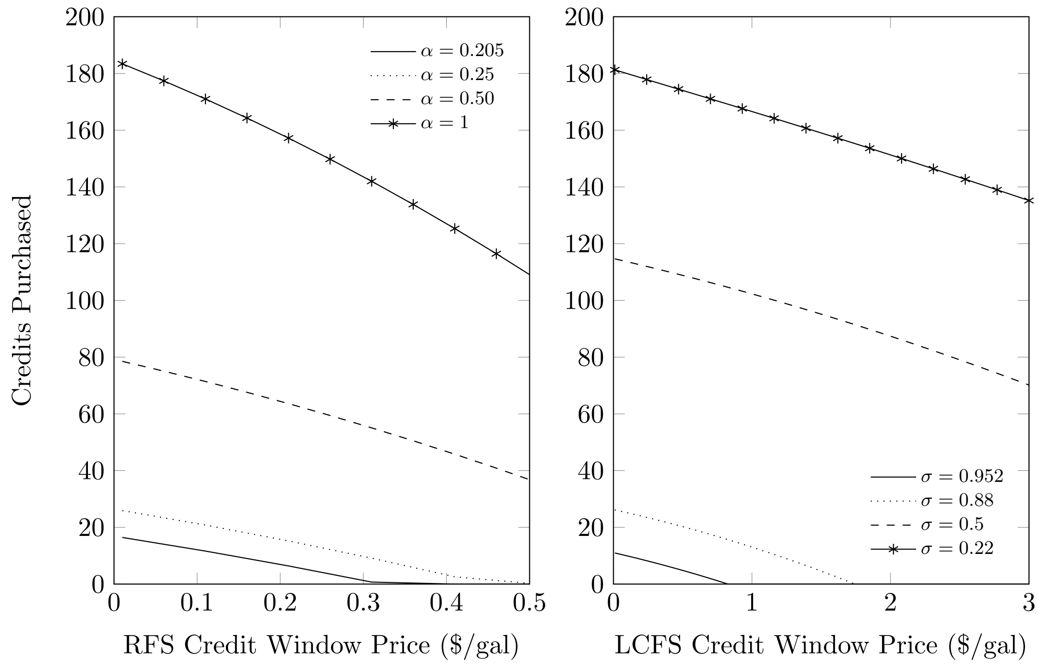


(b)

*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.

C Additional Simulation Results

Figure C.1: Compliance Credit Purchases



Notes: The graphs plot the compliance credits purchased on the y-axes against compliance credit prices on the x-axes for different RFS mandated shares α and different LCFS mandated carbon intensity standards σ, respectively.