

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

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## Abstract

Policymakers at the federal and state level have generally favored renewable fuel mandates over taxes and cap and trade programs to address climate change concerns and reduce emissions from the transportation sector. Given difficulties with deploying and developing commercially viable fuel alternatives to fossil fuels, fuel mandates risk large increases in short-run compliance costs as the policies become more stringent. We study the effects and efficiency of two types of mandates, a renewable share mandate similar to the federal Renewable Fuel Standard and a carbon intensity standard similar to California's Low Carbon Fuel Standard, as well as the effects of two cost containment provisions, a hard cap and a soft cap, on compliance credit prices. We show numerically that both fuel mandates in isolation are only able to achieve around a quarter to a third of the efficiency of the first-best policy; however, when combined strategically with a hard cap on compliance costs, the efficiency of both policies can increase substantially. Policies which act to relax the standard in response to high compliance costs achieve only moderate efficiency gains.

**JEL Codes:** H23, Q42, Q54, Q58

**Keywords:** Renewable fuels, second-best policies, share mandates, intensity standards

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# 1 Introduction

The transportation sector is estimated to be responsible for over a quarter of greenhouse gas emissions in the United States.<sup>1</sup> The vast majority of carbon emissions from the sector are the direct result of the combustion of fossil fuels from internal combustion engines (Intergovernmental Panel on Climate Change, 2007). Rather than establish a carbon tax or pursue a cap and trade program covering all transportation emissions, policy-makers at the federal and state levels in the US predominantly favor renewable share mandates and carbon intensity standards to reduce fuel emissions.<sup>2</sup> The two most prominent policies currently in place in the US are the federal Renewable Fuel Standard (RFS), a renewable share mandate, and California’s Low Carbon Fuel Standard (LCFS), a carbon intensity standard. Several other states have also considered implementing similar policies as California’s LCFS, and legislation is being pursued at the federal level to replace or supplement the federal RFS with a national LCFS (Yeh et al., 2012).<sup>3</sup>

In this paper, we formalize, expand upon and synthesize the previous literature by developing a theory model to study both a renewable fuel share mandate and a carbon intensity standard. We study the effects of each policy on key market outcomes including fuel prices and the volume of fuels. We also analytically and numerically derive the optimal level of each policy under alternative assumptions regarding the level of carbon damages and the availability of renewable fuels.<sup>4</sup> In addition, we study the effects of two cost containment mechanisms which have either been implemented or proposed in practice: (1) a credit window whereby regulated parties can purchase an unlimited number of compliance credits from the regulator at a fixed price; and (2) a clean fuel multiplier whereby the regulator allows parties to inflate the accounting of certain renewable fuels towards the respective standard. We refer to the former as a ‘hard cap’ and the latter as a ‘soft cap’ on compliance costs, for reasons which will become apparent in Section 4.

We show that whenever renewable fuels are costly to incorporate into the fuel supply such that the short-run renewable fuel supply curves are particularly steep, the two cost containment mechanisms have the benefit of both restraining compliance costs from exceeding desired levels as well as improving the efficiency of both fuel mandates. When both the standard and cost containment mechanism are set strategically, the efficiency of each program may increase. In a special case, a LCFS with a hard cap on credit prices may achieve the first-best, though the level of the LCFS in this scenario is unrealistic in practice. Using a numerical model of the US gasoline market, we show that the efficiency gains from strategically incorporating cost containment mechanisms into fuel mandates can be substantial. In particular, we show that hard caps on compliance credit prices coupled with stringent fuel mandates can lead to large welfare gains compared to the second-best fuel mandates alone. In addition, we show that a clean fuel multiplier can yield modest improvements relative to the second-best policies alone.

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<sup>1</sup>See <http://www.epa.gov/climatechange/ghgemissions/sources/transportation.html>.

<sup>2</sup>An exception is California’s cap and trade program. Beginning in 2015, refiners in California will hold an obligation under the program for carbon emissions from the combustion of all fossil fuels sold in the state. The most aggressive policy aimed at reducing carbon emissions in the state, however, remains the Low Carbon Fuel Standard, which is a carbon intensity standard.

<sup>3</sup>The legislature in Oregon passed a bill in 2009 authorizing the state’s Environmental Quality Commission to adopt a LCFS. In 2011, the state’s LCFS advisory committee released a report outlining how the program could be designed; however, the program has yet to be implemented (Langston et al., 2011). In 2009, Washington state’s governor issued Executive Order 09-05, directing the state’s Department of Ecology to study whether adopting a LCFS would meet the state’s greenhouse gas reduction goals. For a more exhaustive list of all states and regions which have considered or implemented a LCFS, see <http://nationallcfsproject.ucdavis.edu/map/>.

<sup>4</sup>Throughout the paper, we use the terms renewable, alternative and low carbon intensity interchangeably to describe fuels with low carbon emissions derived from sources other than fossil fuels.

The paper proceeds as follows. Section 2 provides a brief background of both the Renewable Fuel Standard and the Low Carbon Fuel Standard, as well as discusses cost containment provisions which have either been considered or implemented under each policy. Section 3 reviews the previous literature. Section 4 presents our analytical model and derives the main results regarding the effect of each policy, the effects of cost containment under each policy, as well as the optimal level of the policies and cost containment provisions. Section 5 presents our numerical model and results for a model of the US gasoline market, and Section 6 concludes.

## 2 Renewable fuel policies

### 2.1 The Renewable Fuel Standard

The Renewable Fuel Standard (RFS) was established by the Energy Policy Act of 2005 and was expanded by the Energy Independence and Security Act (EISA) of 2007, creating the RFS2. The program is a central component of US energy policy and sets ambitious standards for renewable fuel consumption with the goal of expanding consumption to 36 billion gallons (bgal) a year by 2022, which constitutes around a quarter of the current US fuel supply. The Environmental Protection Agency (EPA) administers the program, and is allowed discretion when setting each year's standards. In addition to expanding the total biofuel component of the RFS, the RFS2 created new categories of renewable fuel and set separate volume requirements for each.<sup>5</sup> In 2013, the total biofuel mandate was 16.55 bgal, of which a maximum of 13.8 bgal could be met using conventional corn ethanol and the rest must be met with the other categories of biofuels. In contrast, the 2022 total mandate is currently set at 36 bgal, of which conventional corn ethanol is limited to 15 bgal (Environmental Protection Agency, 2013a).

### 2.2 California's Low Carbon Fuel Standard

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

Under the LCFS, obligated parties in California must reduce the weighted average carbon intensity of fuel sold in the state by pre-specified amounts each year. The program is agnostic as to which fuels can be used to meet the standard, so long as all production pathways are approved and the fuels are assigned carbon intensity values by the ARB.<sup>6</sup> For example, provisions are made such that electricity providers for plug-in vehicles as well as hydrogen fuel providers for hydrogen vehicles may generate LCFS credits which can be sold to regulated parties.<sup>7</sup> Thus, the fuel industry in California faces only technological and economic constraints in choosing the optimal fuel mix to comply with the program.

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<sup>5</sup>The additional categories under the law are: (1) cellulosic biofuel; (2) biodiesel; and (3) advanced biofuel.

<sup>6</sup>Carbon intensity factors represent the ARB's best guess as to the average carbon equivalent emissions rate for a given fuel. Low carbon intensity fuels, or fuels which offer the largest average carbon emission reductions relative to fossil fuels, include biofuel derived from cellulosic feedstock, natural gas, hydrogen fuel, and electricity. Conventional corn-based ethanol and biodiesel derived from soybeans have carbon intensity factors which constitute 80%-100% of the carbon intensity of gasoline and diesel.

<sup>7</sup>The full list of approved fuels is available at [http://www.arb.ca.gov/fuels/lcfs/1214091cfs\\_lutables.pdf](http://www.arb.ca.gov/fuels/lcfs/1214091cfs_lutables.pdf).

## 2.3 Tradeable credits and compliance costs

A feature common to the RFS and LCFS is the provision of a compliance credit trading program. Obligated parties under both policies are defined as refiners and importers of gasoline and diesel fuel. Policy makers allow firms to trade compliance credits amongst themselves which must be turned in at the end of each compliance period. Given the growing number of small firms producing renewable fuels and generating credits under the programs as well as the fact that most renewable fuels are blended downstream of the refining process, allowing small firms and downstream blenders to generate credits and sell them to obligated parties upstream creates substantial flexibility in both programs and reduces the number of regulated parties and implementation costs.

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

Under the LCFS, credits and deficits are denominated in tons of CO<sub>2</sub> equivalence and calculated using the relative carbon intensity values assigned to each fuel pathway by the California ARB. For example, refiners and importers of gasoline, which has a carbon intensity factor higher than the standard, generate deficits under the program equal to the volume of fossil fuels multiplied by the difference between the intensity factor of gasoline and the standard in the year the fuel is produced. Firms which produce fuels with carbon intensity factors below the standard generate credits equal to the volume of renewable produced fuel multiplied by the difference between the standard and their lower intensity factors. Thus, credits (deficits) are generated only for the amount of emissions below (in excess) of the LCFS. Refiners can maintain compliance with the program by purchasing credits from low carbon intensive fuel producers, producing or blending renewable fuels themselves, reducing their production, or lowering the carbon intensity factors of their own fuel by changing their production pathways.

## 2.4 Implementation issues and cost containment mechanisms

Implementing a policy such as the RFS or LCFS is more involved than simply setting a standard. Under intensity standards, carbon intensity factors for each type of fuel are difficult to assign, and the values depend crucially on contentious assumptions regarding the induced land use change from the expansion of land used to grow energy crops (Searchinger et al., 2008). For both policies, setting the standards as well as determining other key features of the policy are often the result of both scientific and political processes (Holland et al., 2013).

To date, the predominant fuel used to meet both standards is conventional, corn-based ethanol. In a recent status review of the LCFS, Yeh et al. (2013) find as of Spring 2013 that around 78% of credits generated under the LCFS have been derived from conventional ethanol, with the second and third highest volume of credits generated by natural gas and biodiesel at 12% and 9%, respectively. Under the RFS, corn-based ethanol can be used to meet over 80% of the mandate, or 13.8 billion gallons, in 2013 (Environmental Protection Agency, 2013a).

The success of both the RFS2 and LCFS in coming years faces a number of challenges. The two largest threats to the viability of both programs are: (1) the ‘blend wall’; and (2) the lack of development of low carbon fuels such as cellulosic ethanol or other alternative fuels such as natural gas, electric and hydrogen.

The blend wall refers to the notion that consumption of ethanol beyond 10% of the US fuel supply is costly. Ethanol has been traditionally blended with gasoline at two levels: 10% ethanol, referred to as E10; and 85% ethanol, referred to as E85.<sup>8</sup> Blends up to E10 have been approved by the EPA for decades. In 2011, the EPA granted a partial waiver for E15 blends, though the waiver was only approved for model year vehicles 2001 and newer due to concerns of increased engine corrosion from higher blend fuels in older vehicles (Environmental Protection Agency, 2011). The waiver maintains strict Reid Vapor Pressure (RVP) limits, which effectively restricts E15 from being sold in many urban regions of the United States in the summer when more stringent air quality standards are in effect. As a result, little E15 has been sold to date, leaving the two predominant fuel blends at E85 and E10. To sell E85 requires consumers to have special vehicles known as flex fuel vehicles and gasoline station owners to invest in special fueling infrastructure. While many flex fuel vehicles have been produced and are currently on the road, the penetration of E85 fueling stations has been mostly limited to the Midwestern United States. This increases concerns among industry actors that blending more than 10% ethanol may be costly in the short run.<sup>9</sup>

The second threat to the viability of the RFS and LCFS is the lack of development of low carbon intensive fuels. Under the RFS2, fuels derived from cellulosic biomass were initially mandated to reach 16 billion gallons by 2022. Thus far, actual cellulosic production in the US is far below mandated levels. For example, the RFS2 mandate originally required 100 million gallons of ethanol derived from cellulosic feedstock to be blended into the US fuel supply for 2012. Actual production was essentially zero (Energy Information Agency, 2012b). The success of both mandates in coming years depend crucially on the development of low carbon, advanced fuels. For example, Yeh et al. (2013) find the current fuel mix including all excess credits generated to date in California will only allow the industry to maintain compliance with the LCFS through the end of 2013.

Both the Environmental Protection Agency and the California Air Resources Board have either taken direct action or considered implementing provisions to address the fuel industry’s inability to meet each standard in the short run. For example, the EPA has allowed obligated parties to purchase cellulosic RINs through an open credit window at a fixed price to account for their cellulosic fuel obligation under the RFS2 since 2010. In addition, in November 2013, the EPA publicly acknowledged difficulties with meeting the RFS2 in coming years due to both the lack of development of cellulosic biofuel as well as the presence of the blend wall (Environmental Protection Agency, 2013b). As a result, the EPA proposed substantial reductions to both the cellulosic mandate as well as the overall biofuel mandate in 2014 and beyond.<sup>10</sup> In May 2013, the ARB released a white paper discussing a number of mechanisms to contain compliance costs under the LCFS in the short run.<sup>11</sup> The paper discusses a number of provisions meant to ensure compliance costs are

<sup>8</sup>The Clean Air Act Amendments (CAAA) of 1977 prohibit any fuel additive from being blended into the US gasoline supply unless the EPA grants a waiver for the fuel. In order to obtain a waiver, parties must demonstrate the additive will not lead to higher emissions of key criteria pollutants (see Clean Air Act Section 211(f)). The waivers are difficult to obtain for low blends of ethanol because at lower blends ethanol increases the volatility of fuels which can violate Reid Vapor Pressure (RVP) requirements under the CAAA of 1990.

<sup>9</sup>Exacerbating the problem under the RFS, the original volumes specified by EISA were set under the assumption that gasoline consumption in the United States would increase each year. Instead, US gasoline consumption has decreased since 2007. As a result, the blend wall has become a concern much sooner than originally anticipated.

<sup>10</sup>For 2014, the proposed overall biofuel standard is 15.21 bgals, which is slightly below the finalized standards for 2013 and nearly 3 bgals below the volumes mandated in the EISA 2007 (Environmental Protection Agency, 2013b).

<sup>11</sup>The paper is available at <http://www.arb.ca.gov/fuels/lcfs/regamend13/20130522ccp.conceptpaper.pdf>.

constrained to reasonable levels. In a report prepared for the California Air Resources Board, Lade and Lin (2013) discuss both compliance costs drivers under a LCFS as well as study the proposed cost containment mechanisms. In this paper, we formalize and expand upon Lade and Lin (2013) by developing a theory model to study both a renewable fuel share mandate and a carbon intensity standard.

### 3 Previous literature

The market effects of carbon intensity standards and renewable fuel share mandates have been studied by a number of authors (de Gorter and Just, 2009; Holland et al., 2009; Lapan and Moschini, 2012; Lade and Lin, 2013). The literature highlights the complex nature of the policies. Two results which have emerged are that both policies act as implicit taxes on conventional fuels and implicit subsidies for renewable fuels, and that the policies are not able to achieve the first-best outcome when the only market failure is the presence of unpriced carbon emissions.

In addition to the papers studying the effects of fuel mandates, there is a growing literature studying unintended consequences from the policies as well as their relative efficiency in the presence of additional market complexities. The papers follow in the spirit of the literature on second-best policies, and compare the performance of renewable share mandates and intensity standards with market-based policy instruments such as carbon taxes and cap and trade programs.

For example, Holland (2012) studies the efficiency of intensity standards in the presence market power, finding that a renewable share mandate can be more efficient than a carbon tax when firms are able to influence fuel prices. Holland et al. (2011) compare a national RFS and LCFS with a transportation sector cap and trade program. The authors set the level of each policy so that the same amount of emission reductions are achieved under each policy, and find a RFS and LCFS are much more costly means of reducing carbon emissions than a cap and trade program or tax. Holland et al. (2013) study the effects of a RFS and LCFS on land use and incentives for innovation in low carbon fuel technologies and emissions. As expected, the authors find that land use change is much larger under a RFS and LCFS compared to a cap and trade program. Interestingly, the authors also find that incentives to innovate and invest in renewable fuels, a key policy goal of the LCFS and RFS, may be less than the corresponding incentives under a cap and trade program.

Rajagopal et al. (2011) study the performance of a RFS and LCFS when the policies can only be applied at the national level and the economy is open to trade. The authors use alternative metrics to study the performance of both policies such as the overall share of renewable fuel production under each policy, total emission reductions under each policy, and the effect of each policy on final fuel prices. They find a RFS may be preferable if a fuel policy may only be applied at the national level and the economy is open to trade.

A small literature exists studying the potential to increase the efficiency of fuel mandates when regulators set the policies strategically. Lemoine (2013) studies a LCFS when carbon intensity factors are uncertain and the regulator has the ability to strategically set both the level of the carbon intensity standard and the assigned intensity factors of each fuel. He shows that the second-best standard may involve a regulator setting carbon intensity factors which are different than their expected values. Holland et al. (2009) derive characteristics of a second-best LCFS, but do not explicitly solve for the second-best carbon intensity level analytically or numerically.

In this paper, we formalize, expand upon and synthesize the previous literature by developing a theory model to study both a renewable fuel share mandate and a carbon intensity standard. We study the effects of each policy on key market outcomes including fuel prices, emissions, and the volume of renewable fuel. We also analytically and numerically derive the optimal level of each policy under alternative assumptions regarding the level of carbon damages and the availability of renewable fuels. In addition, we study the effects of two cost containment mechanisms which have either been implemented or proposed in practice: a 'hard cap' and a 'soft cap'.

## 4 Model

To study the effect of each policy and cost containment mechanism, we model a competitive industry composed of  $N$  price taking firms which produce a homogeneous fuel,  $Q$ . Suppose the industry uses two inputs in production: (1) a conventional fuel input,  $q^c$ ; and (2) a renewable fuel input,  $q^r$ .<sup>12</sup> Assume the inputs are perfect substitutes such that  $Q = q^c + q^r$ . Thus, we assume consumers do not value the source of the fuel they consume, but only the volume of final fuel.

In the context of transportation fuels, the empirical literature studying how consumers value alternative fuels compared to conventional fossil fuels is limited to date. Anderson (2010) finds that consumers in the Midwest are willing to pay a premium for E85, while Abu-Sneneh et al. (2012) find evidence suggesting the price of E10 does not fully discount the loss in energy due to ethanol blending.<sup>13</sup> Our model can be adapted to account for differences in preferences for renewable fuels. So long as the relative values consumers place on each fuel are additive and linearly separable, the subsequent results would only need to be adjusted by a scale factor on either fuel. For example, if consumers value only the energy content of fuels, we can assume the fuels are perfect substitutes whenever they are denominated in common energy units such as mega-joules (MJ).

Suppose each input is associated with emission factor  $\phi^j$  for  $j = c, r$ . Emissions are associated with damages, captured by the damage function  $D(q^c, q^r; \phi)$ , where  $\phi = (\phi^c, \phi^r)$  is the vector of emissions per unit of each fuel. For simplicity, assume the damage function is linear in total emissions such that:

$$D(q^c, q^r; \phi) = \Psi(\phi^c q^c + \phi^r q^r),$$

where  $\Psi$  is the marginal damages of emissions.

In what follows, we first study the effects of each policy in isolation as well as the effects of the two cost containment mechanisms on the market. We consider a 'hard cap' on compliance costs, instituted by allowing compliance credits to be available through an open credit window at a fixed price. In addition, we study a 'soft cap' on credit prices, whereby the regulator allows credits generated by renewable fuels to account more towards compliance than other fuels through a credit multiplier. We then derive and characterize the second-best level of each policy analytically, as well as the second-best level of cost containment provisions conditional on each standard already being in place.

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<sup>12</sup>The assumption is made for notational ease. The results do not change if we assume there are multiple types of each fuel. See Lade and Lin (2013), Appendix A.

<sup>13</sup>A gallon of ethanol has around 70% of the energy content as a gallon of gasoline regardless of the feedstock from which ethanol is derived. A gallon of neat biomass-based diesel has around 95% of the energy content of conventional diesel fuel.

## 4.1 Market effects of fuel mandates

Consider the competitive market outcome under no regulation. Given our assumption that the industry is perfectly competitive, we model the market equilibrium using a representative firm which prices competitively. Assuming aggregate increasing, convex cost curves  $C^c(q^c)$  and  $C^r(q^r)$  for conventional and renewable fuel, respectively, the solution to the representative firm's problem will replicate the competitive market equilibrium (Mas-Colell et al., 1995).<sup>14</sup> The representative firm's problem is to choose the optimal fuel mix so as to maximize profits:

$$\max_{q^c, q^r \geq 0} p(q^c + q^r) - C^c(q^c) - C^r(q^r).$$

The Karush-Kuhn-Tucker optimality conditions are given by:<sup>15</sup>

$$\begin{aligned} [q^c :] \quad & p - C^{c'}(q^c) \leq 0 \\ [q^r :] \quad & p - C^{r'}(q^r) \leq 0. \end{aligned}$$

The conditions hold with equality whenever the market clearing quantity of each fuel is strictly positive. Next, consider the consumer side of the market. We assume consumers' have quasi-linear preferences for fuel given by utility function  $U(Q)$  with  $U'(Q) \geq 0$  and  $U''(Q) \leq 0$ . Given quasilinear preferences, we can model the consumers' problem using a representative consumer with an associated maximization problem given by:

$$\max_Q U(Q) - pQ + \omega,$$

where  $\omega$  is the aggregate wealth of consumers.<sup>16</sup> Consumers choose their fuel consumption where  $U'(Q) \leq p$ , and the constraint binds so long as a positive amount of fuel is consumed. Combining the representative firm and consumer optimality conditions along with the market clearing condition  $Q = q^c + q^r$  fully characterizes the competitive market equilibrium.

Neither the representative firm nor the representative consumer takes into consideration the marginal damages from each fuel when making their production and consumption decision. Because each fuel has an additional cost on society equal to the emission damages, the competitive market outcome leads to the classical market failure characterized by over-consumption of fuels and an inefficiently high level of emissions. The market failure can be corrected using either a Pigouvian tax or by capping emissions from the fuel sector at the first-best pollution level (Pigou, 1920; Coase, 1960).

For both political economy reasons as well as energy security concerns, policymakers at both the state and federal level have favored renewable fuel mandates over Pigouvian taxes or cap and trade programs to correct market failures in the fuel sector.<sup>17</sup> We study two mandates: (1) a renewable fuel share mandate

<sup>14</sup>Note that while we only allow a single aggregate cost function for each firm, the representative refiner's problem does not preclude underlying heterogeneity in individual firms' costs.

<sup>15</sup>Primes are used throughout to denote partial derivatives. Where primes are ambiguous, we use conventional partial derivative notation to be explicit about the derivative.

<sup>16</sup>See Mas-Colell et al. (1995) chapter 10.B.

<sup>17</sup>We do not attempt to model or quantify energy security benefits in this paper, as the energy security benefits of reducing petroleum imports are difficult to fully define and quantify. The debate surrounding energy security benefits of renewable fuel mandates has remained mostly a fixture of the political and popular media arenas. See Metcalf (2013) for a recent discussion regarding the contrast between energy policy as viewed by economists and policymakers. An exception is Leiby (2007), who estimates the cost of oil dependence as the energy-security related, demand-sensitive costs that are not reflected in market prices, but does not include federal expenditures associated with achieving these goals and the difficult-to-quantify foreign policy impact of oil import reliance. Thus, his estimate is not a measure of the full social costs of oil imports, or the full magnitude of the oil dependence and security problem.

which we refer to as the RFS since it is similar to the federal RFS; and (2) an energy-based carbon intensity standard which we refer to as the LCFS since it is similar to California's LCFS. We refer to the two policies generally as fuel mandates in contrast to taxes or emission limits.<sup>18</sup> For notational simplicity, we write each policy function as  $\varphi(q^c, q^r; \theta) \geq 0$ , where  $\theta$  are the policy parameters. Under a renewable fuel mandate, the representative firm's problem can be written as:

$$\mathcal{L} = \max_{q^c \geq 0; q^r \geq 0} p(q^c + q^r) - C^c(q^c) - C^r(q^r) + \lambda [\varphi(q^c, q^r; \theta)],$$

where  $\lambda$  is the Lagrange multiplier on the mandate constraint, which is positive whenever the policy binds on the industry and equal to zero otherwise.

The RFS requires the share of renewable fuel to be greater than a specified renewable volume obligation set by the EPA each year. Firms determine their individual compliance obligation by multiplying the amount of conventional fuel produced by the renewable volume obligation.<sup>19</sup> We write the RFS policy as  $q^r \geq \alpha q^c$ , where  $\alpha$  is the renewable volume obligation.

California's LCFS is an energy-based carbon intensity standard and regulates the average carbon intensity of fuel sold in the state. The California Air Resources Board (ARB) sets both the carbon intensity factors for each fuel as well as the standard in each year. We simplify the problem and assume the regulator knows each fuel's intensity factor, and write the LCFS policy constraint as  $\frac{\phi^c q^c + \phi^r q^r}{q^c + q^r} \leq \sigma$ , where  $\sigma$  is the standard.

We rewrite both policies to satisfy  $\varphi(q^c, q^r; \theta) \geq 0$  as follows:

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

where  $\theta = \alpha$  for the RFS and  $\theta = \sigma$  for the LCFS.

The Karush-Kuhn-Tucker conditions under a renewable fuel mandate are given by:

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

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

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

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

Our results corroborate the findings from previous work (de Gorter and Just, 2009; Holland et al., 2009; Lapan and Moschini, 2012). In particular, conditions (1) and (2) state that both policies act as implicit

<sup>18</sup>Given our assumption of a single renewable fuel, we do not model the RFS using a nested mandate structure. Thus, our model is most applicable to studying the RFS or the overall biofuel mandate under the RFS2.

<sup>19</sup>The renewable volume obligation is phrased as the amount of renewable fuel mandated by EISA divided by the projected volume of gasoline and diesel production in the next year. For example, the total renewable fuel mandate is calculated as:

$$\text{Std}_{RF} = \frac{Q^r}{Q_p^g + Q_p^d - Q_p^r - Q_p^e},$$

where  $Q^r$  is the mandated volume of renewable fuel,  $Q_p^g$  is projected gasoline production,  $Q_p^d$  is projected diesel production,  $Q_p^r$  is projected renewable fuel production and  $Q_p^e$  is projected production from exempted sources.

taxes on conventional fuels and implicit subsidies for renewable fuels. Under the policies, the level of the tax and subsidy is endogenous, and the Lagrange multiplier on the policy constraint adjusts to the point where the mandate is just met whenever the policy binds on the industry. The following lemma synthesizes and formalizes the previous literature by characterizing the qualitative nature of both policies and illustrating their similarity.

**Lemma 1:** *Under both fuel mandates, the equilibrium price is a weighted average of the marginal costs of each fuel, where the weights correspond to the share of each fuel required to meet the respective mandate.*

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

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

Given increasing and strictly convex cost functions, the two conditions characterize the unique equilibrium for both fuel mandates.<sup>20</sup> Equating the two optimality conditions, we can write the Lagrange multiplier, or the marginal value of relaxing each policy, as follows:

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

Substituting the expression for  $\lambda$  into either optimality condition above yields:

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

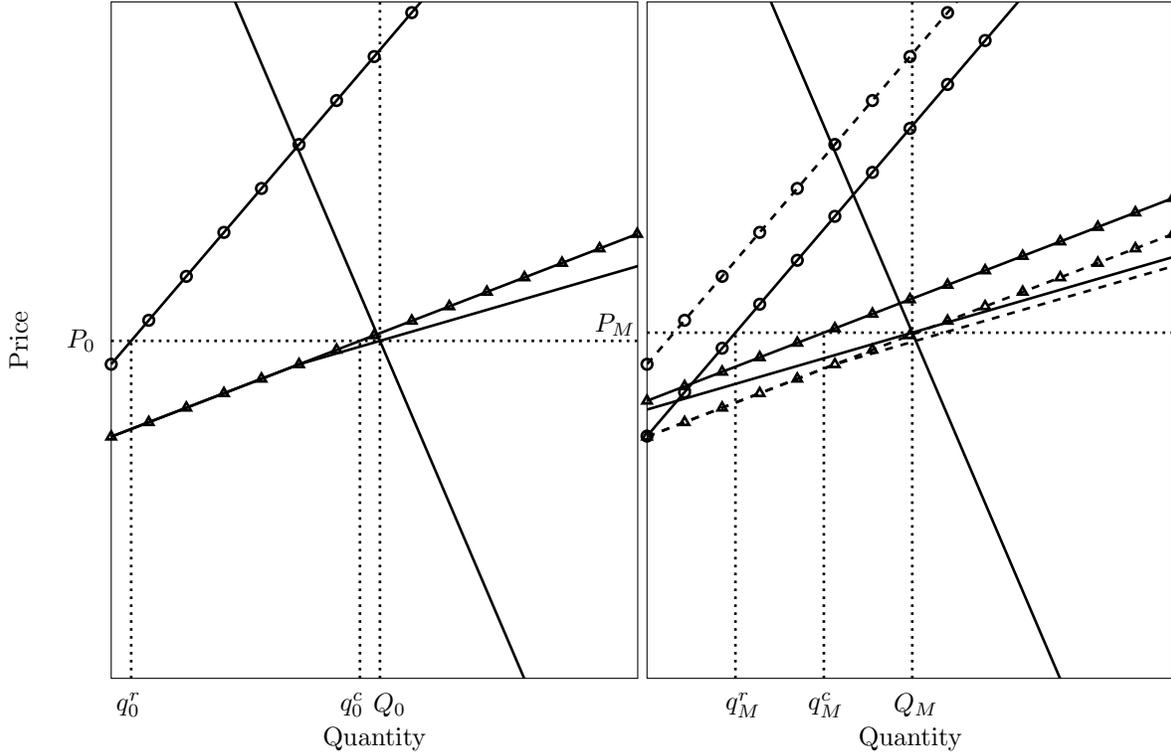
The equations show the final fuel price in equilibrium is equal to the weighted average of the marginal costs of each fuel, where the weights correspond to the share of each fuel required to meet the respective standard.  $\square$

Lemma 1 illustrates that while the two policies are phrased in a different manner, both act as either an explicit (RFS) or implicit (LCFS) renewable fuel share mandate. This feature makes any analysis of the two types of fuel mandates very similar. The distinguishing factor between the policies is how the implicit or explicit share mandate on renewable fuels is constructed. Under the RFS, the share mandate is set directly by  $\alpha$ , while for a LCFS the share mandate is based on the relative difference of the carbon intensity assignment of both the conventional and renewable fuel.

Figure 1 illustrates the effect of both policies with linear supply and demand curves. The left graph illustrates the initial equilibrium, and the right graph illustrates the equilibrium under either a RFS or LCFS. In both figures, the downward sloping line is the fuel demand curve, the line with triangles is the conventional fuel supply curve, the circled line is the renewable fuel supply curve, and the solid upward sloping line is the total fuel supply curve, which is equal to the horizontal sum of the renewable and conventional supply curves. In the left graph, the total and conventional fuel supply curves are the same until the price level reaches the intercept of the renewable fuel supply curve. The market clearing prices,  $P_0$  and  $P_M$ , are found where the total fuel supply curve intersects the fuel demand curve, and the supply of each fuel,  $q_i^c$  and

<sup>20</sup>It can be shown the Hessian of the objective function is negative semidefinite by assumption, guaranteeing uniqueness of the equilibrium (Varian, 1992).

Figure 1: Market Effects of Fuel Mandates\*



Notes: The left graph presents the initial market equilibrium, and the right graph illustrates the equilibrium under either a RFS or a LCFS. The downward sloping line is the fuel demand curve, the line with triangles is the conventional fuel supply curve, the circled line is the renewable fuel supply curve, and the solid upward sloping line is the total fuel supply curve, which equals the horizontal sum of the renewable and conventional input supply curves.

$q_i^r$  for  $i = 0, M$ , is given by the corresponding quantity where the equilibrium price intersects the individual supply curves.

Consider a binding fuel policy, illustrated in the right graph. The dashed lines represent the initial supply curves, while the solid lines illustrate the supply curves net of the implicit subsidy and tax under the LCFS or RFS. Under the RFS every unit of renewable fuel is associated with a credit which can be traded at the RFS credit price, while for every unit of conventional fuel, obligated parties must purchase  $\alpha$  credits. Under a LCFS, every unit of renewable fuel generates  $(\sigma - \phi^r)$  credits which can be sold to obligated parties, while every unit of conventional fuel generates  $(\phi^c - \sigma)$  deficits which must be accounted for by purchasing credits.

The key to understanding compliance costs under each policy is to recognize that the level of the subsidy and tax is endogenous, and the Lagrange multiplier of the policy constraint, which will be shown to equal the compliance credit price, adjusts until the fuel mix just meets the standard in equilibrium. Thus, the renewable supply curve will shift down and to the right while the conventional supply curve will shift up and to the left until the market clearing price and quantities, determined by the intersection of the total fuel supply curve and demand curve, is such that the total fuel supply complies with the mandate. The resulting equilibrium under a fuel mandate in Figure 1 induces slightly higher fuel prices and slightly lower fuel consumption relative to the no policy equilibrium.

As discussed in Lemma 1, for given demand and convex supply curves, there exists a unique equilibrium under each policy. In practice, both the RFS and LCFS have been set at initially low levels and become

more stringent over time. A natural question to ask is how, under a binding policy, market outcomes change as the standard becomes more stringent. Proposition 1 presents the results.<sup>21</sup>

**Proposition 1: Market effects of fuel mandates**

- i Under both the RFS and LCFS, increasing the stringency of the policy reduces the quantity of conventional fuel in equilibrium.*
- ii Under a RFS, increasing the stringency of the policy increases the volume of renewable fuel if  $\frac{1}{\xi^c} - \frac{1}{\eta^d} > \frac{\alpha\lambda}{p}$ , where  $\xi^c$  is the price elasticity of supply for the conventional input and  $\eta^d$  is the elasticity of demand. For a LCFS, the quantity of renewable fuels increase if  $\frac{1}{\xi^c} - \frac{1}{\eta^d} > (\phi^c - \sigma)\frac{\lambda}{p}$ .*
- iii Fuel prices increase if the total fuel supply decreases, and decreases if total fuel supply increases.*

• **Proof:** Let  $\theta = \alpha$  for the RFS and  $\theta = \sigma$  for the LCFS. The market equilibrium for an interior solution under a binding mandate is characterized by equations (1) and (2), where we substitute  $U'(Q) = p$  in both equations, as well as the policy function  $\varphi(q^c, q^r; \theta) = 0$ . To conduct comparative statics with respect to  $\theta$ , we can take the total derivative of the three equations with respect to  $\theta$ , which can be written in matrix form as:<sup>22</sup>

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

Let  $\eta^d$  denote the price elasticity of demand for fuel and  $\xi^i$  denote the price elasticity of supply for  $i = c, r$ . Given our representative firm and consumer model,  $U'(Q)$  is equivalent to the inverse market demand curve for fuel,  $D^{-1}(Q)$ , and  $C^{i'}(\cdot)$  is equal to the inverse market supply curve,  $S^{i,-1}(Q)$ , for  $i = c, r$ . We can therefore write  $U''(Q) = \frac{\partial D^{-1}(Q)}{\partial Q} = \frac{1}{\eta^d} \frac{p}{Q}$ ,  $C^{i''}(q^i) = \frac{\partial S^{i,-1}(q^i)}{\partial q^i} = \frac{1}{\xi^i} \frac{p}{q^i}$  for  $i = c, r$ . Substituting, we have:

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

The matrix  $H$  is the bordered Hessian for our maximization problem, where the Hessian matrix 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 which states:

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

where  $H$  is the bordered Hessian and  $H^i(\cdot)$  is the matrix  $H$  with the  $i$ th column replaced with column  $D$ . Note that  $\det(H) > 0$  for both policies by concavity of the objective function (Varian, 1992).<sup>23</sup> Thus, the signs of the effects on each variable are determined by sign ( $\det(H^i)$ ).

<sup>21</sup>Both the RFS and LCFS allow firms to bank credits over time. If firms anticipate higher compliance costs in the future, firms will bank more credits presently and there may be over-compliance in early years. Our static model does not capture these dynamic effects.

<sup>22</sup>Note that  $\frac{dQ}{dq^c} = \frac{dQ}{dq^r} = 1$ . In addition,  $\frac{\partial^2\varphi(\cdot)}{\partial q^c\partial q^r} = \frac{\partial^2\varphi(\cdot)}{\partial q^r\partial q^c} = 0$  for both policies.

<sup>23</sup>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.

First consider the RFS. The total derivatives for  $q^c$  and  $q^r$  are given by:

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

Increasing the stringency of the RFS decreases the volume of conventional fuel. The volume of renewable fuel increases if and only if  $\frac{1}{\xi^c} - \frac{1}{\eta^d} > \alpha\frac{\lambda}{p}$ . In equilibrium  $p(Q) = U'(Q) = D^{-1}(Q)$ , thus:

$$\begin{aligned}\frac{dp}{d\alpha} &= \frac{\partial D^{-1}(Q)}{\partial q^c} \frac{dq^c}{d\alpha} + \frac{\partial D^{-1}(Q)}{\partial q^r} \frac{dq^r}{d\alpha} \\ &= \frac{1}{\eta^d} \frac{p}{Q} \frac{dQ}{d\alpha}.\end{aligned}$$

The condition states that final fuel prices increase if the total fuel supply decreases, and decreases if the total fuel supply increases.

Next consider the LCFS.<sup>24</sup> Increasing  $\sigma$  relaxes the policy constraint, so the sign of the effect of increasing the stringency of the LCFS is  $-\text{sign}\left(\frac{dx}{d\sigma}\right)$ . The comparative statics are given by:

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

Increasing the stringency of the policy decreases the volume of conventional fuel, while it increases the volume of renewable fuel if and only if  $\frac{1}{\xi^c} - \frac{1}{\eta^d} > (\phi^c - \sigma)\frac{\lambda}{p}$ . The effect of the LCFS on fuel prices is:

$$\frac{dp}{d\sigma} = \frac{1}{\eta^d} \frac{p}{Q} \left( \frac{dQ}{d\sigma} \right). \square$$

Proposition 1 further illustrates the similarity of the two fuel mandates. Increasing the stringency of both policies decreases the volume of conventional fuels, and increases the volume of renewable fuel so long as  $\frac{1}{\xi^c} - \frac{1}{\eta^d}$  is large enough. In words, increasing the stringency of both policies will increase the volume of renewable fuels if the supply elasticity of conventional fuels and the elasticity of demand are inelastic. If price changes do not induce consumers to reduce consumption or conventional firms to reduce the supply of fuel, the only means of complying with the policies is to increase the volume of renewable fuels. If, however, consumers reduce fuel consumption and fossil fuel producers reduce production in response to the policies, the volume of renewable fuels need not increase to maintain compliance with each fuel mandate. In the extreme scenario where fuel demand or the supply of conventional fuel is perfectly inelastic, the policies will unambiguously increase renewable fuels.

The overall effect of the mandates on fuel prices depends on the countervailing effects from increasing renewable fuel and decreasing conventional fuel. Thus, the pass through of the costs from the policy onto consumers depends crucially on the supply response of renewable fuels. Substituting the total derivatives of the policies on fuel supply into the total derivative on prices, it can be shown that a necessary condition for the policy to reduce fuel prices is that  $\xi^r > \xi^c$ , i.e., the elasticity of supply for renewable fuels must be higher than the elasticity of supply of conventional fuels.

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<sup>24</sup>Note that  $\frac{\partial \varphi(\cdot)}{\partial q^c} = (\sigma - \phi^c) < 0$ ,  $\frac{\partial \varphi(\cdot)}{\partial q^r} = (\sigma - \phi^r) > 0$ ,  $\frac{\partial^2 \varphi(\cdot)}{\partial q^c \partial \sigma} = 1$ ,  $\frac{\partial^2 \varphi(\cdot)}{\partial q^r \partial \sigma} = 1$ , and  $\frac{\partial \varphi(\cdot)}{\partial \sigma} = Q = q^c + q^r$ .

## 4.2 Trading and compliance credit markets

The RFS and LCFS are implemented by allowing firms to trade credits which must be turned into the regulator at the end of each compliance period. In order to use a representative firm to model the policies, we require a robust and liquid market for compliance credits. To study the credit trading market in more detail, consider an individual firm's problem under a fuel mandate. Each firm's maximization program is equivalent to the representative firm's problem, however, each firm has the additional option of purchasing compliance credits,  $x_i$ , from other firms in lieu of physically blending renewable fuel into its final product. The policy functions for each firm are therefore given by:

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

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

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

where  $p^{\text{cred}}$  is the market clearing compliance credit price. Note that firms are allowed to have heterogeneous costs in the model above. In fact, trading in the market for compliance credits is driven by cost heterogeneity. Each firm's Karush-Kuhn-Tucker optimality conditions are:

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

In an interior solution, all conditions hold with equality. The third condition states that each firm's marginal cost of meeting the policy,  $\lambda_i$ , will be equal to the credit price,  $p^{\text{cred}}$  in equilibrium. The competitive market equilibrium is characterized by the  $4 * N$  first order conditions as well as the market clearing condition  $\sum_{i=1}^N x_i = 0$ , which guarantees that the number of compliance credits generated equals the number of deficits accrued.<sup>25</sup>

A number of complications may prevent the competitive equilibrium above from being achieved. If there are any costs to trading credits, the equilibrium above will not hold (Stavins, 1995). In addition, the equilibrium will not hold if there is uncertainty in the market regarding the availability of credits (Montero, 1997), or if any firm is able to exercise market power in the credit market (Hahn, 1984). Absent these issues, an advantage of the equilibrium result is that we can treat the Lagrange multiplier on the aggregate policy constraint as the market clearing compliance credit price.

Because compliance credit prices are equated to the aggregate Lagrange multiplier, the price of credits provide a direct measure of the cost of each policy. To see this, note that we can write the value function for the industry as:

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

where  $V(\cdot)$  is evaluated at the optimal values of  $q^c$  and  $q^r$ . Appealing to the Envelope Theorem, the marginal value of relaxing each standard is given by  $\frac{\partial V(q^c, q^r)}{\partial \alpha} = -\lambda q^c$  for the RFS and  $\frac{\partial V(q^c, q^r)}{\partial \sigma} = \lambda Q$  for the LCFS.<sup>26</sup> Thus, the market clearing credit price is a direct measure of compliance costs for both policies.

<sup>25</sup>The proof of the existence of a competitive market equilibrium is similar to Montgomery (1972). The proof requires upper hemi-continuity of the demand correspondences and applying Kakutani's fixed-point theorem (Mas-Colell et al., 1995).

<sup>26</sup>The difference in signs is due to the different interpretation of each policy variable. For the RFS, as  $\alpha$  increases the mandated share of renewable fuel increases and the policy becomes more stringent. For the LCFS, as  $\sigma$  increases, the average carbon intensity requirement on fuels increases and the policy becomes less stringent.

### 4.3 Cost containment mechanisms

Now consider scenarios in which the regulator wishes to limit the compliance costs of a fuel mandate using a mechanism which intervenes directly in the compliance credit market. We characterize cost containment mechanisms in two broad categories: (1) a ‘hard cap’ on compliance credit prices whereby the cost containment mechanism guarantees the price of compliance credits never exceeds a specified level; and (2) a ‘soft cap’ on credit prices whereby the mechanism puts downward pressure on compliance credit prices, but does not guarantee compliance costs will be contained at a given level. We model the hard cap as being implemented through an open credit window where firms can purchase unlimited compliance credits from the regulator at a fixed price, and the soft cap as being implemented by a renewable fuel multiplier where the regulator increases the number of credits generated by each unit of renewable fuel. Both policies could be implemented using alternative mechanisms. For example, a hard cap could be implemented by imposing a fixed noncompliance penalty on firms and a soft cap could be implemented by relaxing the standard in a given compliance period.

First consider the effect of a ‘hard cap’ on compliance credit prices. Let  $c$  denote the total number of credits bought from the regulator through the credit window and  $\bar{p}^{\text{cred}}$  be the credit window price set by the regulator. The policy constraints in this case are given by:

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

The representative firm’s problem is given by:<sup>27</sup>

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

The KKT conditions for the maximization program are:

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

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

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

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

The conditions state that whenever the regulator establishes an open credit window, if compliance costs are below the window price then firms will not purchase credits and credit prices will equal  $\lambda$ . If, however, compliance costs reach or exceeds the credit window price, firms will purchase from the window and compliance credit prices will equal  $\bar{p}^{\text{cred}}$ . Hence, the open credit window option places a hard cap on credit prices equal to the credit window price,  $\bar{p}^{\text{cred}}$ .

Whenever the regulator is considering instituting a cost containment mechanism, setting the credit window price will have direct implications on the maximum potential cost of the fuel mandate. A natural question is to ask how the market is affected by the choice of the credit price. Proposition 2 summarizes the comparative statics with respect to the credit price,  $\bar{p}^{\text{cred}}$  under a binding cap such that  $\lambda = \bar{p}^{\text{cred}}$ .

**Proposition 2:** *Suppose the cost containment mechanism binds such that  $\lambda = \bar{p}^{\text{cred}}$ . As the emergency credit price  $\bar{p}^{\text{cred}}$  increases, the quantity of conventional fuel decreases, the quantity of renewable fuel increases, and the quantity of compliance credits purchased decreases for both policies. Market clearing fuel prices increase if the total volume of fuel decreases and decrease if the total volume of fuel increases.*

<sup>27</sup>We restrict the number of credits to be non-negative so that firms cannot sell credits to the regulator.

- **Proof:** To solve for the sign of each variable, take the total derivative of the optimality conditions and policy constraint with respect to the credit window price. Note that  $\lambda$  in this case is no longer endogenous as  $\lambda = \bar{p}^{\text{cred}}$  by assumption. Thus, we take the total derivative of the three conditions with respect to  $q^c$ ,  $q^r$ , and  $c$ , given by:

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

We solve the system of equations using Cramer's rule. It can be shown  $\det(H) > 0$  for both policies, so the sign of the derivatives is determined by the sign of the numerator.<sup>28</sup>

First consider the RFS. Solving the system of equations yields:

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

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

The total derivative with respect to price is given by:

$$\frac{dp}{d\bar{p}^{\text{cred}}} = \frac{1}{\eta^d} \frac{p}{Q} \frac{dQ}{d\bar{p}^{\text{cred}}}.$$

Thus, increasing the credit window price whenever firms purchase from the credit window decreases the volume of conventional fuel, increases the volume of renewable fuel, and decreases the number of credits firms purchase in equilibrium.

Next consider the LCFS. Solving the system of equations yields:

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

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

Increasing the credit window price decreases the volume of conventional fuels, increases the volume of renewable fuels and decreases the number of compliance credits purchased. Fuel prices decrease if the supply of total fuel increases and increase otherwise.  $\square$

Proposition 2 states that as  $\bar{p}^{\text{cred}}$  increases, the cost of complying with both mandates increases, which unambiguously decreases the volume of conventional fuels, increases renewable fuels, and reduces the demand for compliance credits. The dynamics hold so long as firms purchase credits from the open window.

<sup>28</sup>For the RFS  $\det(H) = \frac{1}{\xi^r} \frac{p}{q^r} \left( \frac{1}{\xi^c} \frac{p}{q^c} - \frac{1}{\eta^d} \frac{p}{Q} \right) - \frac{1}{\eta^d} \frac{1}{\xi^c} \frac{p^2}{Qq^c} > 0$  and for the LCFS  $\det(H) = \frac{1}{\xi^r} \frac{p}{q^r} \left( \frac{1}{\xi^c} \frac{p}{q^c} - \frac{1}{\eta^d} \frac{p}{Q} \right) - \frac{1}{\eta^d} \frac{1}{\xi^c} \frac{p^2}{Qq^c}$ .

Next consider the effect of the second cost containment mechanism, a ‘soft cap’ on credit prices implemented by a multiplier on credits generated from renewable fuels. We specify the multiplier under both policies as  $\gamma > 1$ , where the renewable fuel generates  $\gamma q^r$  credits. The policy constraints are given by:

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

The representative firm’s problem is equivalent to the problem from Section 3.1; however, the optimality conditions incorporate  $\gamma$  such that:

$$[q^c :] \quad p - C^c(q^c) + \lambda \frac{\partial \varphi(\cdot)}{\partial q^c} \leq 0 \quad (6)$$

$$[q^r :] \quad p - C^r(q^r) + \lambda \frac{\partial \varphi(\cdot)}{\partial q^r} \leq 0 \quad (7)$$

$$\lambda[\varphi(q^c, q^r; \theta)] = 0, \quad (8)$$

where  $\frac{\partial \varphi(\cdot)}{\partial q^c} = -\alpha$  and  $\frac{\partial \varphi(\cdot)}{\partial q^r} = \gamma$  for the RFS; and where  $\frac{\partial \varphi(\cdot)}{\partial q^c} = (\sigma - \phi^c)$  and  $\frac{\partial \varphi(\cdot)}{\partial q^r} = (\sigma - \phi^r)\gamma$  for the LCFS. Proposition 3 summarizes the comparative statics for each policy with respect to the credit multiplier and is followed by intuition for the result.

**Proposition 3:** *Increasing the renewable fuel multiplier under either policy increases the volume of conventional fuel and decrease compliance costs. Increasing the renewable fuel multiplier will decrease the amount of renewable fuels if  $\frac{1}{\xi^c} - \frac{1}{\eta^d} > \alpha \frac{\lambda}{p}$  under a RFS and if  $\frac{1}{\xi^c} - \frac{(\gamma - \sigma)\sigma + (\sigma - \gamma)\phi^r + (\sigma - \phi^r)\phi^c}{\phi^c - \gamma\phi^r + (\gamma - 1)\sigma} \frac{1}{\eta^d} > (\phi^c - \sigma)(\sigma - \phi^r) \frac{\lambda}{p}$  under a LCFS.*

- **Proof:** First, take the total derivative of the optimality conditions and policy constraints with respect to the credit multiplier. The total derivatives are written in elasticity form as:

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

It can be shown that  $\det(H) > 0$  for both policies.<sup>29</sup>

First consider the RFS. Solving the system of equations using Cramer’s rule yields:

$$\begin{aligned} \frac{dq^c}{d\gamma} &= \left( \alpha \gamma \lambda + \alpha \left( \frac{p}{\xi^r} - \frac{p}{\eta^d} \right) \right) \det(H)^{-1} > 0 \\ \frac{dq^r}{d\gamma} &= \left( \frac{\alpha^2 + \alpha \gamma}{\alpha + \gamma} \frac{p}{\eta^d} - \alpha \frac{p}{\xi^c} + \alpha^2 \lambda \right) \det(H)^{-1} \end{aligned}$$

$$\frac{d\lambda}{d\gamma} = \left( \left( \gamma \lambda + \frac{p}{\xi^r} \right) \left( \frac{1}{\eta^d} \frac{p}{Q} - \frac{1}{\xi^c} \frac{p}{q^c} \right) + \alpha \lambda \frac{1}{\eta^d} \frac{p}{Q} + \frac{\alpha}{\alpha + \gamma} \frac{p}{\eta^d} \frac{1}{\xi^c} \frac{p}{q^c} \right) \det(H)^{-1} < 0.$$

Increasing the multiplier increases the volume of conventional fuel and decreases compliance costs,  $\lambda$ . Increasing the multiplier decreases the volume of renewable fuel if and only if  $\frac{1}{\xi^c} - \frac{1}{\eta^d} > \alpha \frac{\lambda}{p}$ . The effect on fuel prices depends on whether the total quantity of fuel increases or decreases.

<sup>29</sup>For the RFS,  $\det(H) = \alpha^2 \left( \frac{1}{\xi^r} \frac{p}{q^r} - \frac{1}{\eta^d} \frac{p}{Q} \right) + \gamma^2 \left( \frac{1}{\xi^c} \frac{p}{q^c} - \frac{1}{\eta^d} \frac{p}{Q} \right) - 2\alpha \gamma \frac{1}{\eta^d} \frac{p}{Q} > 0$ . For the LCFS  $\det(H) = (\phi^c - \sigma)^2 \left( \frac{1}{\xi^r} \frac{p}{q^r} - \frac{1}{\eta^d} \frac{p}{Q} \right) + (\sigma - \phi^r)^2 \gamma^2 \left( \frac{1}{\xi^c} \frac{p}{q^c} - \frac{1}{\eta^d} \frac{p}{Q} \right) - 2(\phi^c - \sigma)(\sigma - \phi^r) \gamma \frac{1}{\eta^d} \frac{p}{Q} > 0$ .

Next consider the LCFS. The comparative statics of increasing  $\gamma$  under a LCFS are given by:

$$\begin{aligned}\frac{dq^c}{d\gamma} &= \left( (\phi^c - \sigma)(\sigma - \phi^r) \left( \frac{p}{\xi^r} - \frac{p}{\eta^d} \frac{q^r}{Q} \right) - (\sigma - \phi^r)^2 \gamma \frac{p}{\eta^d} \frac{q^r}{Q} + (\sigma - \phi^r)^2 (\phi^c - \sigma) \gamma \lambda \right) \det(H)^{-1} > 0 \\ \frac{dq^r}{d\gamma} &= \left( \frac{(\gamma - \sigma)\sigma + (\sigma - \gamma)\phi^r + (\sigma - \phi^r)\phi^c}{\phi^c - \gamma\phi^r + (\gamma - 1)\sigma} (\phi^c - \sigma) \frac{p}{\eta^d} - (\phi^c - \sigma) \frac{p}{\xi^c} + (\phi^c - \sigma)^2 (\sigma - \phi^r) \lambda \right) \det(H)^{-1} \\ \frac{d\lambda}{d\gamma} &= \left( \left( (\sigma - \phi^r) \frac{p}{\xi^r} + (\sigma - \phi^r)^2 \gamma \lambda \right) \left( \frac{1}{\eta^d} \frac{p}{Q} - \frac{1}{\xi^c} \frac{p}{q^c} \right) + \frac{\phi^c - \sigma}{\gamma} \frac{1}{Q} \frac{p}{\eta^d} \frac{p}{\xi^c} \right. \\ &\quad \left. + (\phi^c - \sigma)(\sigma - \phi^r) \lambda \frac{p}{\eta^d} \frac{1}{Q} \right) \det(H)^{-1} < 0.\end{aligned}$$

Increasing the renewable fuel multiplier increases the volume of conventional fuels and decreases compliance costs. The multiplier decreases the volume of renewable fuels if and only if  $\frac{1}{\xi^c} - \frac{(\gamma - \sigma)\sigma + (\sigma - \gamma)\phi^r + (\sigma - \phi^r)\phi^c}{\phi^c - \gamma\phi^r + (\gamma - 1)\sigma} \frac{1}{\eta^d} > (\phi^c - \sigma)(\sigma - \phi^r) \frac{\lambda}{p}$ . The effect on overall fuel prices depends on whether the equilibrium quantity of total fuel increases or decreases.  $\square$

Increasing the renewable fuel multiplier has a similar effect as reducing each standard.<sup>30</sup> Increasing the multiplier increases the volume of conventional fuels in equilibrium and decreases compliance costs. As in Proposition 1, increasing the multiplier decreases the volume of renewable fuel whenever the supply elasticity of conventional fuel and the elasticity of demand are inelastic. Thus, if fuel demand is fairly inelastic, relaxing the stringency of each policy by increasing the renewable fuel multiplier will likely decrease the total volume of renewable fuel on the market.

#### 4.4 Second-best policies

Now consider the optimal fuel mandates with and without cost containment provisions. As noted by de Gorter and Just (2009), Holland et al. (2009), Lapan and Moschini (2012), among others, the RFS and LCFS alone are unable to achieve the first-best outcome whenever the only market failure is unpriced carbon emissions. The divergence arises because fuel mandates such as the RFS and LCFS implicitly or explicitly regulate the rate or intensity of emissions rather than the level.<sup>31</sup> Figures 2 and 3 illustrate the inefficiencies of fuel mandates graphically. In both figures, the solid circles represent iso-welfare curves when damages from the pollution externalities are not included in either production or consumption decisions, and the dashed circles represent iso-welfare curves when pollution externalities are internalized.<sup>32</sup> In the absence of any policy, the competitive market maximizes consumer and producer surplus at point A, which differs from the social optimum at point B.

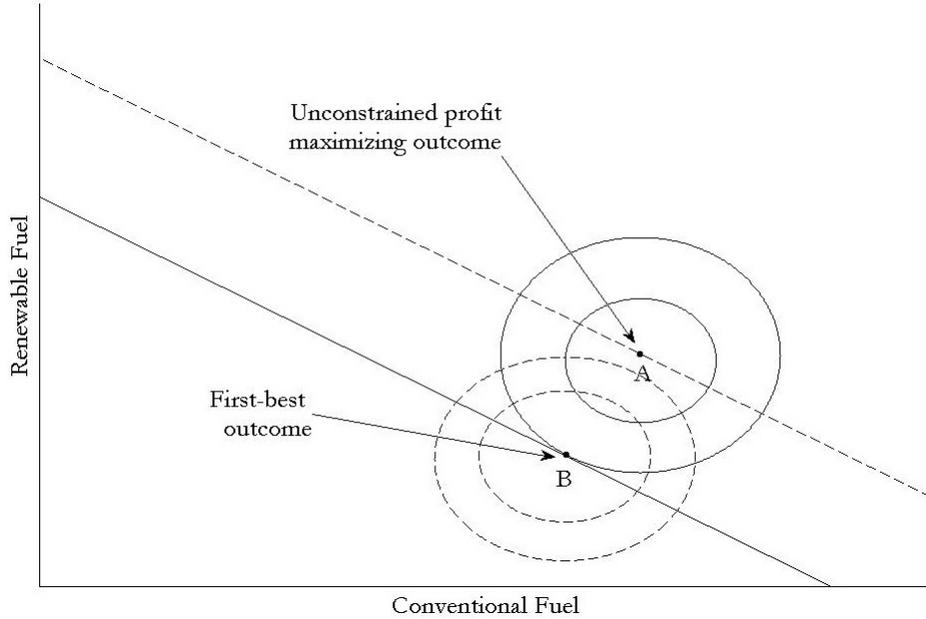
Given the existence of a pollution externality, government intervention in the market may improve social welfare. In order to achieve the first-best equilibrium, the government must enact a policy which aligns the competitive market outcome with the social welfare maximizing outcome, B. This can be achieved either by

<sup>30</sup>To see this, note that we can write the multiplier under the RFS as  $\frac{\gamma q^r}{q^c} = \frac{(1+\nu)q^r}{q^c} \geq \alpha$ , where  $\gamma = 1 + \nu$ . Rearranging yields the constraint  $\frac{q^r}{q^c} \geq \left( \alpha - \nu \frac{q^r}{q^c} \right)$ . Thus, increasing the multiplier for values greater than 1 is equivalent to reducing the share mandate on renewable fuels by  $\nu \frac{q^r}{q^c}$ . A similar argument shows the same feature holds for the LCFS constraint.

<sup>31</sup>See Helfand (1992) for a more general discussion of the relative efficiency of alternatively phrased mandates.

<sup>32</sup>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  $U(Q) - C^c(q^c) - C^r(q^r) - D(Q)$ . Given our assumptions, both functions are globally concave and therefore have a unique maximum.

Figure 2: The competitive outcome and the first-best



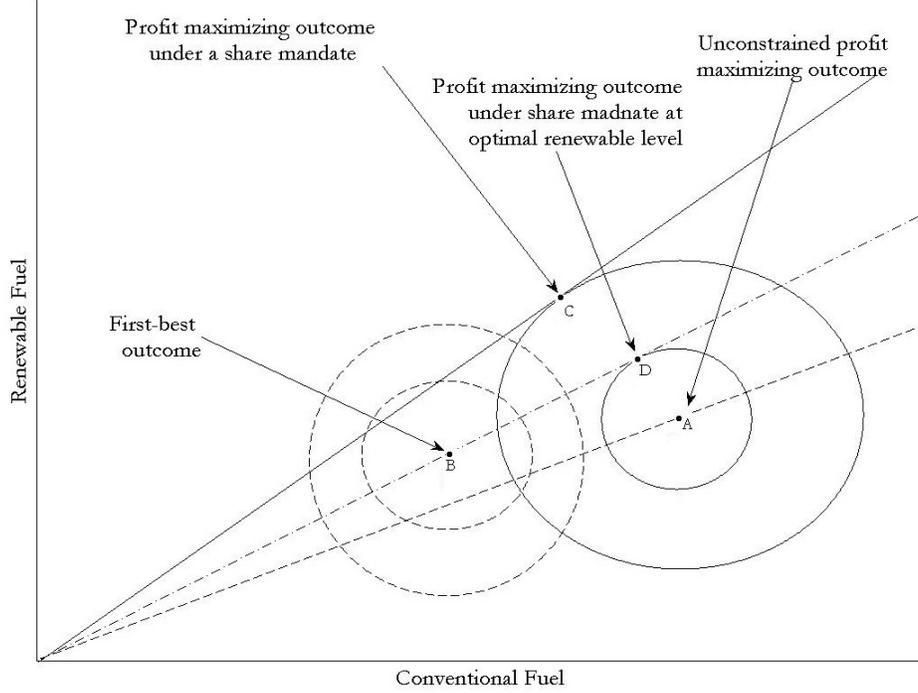
Notes: The solid circles are iso-welfare curves less damages from emissions and the dotted circles represent the iso-social welfare curves. In the presence of an unpriced externality, the market maximizes profit at  $A$ , which does not correspond to the welfare maximizing point  $B$ . The lines parallel to the origin are iso-emission lines with slope  $(-\phi^c/\phi^r)$  where  $\phi^i$  is the emissions factor for  $i = c, r$ . The dashed line represents the initial level of emissions under no policy intervention. If the government institutes a cap and trade program where the cap is set at the first-best level, represented by the solid line, the resulting competitive market equilibrium will maximize at point  $B$ , corresponding to the social welfare maximizing outcome.

instituting an appropriately designed cap and trade program or by taxing the emissions from each input. For illustrative purposes, suppose the government institutes a cap and trade program. We represent emissions in Figure 2 using lines perpendicular to the origin with slope  $(-\phi^c/\phi^r)$ . The dashed perpendicular line represents the level of emissions under the competitive market outcome, while the solid line represents the first-best level of emissions. If the government institutes a cap and trade program with the cap set at the first-best emissions level, the competitive market outcome will maximize at point  $B$ , the socially optimal equilibrium.

Next consider a LCFS or RFS. As shown in Lemma 1, the policies act as explicit or implicit renewable share mandates. We can therefore represent the policies in Figure 3 using rays from the origin, with the slope of the ray corresponding to the share of renewable fuel required to meet the policy. Any binding share mandate must pass to the left of the initial share of renewable fuels, or the dashed ray passing through point  $A$ . Consider the effect of a binding fuel mandate, illustrated by the solid ray from the origin. Under the policy, firms maximize profits at point  $C$ , resulting in higher renewable and conventional fuel production and higher emissions than the efficient outcome  $B$ .

To illustrate why the fuel policy cannot achieve the first-best outcome, suppose the regulator knows the share of renewable fuels or the carbon intensity of fuels under a first-best policy and sets either the LCFS or RFS at this level, represented by the dotted line through point  $B$ . Despite being set at the ‘optimal’ share, under a share mandate the market will maximize at  $D$ , away from the first-best outcome. Though the policy acts as an implicit tax on conventional fuel, because it also acts as an implicit subsidy for renewable fuels,

Figure 3: The competitive outcome and fuel mandates



Notes: The solid circles are iso-welfare curves less damages from emissions and the dotted circles represent the iso-social welfare curves. In the presence of an unpriced externality, the market maximizes profit at A, which does not correspond to the welfare maximizing point B. The rays from the origin represent fuel mandates. If the government sets a fuel mandate at the ‘first-best’ level through B, the market will maximize at D.

firms and consumers will have an incentive to produce and consume more fuel than the socially optimal level even when the share mandate is set ‘optimally’. Thus, in Figure 3, both renewable and conventional fuel production remain sub-optimally high under a LCFS or RFS.

Given a chosen policy, a regulator may still seek to set an optimal, or second-best policy. Assume the regulator seeks to maximize social welfare given a chosen policy instrument. The government’s second-best problem can be written as:

$$\max_{\theta} SW(q^c, q^r) = U(Q) - C^c(q^c) - C^r(q^r) - D(q^c, q^r),$$

where  $\theta$  is the policy parameter with  $\theta = \alpha$  for the RFS and  $\theta = \sigma$  for the LCFS. Proposition 4 characterizes the second-best RFS and LCFS.<sup>33</sup>

**Proposition 4:** *Suppose increasing the stringency of the RFS and LCFS increases the volume of renewable fuel. A second-best RFS,  $\alpha^*$ , is characterized by  $\alpha^* \lambda < \Psi \phi^c$ . A second-best LCFS,  $\sigma^*$ , is characterized by  $(\phi^c - \sigma^*) \lambda < \Psi \phi^c$ . The second-best optimal policies are given by:*

$$[\text{RFS:}] \quad \alpha^* = \frac{\Psi}{\lambda} \frac{d(\phi^c q^c + \phi^r q^r)}{\frac{d\alpha}{dq^c}} + \frac{dq^r}{\frac{d\alpha}{dq^c}};$$

$$[\text{LCFS:}] \quad \sigma^* = \frac{(\lambda - \Psi) \frac{d(\phi^c q^c + \phi^r q^r)}{d\sigma}}{\lambda \frac{dQ}{d\sigma}}.$$

<sup>33</sup>The results are similar to and synthesize those derived by Lapan and Moschini (2012) for the an optimal share mandate as the federal Renewable Fuel Standard and Holland et al. (2009) for an intensity standard.

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

$$\max_{\theta} U(Q) - C^c(q^c) - C^r(q^r) - D(q^c, q^r).$$

Consider an interior solution for both policies such that  $\alpha^0 \leq \alpha \leq 1$  for the RFS and  $\phi^r \leq \sigma \leq \sigma^0$  for the LCFS, where  $\alpha^0$  and  $\sigma^0$  correspond to the initial share of renewable fuels and initial carbon intensity of fuels, respectively. The level of the LCFS is constrained from below by the lowest carbon intensity factor, otherwise the policy could not be achieved using any fuel on the market. The optimality conditions for a interior solution are given by:

$$\left( U'(Q) - C^c(q^c) - \Psi\phi^c \right) \frac{dq^c}{d\theta} + \left( U'(Q) - C^r(q^r) - \Psi\phi^r \right) \frac{dq^r}{d\theta} = 0. \quad (9)$$

First consider the RFS. Substituting equations (1) and (2) along with the representative consumer's optimality conditions into equation (9) and rearranging yields:

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

The condition is satisfied so long as  $\alpha^* \lambda < \Psi\phi^c$ , i.e., the implicit tax on the conventional fuel must be less than its marginal damages. Solving for  $\alpha^*$  yields:

$$\alpha^* = \frac{\Psi}{\lambda} \frac{d(\phi^c q^c + \phi^r q^r)}{\frac{dq^c}{d\alpha}} + \frac{\frac{dq^r}{d\alpha}}{\frac{dq^c}{d\alpha}}.$$

Note that a necessary condition for  $\alpha^* > 0$  is that  $\frac{d(\phi^c q^c + \phi^r q^r)}{d\alpha} < 0$ , i.e, an optimal policy must decrease total emissions on the margin.

Next consider the LCFS. Making the proper substitutions yields the following expression characterizing the optimal policy:

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

The condition is satisfied so long as  $(\phi^c - \sigma^*)\lambda < \Psi\phi^c$ , i.e., the implicit tax on conventional fuels must be less than the marginal damages of the fuel. Solving for  $\sigma^*$  yields:

$$\sigma^* = \frac{(\lambda - \Psi) \frac{d(\phi^c q^c + \phi^r q^r)}{d\sigma}}{\lambda \frac{dQ}{d\sigma}}. \square$$

Proposition 4 states that a second-best fuel mandate should be set at a level where the implicit tax on conventional fuel,  $\alpha\lambda$  for the RFS and  $(\phi^c - \sigma)\lambda$  for the LCFS, is less than the marginal damages of the conventional fuel,  $\Psi\phi^c$ . The results highlight an important feature of efficient fuel mandates. First, because the conventional and renewable input are substitutes, taxing the conventional good leads to substitution across fuels and increases use of the renewable input. Second, increasing the implicit tax on conventional fuels also acts to increase the subsidy for renewable fuels. Both effects counter emission reductions due to decreases in conventional fuel consumption with increases in emissions due to expanding consumption of renewable fuels. Thus, an efficient mandate must balance the increase in emissions due to increasing use of renewable fuels with the decrease in emissions due to conventional fuel use declining.

## 4.5 Improving the second-best through cost containment mechanisms

The decision to implement a cost containment mechanism can be motivated by a number of factors. When market outcomes are uncertain, a policy which places a hard cap on compliance costs can act to eliminate small probability, high compliance cost events (Nemet, 2010). Given the ability of firms to bank credits, the mere anticipation of potential high future compliance costs may increase demand for credits in the present and increase prices. Here we consider the motivation in a different light. We consider scenarios in which a fuel mandate is set at a level which has led to undesirably high compliance costs. Rather than eliminating the policy, we imagine a regulator who wishes to constrain compliance costs either through a hard cap or a soft cap on credit prices to improve the efficiency of the policy. The approach is motivated by the slow development of alternative fuels, which has the potential to increase the cost of the policies considerably in coming years.

First consider the regulator setting an optimal hard cap on compliance credits, summarized by Proposition 5.

**Proposition 5:** *Suppose a credit window price is set at a level where firms purchase from the window. Given either a RFS or a LCFS, a credit window price should be set at a level where the implicit tax on conventional fuels,  $\alpha\bar{p}$  for the RFS and  $(\phi^c - \sigma)\bar{p}$  for the LCFS, is less than the damages associated with the conventional fuel,  $\Psi\phi^c$ . In addition, any adjustment to the credit price must ensure total emissions decrease. The optimal credit window prices are given by:*

$$[\text{RFS:}] \quad \bar{p}_{RFS}^{\text{cred}} = \frac{\Psi \frac{d(\phi^c q^c + \phi^r q^r)}{d\bar{p}^{\text{cred}}}}{\frac{d(\alpha q^c - q^r)}{d\bar{p}^{\text{cred}}}}$$

$$[\text{LCFS:}] \quad \bar{p}_{LCFS}^{\text{cred}} = \frac{\Psi \frac{d(\phi^c q^c + \phi^r q^r)}{d\bar{p}^{\text{cred}}}}{\frac{d(\phi^c q^c + \phi^r q^r)}{d\bar{p}^{\text{cred}}} - \sigma \frac{d(Q)}{d\bar{p}^{\text{cred}}}}.$$

- **Proof:** Let  $\theta \in \{\alpha, \sigma\}$  be the policy and  $\bar{p}^{\text{cred}}$  be the compliance credit price. The regulator's problem is given by:

$$\max_{\bar{p}^{\text{cred}}|\theta} U(Q|\theta) - C^c(q^c|\theta) - C^r(q^r|\theta) - D(q^c, q^r|\theta).$$

Consider an interior solution for  $\bar{p}^{\text{cred}}$  such that  $0 < \bar{p}^{\text{cred}} < \lambda$ . Suppose increasing  $\bar{p}^{\text{cred}}$  increases welfare. The total derivative of the social welfare function with respect to  $\bar{p}^{\text{cred}}$  is given by:

$$\left( U'(Q|\theta) - C^{c'}(q^c|\theta) - \Psi\phi^c \right) \frac{dq^c}{d\bar{p}^{\text{cred}}} + \left( U'(Q|\theta) - C^{r'}(q^r|\theta) - \Psi\phi^r \right) \frac{dq^r}{d\bar{p}^{\text{cred}}} \quad (10)$$

First consider a RFS. Substituting the market clearing equations (3)-(5) and applying Proposition 2, the following must hold if increasing  $\bar{p}^{\text{cred}}$  increases welfare:

$$\underbrace{(\alpha\bar{p}^{\text{cred}} - \Psi\phi^c)}_{?} \underbrace{\frac{dq^c}{d\bar{p}^{\text{cred}}}}_{<0} > \underbrace{(\bar{p}^{\text{cred}} + \Psi\phi^r)}_{>0} \underbrace{\frac{dq^r}{d\bar{p}^{\text{cred}}}}_{>0}.$$

Thus, it must be the case that  $\alpha\bar{p}^{\text{cred}} < \xi\phi^c$ , or the the implicit tax on conventional fuels must be less than its marginal damages. Rearranging, we have:

$$\underbrace{\frac{d(\alpha q^c - q^r)}{d\bar{p}^{\text{cred}}}}_{<0} \bar{p}^{\text{cred}} > \Psi \frac{d(\phi^c q^c + \phi^r q^r)}{d\bar{p}^{\text{cred}}}.$$

The condition states that on the margin, increasing  $\bar{p}^{\text{cred}}$  must result in emission reductions. The opposite conditions must hold for a decrease in  $\bar{p}$  to increase welfare. The optimal  $\bar{p}^{\text{cred}}$  is found by setting equation (10) equal to zero. Solving for  $\bar{p}_{RFS}^{\text{cred}}$  yields:

$$\bar{p}_{RFS}^{\text{cred}} = \frac{\Psi \frac{d(\phi^c q^c + \phi^r q^r)}{d\bar{p}^{\text{cred}}}}{\frac{d(\alpha q^c - q^r)}{d\bar{p}^{\text{cred}}}}.$$

Next consider the LCFS. Again, substituting (3)-(5) and using Proposition 2, the following condition characterizing when increasing  $\bar{p}^{\text{cred}}$  increases welfare:

$$\underbrace{((\phi^c - \sigma)\bar{p}^{\text{cred}} - \Psi\phi^c)}_{?} \underbrace{\frac{dq^c}{d\bar{p}^{\text{cred}}}}_{<0} > \underbrace{((\sigma - \phi^r)\bar{p}^{\text{cred}} + \Psi\phi^r)}_{>0} \underbrace{\frac{dq^r}{d\bar{p}^{\text{cred}}}}_{>0} > 0.$$

In order for the condition to hold, it must be the case that  $(\phi^c - \sigma)\bar{p}^{\text{cred}} < \Psi\phi^c$ . Rearranging, we have:

$$\Psi \frac{d(\phi^c q^c + \phi^r q^r)}{d\bar{p}^{\text{cred}}} < \underbrace{\left( \frac{d((\phi^c - \sigma) dq^c - (\sigma - \phi^r) dq^r)}{d\bar{p}^{\text{cred}}} \right)}_{<0} \bar{p}^{\text{cred}}.$$

The condition states that on the margin, the resulting increase in emissions due to the increase in renewable fuels from increasing  $\bar{p}^{\text{cred}}$  must be offset by a corresponding decrease in emissions from conventional fuels in order for welfare to increase. The opposite must hold for a decrease in  $\bar{p}^{\text{cred}}$  to increase welfare. Solving for the optimal  $\bar{p}^{\text{cred}}$  yields:

$$\bar{p}_{LCFS}^{\text{cred}} = \frac{\Psi \frac{d(\phi^c q^c + \phi^r q^r)}{d\bar{p}^{\text{cred}}}}{\frac{d(\phi^c q^c + \phi^r q^r)}{d\bar{p}^{\text{cred}}} - \sigma \frac{d(Q)}{d\bar{p}^{\text{cred}}}}. \square$$

Proposition 5 is similar to Proposition 4 in that the optimal credit window price must satisfy the condition that the implicit tax on conventional fuels should be set below marginal damages. The reasoning is the same as discussed previously. Namely, an increase in the implicit tax on conventional fuels increases the use of renewable fuels due to substitution across inputs, as well as increases the implicit subsidy for renewable fuels. The proposition highlights an important feature of the hard cap on compliance credit prices. Given a policy set at an inefficient level, the hard cap on credit prices allows the regulator an additional mechanism with which she can increase the efficiency of the program and ensure compliance costs do not become excessive.

For example, suppose before enacting the policy, the regulator believed the marginal cost of the renewable fuel would be  $C'_L(q^r)$ . The anticipated market clearing compliance credit price is  $\lambda_L = \frac{C'_L(q^r) - C'_c(q^c)}{\frac{\partial \varphi(\cdot)}{\partial q^r} - \frac{\partial \varphi(\cdot)}{\partial q^c}}$ . Knowing an efficient policy calls for the implicit tax on conventional fuels to be below marginal damages, the regulator sets the policy  $\theta$  such that the implicit tax is given by  $(-\lambda_L \frac{\partial \varphi(\cdot)}{\partial q^c}) < \Psi\phi^c$ . Suppose ex-post marginal costs for renewable fuels are given by  $C'_H(q^r) > C'_L(q^r)$ . Compliance credit prices will adjust endogenously to ensure the fuel mandates are met in equilibrium, and compliance credit prices will be given by  $\lambda_H = \frac{C'_H(q^r) - C'_c(q^c)}{\frac{\partial \varphi(\cdot)}{\partial q^r} - \frac{\partial \varphi(\cdot)}{\partial q^c}} > \lambda_L$ . Suppose credit prices adjust such that  $(-\lambda_H \frac{\partial \varphi(\cdot)}{\partial q^c}) > \Psi\phi^c$ . Clearly the policy is inefficient. By establishing a credit window, however, the regulator can directly constrain  $\lambda$ . Assuming the initial standard was set optimally given the anticipated  $\lambda_L$ , the regulator could set  $\bar{p} = \lambda_L$  to achieve their ex-ante policy goal.

Inspecting the optimality conditions under a LCFS with a hard cap on credit prices reveals a key feature unique to the LCFS, summarized in Corollary 1.

**Corollary 1:** *A LCFS with hard cap on compliance credit prices is able to achieve the first-best outcome, while a RFS with a hard cap on compliance credit prices is unable to achieve the first-best outcome.*

- **Proof:** The first-best solution is found by maximizing  $SW(q^c, q^r)$  with respect to  $q^c$  and  $q^r$ . The KKT conditions for an interior first-best policy are:

$$\begin{aligned} p &= C^{c'}(q^c) + \Psi\phi^c \\ p &= C^{r'}(q^r) + \Psi\phi^r. \end{aligned}$$

First consider the RFS. Rearranging equations (3), (4), and (5) for the RFS with a hard cap on credit prices for an interior solution, we have:

$$\begin{aligned} p &= C^{c'}(q^c) + \bar{p}^{\text{cred}}\alpha \\ p &= C^{r'}(q^r) - \bar{p}^{\text{cred}} \end{aligned}$$

No combination of  $\alpha$  and  $\bar{p}$  is able to replicate the first-best optimality conditions.

Next consider the LCFS. The corresponding conditions for the LCFS are:

$$\begin{aligned} p &= C^{c'}(q^c) + \bar{p}^{\text{cred}}(\phi^c - \sigma) \\ p &= C^{r'}(q^r) + \bar{p}^{\text{cred}}(\phi^r - \sigma). \end{aligned}$$

Setting  $\sigma = 0$  and  $\bar{p} = \Psi$  replicates the first-best optimality conditions.  $\square$

Corollary 1 raises an important distinction between the RFS and the LCFS. Because the LCFS differentiates fuels based on their relative carbon intensities, the policy has the potential to achieve more efficient outcomes than the RFS. Recall that the inefficiency of both policies is driven by the implicit subsidy each provides for fuels below the standard. Whenever the regulator is able to set both the stringency of the policy as well as the maximum level of compliance costs strategically, the optimal LCFS calls for setting a standard which requires the average carbon intensity of each fuel to be zero and setting the hard cap on compliance costs at the level of the marginal damages from emissions. In this case, all fuels are below the standard, and firms are only able to maintain compliance with the policy by purchasing the necessary credits from the regulator to cover the emissions from each fuel. However, given that the optimal LCFS with a hard cap requires setting the LCFS at a technologically infeasible level, it is unlikely such a policy could be passed.

Unlike a LCFS where the regulator can adjust the policy so that every fuel is implicitly taxed, a RFS will always implicitly subsidize renewable fuels. While the level of the implicit tax on conventional fuels may be adjusted by setting the RFS and the cap on compliance credits prices strategically, the level of the cap on credit prices will always also determine the level of the subsidy for renewable fuels.<sup>34</sup>

In addition to a hard cap, the other cost containment mechanism we consider to improve the second-best is a soft cap implemented by a multiplier on credits generated from renewable fuels. Proposition 6 summarizes when a renewable fuel multiplier is optimal and improves welfare given a fuel mandate.

**Proposition 6:** *Given either a RFS or a LCFS, if the renewable fuel multiplier decreases the market clearing volume of renewable fuel on the market, an optimal multiplier ensures the implicit tax on conventional fuels,  $\alpha\lambda$  for the RFS and  $(\phi^c - \sigma)\lambda$  for the LCFS, is less than the marginal damages of conventional fuel. If, however, the multiplier increases the volume of renewable fuel, an optimal multiplier should ensure the*

<sup>34</sup>The same would remain true for a nested mandate structure. While the nested mandate levels and cap on compliance credit prices may be adjusted, yielding efficiency gains beyond using only an overall mandate, the lowest-tiered mandate will always serve as an implicit subsidy for the lowest tiered renewable fuel, preventing the policy from achieving the first-best as under a LCFS.

implicit tax on conventional fuels is greater than the marginal damages of conventional fuels. The optimal renewable fuel multipliers are given by:

$$[\text{RFS:}] \quad \gamma_{RFS}^* = \alpha \frac{\frac{dq^c}{d\gamma}}{\frac{dq^r}{d\gamma}} - \frac{\Psi}{\lambda} \frac{\frac{d(\phi^c q^c + \phi^r q^r)}{d\gamma}}{\frac{dq^r}{d\gamma}}$$

$$[\text{LCFS:}] \quad \gamma_{LCFS}^* = \left( \frac{\phi^c - \sigma}{\sigma - \phi^r} \right) \frac{\frac{dq^c}{d\gamma}}{\frac{dq^r}{d\gamma}} - \frac{\Psi}{(\sigma - \phi^r)\lambda} \frac{\frac{d(\phi^c q^c + \phi^r q^r)}{d\gamma}}{\frac{dq^r}{d\gamma}}.$$

- **Proof:** Let  $\theta \in \{\alpha, \sigma\}$  be the policy and  $\gamma$  the renewable fuel multiplier. The regulator's problem is given by:

$$\max_{\gamma|\theta} U(Q|\theta) - C^c(q^c|\theta) - C^r(q^r|\theta) - D(q^c, q^r|\theta).$$

Consider an interior solution for  $\gamma$  such that  $\gamma > 1$ . Increasing the renewable fuel multiplier increases total welfare whenever the total derivative of the welfare function with respect to  $\gamma$  is greater than zero, given by:

$$\left( U'_{q^c} - C'^c - \Psi\phi^c \right) \frac{dq^c}{d\gamma} + \left( U'_{q^r} - C'^r - \Psi\phi^r \right) \frac{dq^r}{d\gamma} > 0.$$

First consider the RFS. Substituting the market clearing equations (6) and (7) and using the results from Proposition 3, we have the following condition characterizing when increasing the renewable fuel multiplier increases welfare:

$$\underbrace{(\alpha\lambda - \Psi\phi^c)}_{?} \underbrace{\frac{dq^c}{d\gamma}}_{>0} > \underbrace{(\gamma\lambda + \Psi\phi^r)}_{>0} \underbrace{\frac{dq^r}{d\gamma}}_{?}.$$

We have two cases to consider: (i)  $\frac{dq^r}{d\gamma} < 0$  so that the quantity of renewable fuel decreases as the multiplier increases, and (ii)  $\frac{dq^r}{d\gamma} > 0$  so that the amount of renewable fuel increases as the multiplier increases. Under the first scenario, it must be the case that  $\alpha\lambda < \Psi\phi^c$ , or the implicit tax on conventional fuel must be less than marginal damages from the conventional fuel. If, however, the multiplier increases the market clearing quantity of both fuels, then it must be the case that  $\alpha\lambda > \Psi\phi^c$  so that the implicit tax on conventional fuel is greater than the marginal damages from conventional fuels.

The optimal renewable fuel multiplier is found by setting the total derivative equal to zero. Solving for the optimal multiplier yields:

$$\gamma_{RFS}^* = \alpha \frac{\frac{dq^c}{d\gamma}}{\frac{dq^r}{d\gamma}} - \frac{\Psi}{\lambda} \frac{\frac{d(\phi^c q^c + \phi^r q^r)}{d\gamma}}{\frac{dq^r}{d\gamma}}.$$

Now consider the LCFS. Substituting the appropriate optimality conditions yields the following condition characterizing when a renewable fuel multiplier increases total welfare:

$$\underbrace{((\phi^c - \sigma)\lambda - \Psi\phi^c)}_{?} \underbrace{\frac{dq^c}{d\gamma}}_{>0} > \underbrace{((\sigma - \phi^r)\gamma\lambda + \Psi\phi^r)}_{>0} \underbrace{\frac{dq^r}{d\gamma}}_{?} > 0.$$

As before, we have two cases to consider. If the multiplier decreases the quantity of the renewable fuel, it must be the case that  $\lambda(\phi^c - \sigma) < \Psi\phi^c$ , i.e., the implicit tax on conventional fuels must be less than the marginal damages of the conventional fuel. If, however, the multiplier increases the quantity of renewable fuel, then it must be the case that  $\lambda(\phi^c - \sigma) > \Psi\phi^c$ . Solving for the optimal multiplier yields:

$$\gamma_{LCFS}^* = \left( \frac{\phi^c - \sigma}{\sigma - \phi^r} \right) \frac{\frac{dq^c}{d\gamma}}{\frac{dq^r}{d\gamma}} - \frac{\Psi}{(\sigma - \phi^r)\lambda} \frac{\frac{d(\phi^c q^c + \phi^r q^r)}{d\gamma}}{\frac{dq^r}{d\gamma}}. \square$$

The results from Proposition 6 are more nuanced than those from the previous proposition due to potentially adverse consequences from instituting a multiplier. Whenever increasing the multiplier decreases the volume of renewable fuel, similar results apply as derived in Propositions 4 and 5, namely that the multiplier should be adjusted to a level where the implicit tax on conventional fuels is less than its marginal damages. If, however, increasing the multiplier increases the market clearing quantity of renewable fuel, a renewable fuel mandate will unambiguously increase fuel consumption and emissions. As a result, an interior solution should be set at a level where the implicit tax on conventional fuels remains greater than the marginal damages.

Unlike the credit window option, the multiplier only indirectly affects the credit price,  $\lambda$ . Corollary 2 highlights that the inefficiencies associated with both fuel mandates persists under a credit window option.

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

- **Proof:** First consider the RFS. Rearranging equations (6), (7), and (8) for an interior solution to the RFS we have:

$$\begin{aligned} p &= C^c(q^c) + \lambda\alpha \\ p &= C^{r'}(q^r) - \lambda\gamma \end{aligned}$$

No combination of  $\alpha$  and  $\gamma$  is able to replicate the first-best optimality conditions.

Next consider the LCFS. The corresponding conditions for the LCFS are:

$$\begin{aligned} p &= C^c(q^c) + \lambda(\phi^c - \sigma) \\ p &= C^{r'}(q^r) + \gamma\lambda(\phi^r - \sigma) \end{aligned}$$

No combination of  $\gamma \geq 1$  or feasible  $\sigma$  can recreate the first-best optimality conditions.  $\square$

Thus, while soft cap mechanisms will put downward pressure on compliance credit prices, it is not feasible for the policies to achieve the first-best outcome.

## 5 Simulation of the US fuel market

In order to better understand potential short-run effects from the two fuel mandates and cost containment provisions, we develop a numerical model to simulate the US gasoline market similar to the model developed in Lade and Lin (2013). The model is calibrated to replicate baseline fuel volumes and prices observed in 2010. We use the model both to study the likely effect of the policies as well as to study the relative performance of each policy under alternative market conditions. Table 1 summarizes the key parameters of the model.

Table 1: Numerical Simulation Parameters

Variable	Value	Source
<b>Market Parameters</b>		
Fuel Demand Elasticity	0.2	Luchansky and Monks (2009); Hughes et al. (2012)
Gasoline Supply Elasticity	3	Dahl and Duggan (1996); Coyle et al. (2012); Lemoine (2013)
Conventional Ethanol Supply Elasticity	3	Luchansky and Monks (2009); Lee and Sumner (2010)
Cellulosic Ethanol Supply Elasticity	{0.5, 3}	N/A
Marginal CO <sub>2</sub> Damages (\$/ton CO <sub>2</sub> )	{\$50, \$150}	Interagency Working Group on Social Cost of Carbon (2013)
Normalized Gasoline Carbon Intensity	1.0417	N/A
Normalized Conventional Ethanol Carbon Intensity	0.5683	N/A
Normalized Cellulosic Ethanol Carbon Intensity	0.2131	Lemoine (2013)
Baseline Gasoline Consumption (bgal)	128	Energy Information Agency (2012a)
Baseline Conventional Ethanol Consumption (bgal)	12	DOE Energy Efficiency & Renewable Energy Office
Baseline Cellulosic Ethanol Consumption (bgal)	0.2	Lemoine (2013)
Baseline Fuel Price (\$/gal)	\$2.835	Energy Information Agency (2012a)
<b>Policy Parameters</b>		
LCFS Carbon Intensity Constraint	{0.2131, 1}	N/A
RFS Constraint	{0.087, 1}	N/A
Credit Window Permit Price (\$/gal)	{1; 5}	N/A
Cellulosic Credit Multiplier	{1; 5}	N/A

We abstract from real world gasoline markets considerably, assuming three representative firms exist which produce three fuels: (1) conventional gasoline; (2) conventional ethanol; and (3) cellulosic ethanol. In addition, we assume consumers value only the total volume of fuel consumed, and do not adjust fuels for their relative energy content. Alternative assumptions regarding consumer’s valuation of fuels will not change the qualitative results of our model so long as the adjustments are additive and linearly separable. We extend the analytical model from Section 4 and allow for two renewable fuels to capture dynamics currently present in the US renewable fuel market, namely that higher carbon-intensive renewable fuels such as corn-based ethanol are readily available while more advanced biofuels are less available. We do not consider the US diesel market in meeting either the LCFS or RFS. Given the expansion of biodiesel production in recent years, the omission of the market may invalidate the simulated market clearing prices and quantities; however, as discussed in Lade and Lin (2013), the qualitative results of the model are unchanged.<sup>35</sup>

All supply and demand curves are assumed to have constant elasticities and are calibrated so that under no policy the market clears at the specified baseline price and volumes. As shown in Lade and Lin (2013), the market clearing outcomes are sensitive to assumptions regarding the availability of cellulosic ethanol. In addition to the uncertainty regarding the availability of low carbon fuels, there is no clear consensus as to the appropriate assignment of damages from CO<sub>2</sub> emissions. The most recent estimates of the average social cost of carbon adopted by the Environmental Protection Agency and issued by the Interagency Working Group on the Social Cost of Carbon based on a 3% discount rate is \$46/ton CO<sub>2</sub>; however, the values based on the same discount rate range from nearly zero to over \$150/ton CO<sub>2</sub> (Interagency Working Group on Social Cost of Carbon, 2013). In order to model the market outcomes based on alternative assumptions regarding both the availability of cellulosic ethanol and marginal damages from CO<sub>2</sub> emissions, we allow the elasticity of cellulosic ethanol to take on values 0.5 and 3, as well as assume marginal damages from carbon are \$50 and \$150/ton CO<sub>2</sub>. This gives us four baseline scenarios with which to compare the relative performance of the alternative policies.

The RFS requires the total volume of renewable fuel, equal to the sum of cellulosic and conventional ethanol, to be greater than the specified renewable volume obligation. The LCFS requires that the average carbon intensity of all final fuel is less than the given standard, where the carbon intensity assignments are similar to the values for each fuel used by the ARB for the LCFS.<sup>36</sup> We normalize the carbon intensity values such that the carbon intensity of fuels in the absence of any policy,  $\sigma^0$ , is equal to 1. Thus, a LCFS equal to 0.9 requires the average carbon intensity of fuels to decrease by 10%.

For each policy, we solve for the competitive market equilibrium using the model developed by Lade and Lin (2013). To solve for the optimal policies, we conduct a fine grid search of the policy parameters under each scenario, and solve for the policy which maximizes social welfare. From Corollary 1, we know setting the LCFS to zero and the credit price equal to marginal damages will achieve the first-best equilibrium. Given that such a policy is unlikely to be passed, we constrain both fuel mandates to be ‘technologically’ feasible. In particular, we constrain the LCFS to be between the initial carbon intensity of fuels, normalized to 1, and the normalized carbon intensity of cellulosic fuels, 0.2131. Thus, the most ambitious policy the government may pass is to require only the cleanest fuel be used in the fuel market. For a RFS, we constrain the policy to be between the initial share of biofuels, 8.7%, and 100% biofuels.

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<sup>35</sup>See Lade and Lin (2013), Appendix A, pages 43-44.

<sup>36</sup>Specifically, we assume the non-normalized carbon intensity values are given by 100, 80 and 30 for conventional gasoline, conventional ethanol, and cellulosic ethanol, respectively. See [http://www.arb.ca.gov/fuels/lcfs/1214091cfs\\_lutables.pdf](http://www.arb.ca.gov/fuels/lcfs/1214091cfs_lutables.pdf) for the exact values assigned by the ARB.

Before discussing the broader results from the model, first consider the effect of each policy on social welfare for the scenario where the elasticity of supply of cellulosic ethanol is 3 and the marginal damage from CO<sub>2</sub> emissions is \$150/ton CO<sub>2</sub>. For all figures, we normalize the social welfare values to be equal to the percentage of social welfare achieved under the first best.<sup>37</sup> Thus, social welfare under the first-best policy is equal to 100, and another policy which achieves a maximum social welfare value equal to 98 is associated with a deadweight loss equal to 2%. Under no policy, social welfare is equal to around 98.8% points, representing around a 1.2% point loss in welfare. In all figures, we set the horizontal axis equal to the welfare level under no policy, so any values which fall below the horizontal axis represent scenarios where social welfare levels are lower than the no policy equilibrium.

The results for the first-best carbon tax, the second-best RFS, and the second-best LCFS are graphed in Figure 4. In the left graph, social welfare increases as the carbon tax increases, and is maximized where the tax equals the marginal damages of emissions at \$150/ton CO<sub>2</sub>. Social welfare decreases as the carbon tax exceeds marginal damages, however, the welfare gains from having a carbon tax remain positive and large relative to no tax for tax levels exceeding \$200/ton CO<sub>2</sub>.

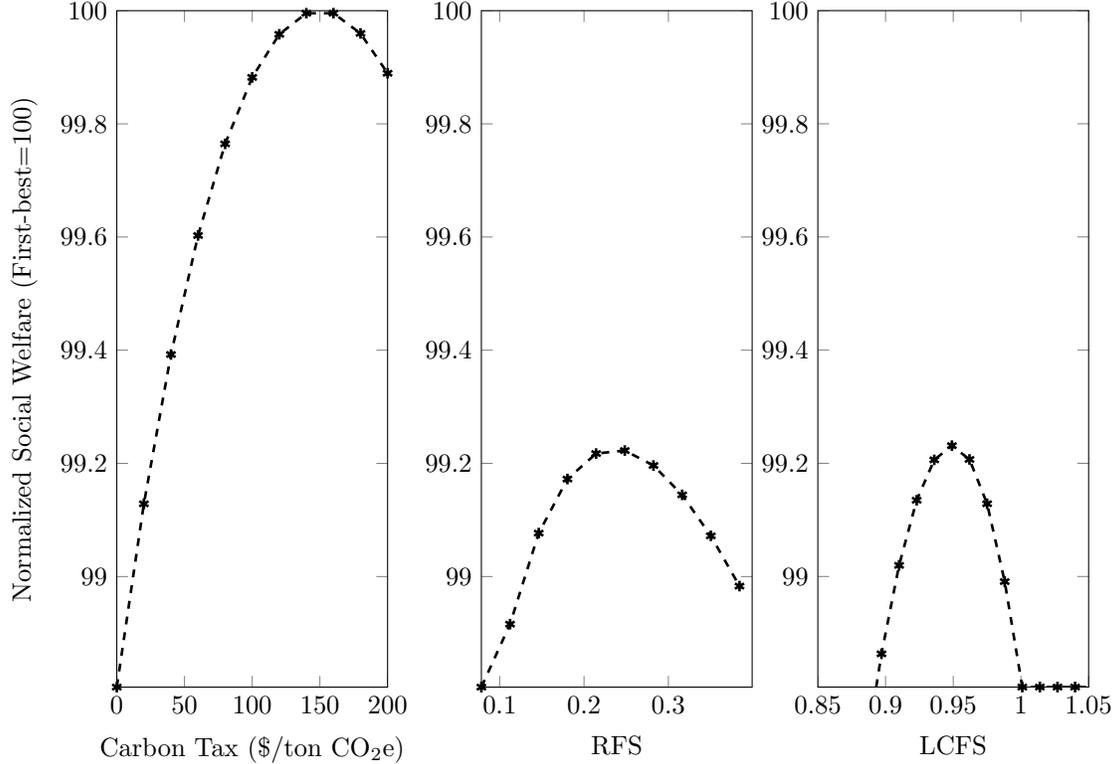
Under a RFS, the policy does not bind on the industry until the standard exceeds 8.7%, the baseline share of renewable fuels in the model. Social welfare increases sharply for low levels of a binding RFS, and is maximized with approximately a 23% standard, after which welfare declines but remains positive for levels exceeding a 40% standard. The LCFS binds on the industry whenever the standard is set below 1. As can be seen, the LCFS increases welfare sharply, and is maximized at around 0.95, or a LCFS which requires a 5% carbon intensity reduction. As the policy becomes more stringent, social welfare sharply decreases and welfare falls below the no policy equilibrium once the standard requires more than a 10% reduction in average fuel carbon intensity.

Now consider the effect of instituting each of the two cost containment mechanisms. Figure 5 graphs social welfare levels for varying credit prices and given RFS and LCFS policies. Each dashed line corresponds to a different standard, where the level of the RFS and LCFS are denoted on the line. The optimal standard and credit price combinations are represented by the dashed-starred lines. Credit prices range from \$0-\$5/credit, where each credit is denominated as a gallon of fuel. When credit prices are \$0/gallon, the equilibrium is equivalent to the no policy equilibrium because compliance with each policy is free.

The results for the RFS are presented in the left graph. For less stringent standards at 15% and 20%, setting a low credit price decreases welfare relative to a non-binding, high credit price. For a more ambitious standard of 40%, setting a non-binding credit price still increases welfare relative to the no policy equilibrium, however, welfare is increased almost four-fold when the credit price is set at a binding level at just over \$0.60/gallon. For very aggressive standards at 60% and 100%, setting a binding RFS credit price is always optimal as the standards alone would decrease social welfare relative to the no policy equilibrium. For a 60% standard, the optimal credit price is around \$0.60/gallon. The optimal combination of a RFS and credit price is given by a 100% standard with around a \$0.40/gallon credit window price.

The results for the LCFS are presented in the right graph of Figure 5. Unlike the RFS, setting a binding credit window price even for a modest carbon intensity reduction of 10% can substantially increase welfare. As the standard becomes more stringent, the optimal credit window price changes slightly, but remains around \$2/gallon. As expected the optimal policy requires setting the most stringent standard and setting the credit window price at a binding level at around \$2/gallon. The welfare gains from setting a stringent

Figure 4: First- and Second-best Policies



policy and binding emergency credit price combination are substantial, with the optimal policy-compliance credit price very nearly reaching the first-best welfare level.

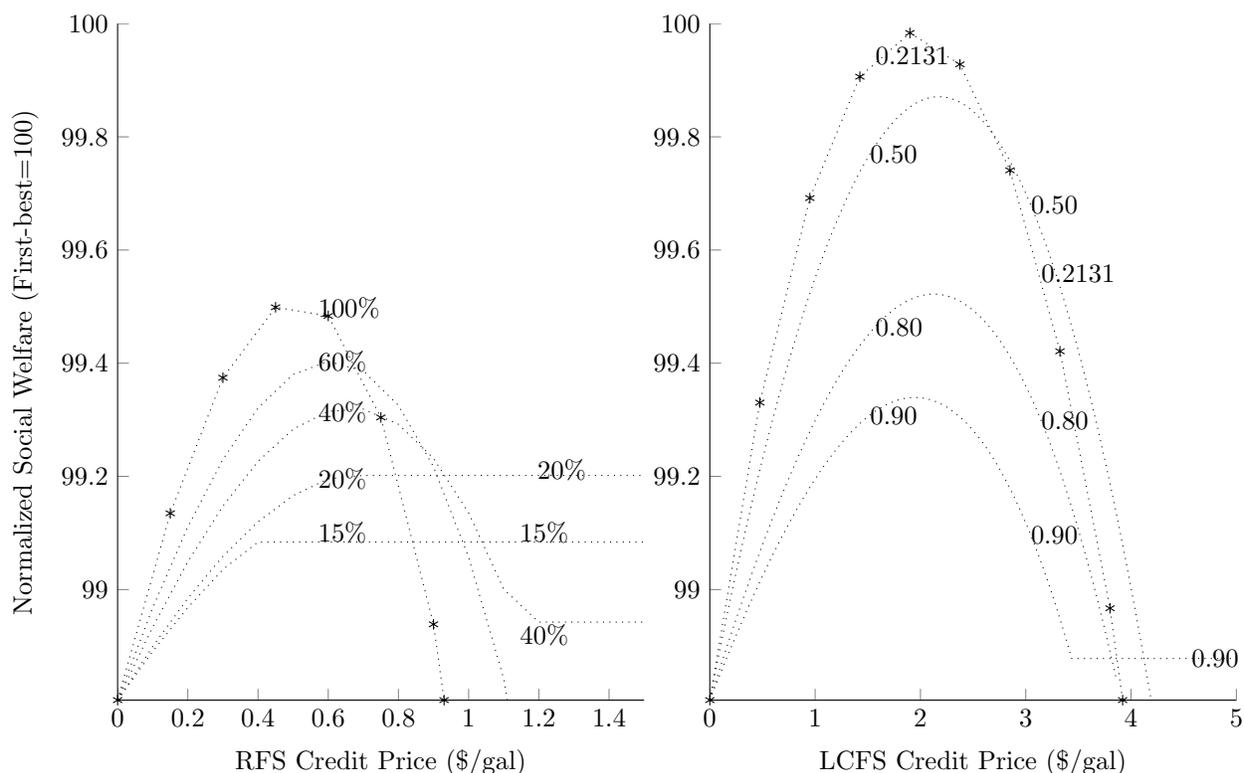
Now consider the effect of a cellulosic fuel multiplier, presented in Figure 6. We allow the multiplier to range between 1, representing no cellulosic fuel multiplier, and 5, where each gallon on cellulosic fuel counts as 5 gallons towards compliance under each program. For the RFS, presented in the left graph, setting a multiplier higher than 1 for relatively low standards such as a 10% or 15% RFS decreases welfare. For a 10% RFS, a multiplier of greater than 3 leads to a non-binding RFS and social welfare returning to the no policy level. Whenever the policy is more stringent such as a 24% or 35% standard, setting a multiplier greater than unity can increase welfare, though the returns are decreasing for very large multipliers. The optimal combination occurs with a 24.23% RFS and multiplier around 2.

The results for the LCFS are similar, where a multiplier greater than 1 decreases social welfare when the policy is set at low levels. The multiplier increases welfare for very stringent policies, however, the optimal policy-cellulosic multiplier combination is achieved by setting the LCFS at its second-best level and not instituting a credit multiplier. Overall, the value of the efficiency gains from a multiplier are modest even for the optimal policy-multiplier combination.

Tables 2 and 3 summarize our results for all four scenarios. The results compare the optimal policies across each of the 3 considered policy instruments. Social welfare values are normalized to be the percentage of the first-best social welfare level for each scenario. In addition, we provide a simple ranking of net consumer

<sup>37</sup>Specifically, for each social welfare value  $x$  for an specific policy, we normalize the value such that  $\bar{x} = \frac{x}{SW_{FB}^{\max}} * 100$ , where  $SW_{FB}^{\max}$  is the maximum social welfare achieved under the first-best solution.

Figure 5: Second-best policies with credit window



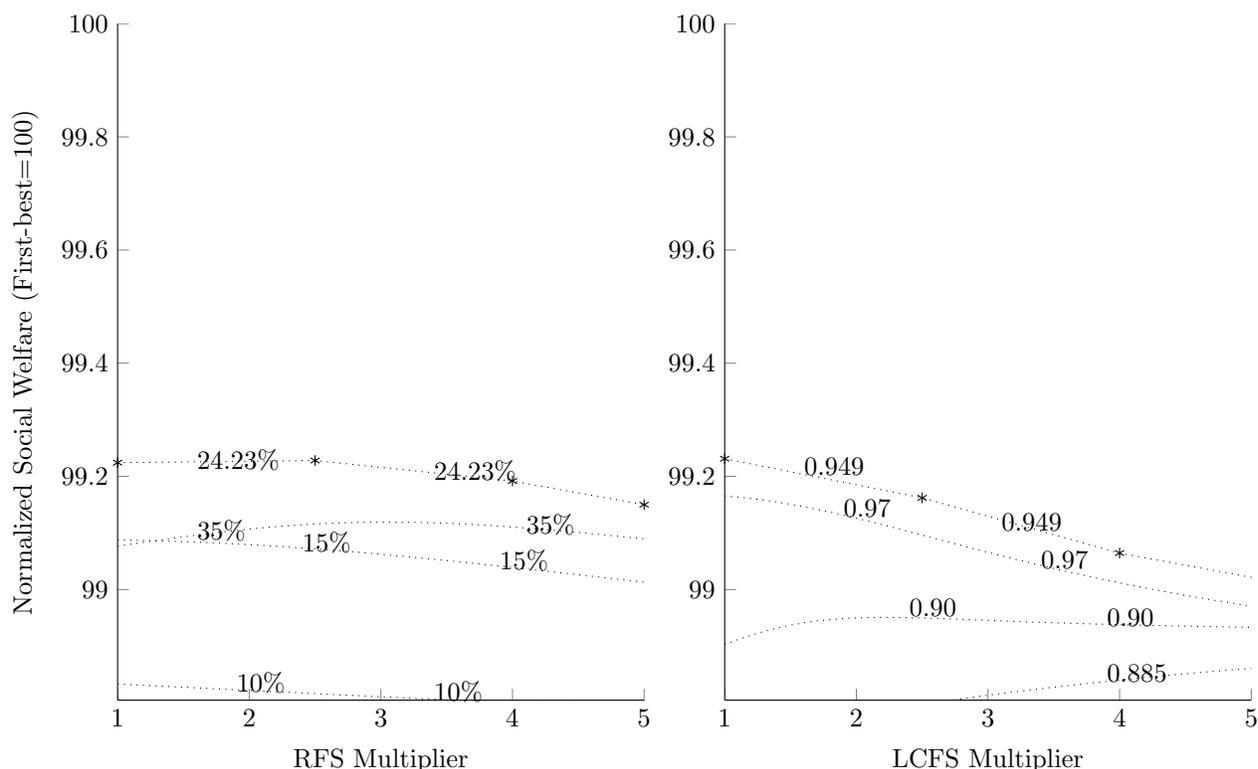
surplus and total producer surplus under each policy, where net consumer surplus is equal to consumer surplus net of damages from carbon emissions.

Comparing social welfare levels across policies, the optimal RFS achieves only modest efficiency gains across the scenarios; however, a RFS with a hard cap on compliance costs is preferred to a LCFS with no cost containment mechanism. As expected, there are only modest welfare gains when a low credit multiplier is instituted, and the gains are especially low for scenarios where the supply elasticity of cellulosic ethanol is 3. Given the similarity between increasing the cellulosic multiplier and decreasing the standard, the results suggest modifying the standard when renewable fuels are unavailable may not yield substantial efficiency gains.

Net consumer welfare is generally maximized under a RFS or RFS with a cellulosic multiplier, with the third and fourth best generally favoring a LCFS or LCFS with a cellulosic multiplier. The results is driven by the relative effect of each policy in final fuel prices. Consumer welfare decreases the most across the scenarios whenever the full cost of emissions are incorporated into the fuel price. As discussed in Section 4.1, the effect of renewable fuel mandates on final fuel prices is muted by the countervailing increase in renewable fuels associated with the decrease in conventional fuels. When a fuel mandate is paired with a hard cap on compliance costs, the policy begins to have similar features as a fixed tax on emissions, which increases welfare but also increases fuel prices and reduces consumer welfare.

Total producer surplus is maximized under the first-best policy, and the relative ranking is similar to the social welfare rankings. Thus, despite the fact that policies such as the LCFS and RFS are ‘technology

Figure 6: Second-best policies with cellulosic multiplier



forcing' policies, total producer welfare is highest whenever market prices accurately reflect the full cost of each fuel. The finding is similar to Holland et al. (2013) who find that the incentive to innovate is highest under a cap and trade program rather than a LCFS or RFS.

When carbon damages are \$150/ton CO<sub>2</sub>, the no policy equilibrium is associated with around a 1.2 percentage point loss in welfare compared to the first best level. The percentage point loss is around 0.2 when damages are \$50/ton CO<sub>2</sub>e. While the percentage loss is small, they are significant when considered in the context of the total value of the US fuel industry. For example, the loss corresponds to over \$15 billion and \$1.8 billion in welfare losses when damages are \$150/ton CO<sub>2</sub> and \$50/ton CO<sub>2</sub>, respectively.<sup>38</sup> By choosing the true 'second-best' policy from the available policy instruments and setting a stringent LCFS with a hard cap on compliance credits, the welfare losses can be reduced to around 0.02 percentage points and 0.01 percentage points, reducing deadweight loss to around \$200 million and \$20 million when damages are \$150/ton CO<sub>2</sub> and \$50/ton CO<sub>2</sub>, respectively. This constitutes substantial efficiency gains.

<sup>38</sup>The calculated values are derived from our model, which is a substantial abstraction from real world gasoline markets. The values are not meant to be used as an actual estimate of welfare losses due to unpriced emissions in the transportation sector, but were calculated only to illustrate the potentially substantial losses despite the small percentage losses displayed in Tables 2 and 3. The losses are in line with those calculated by Holland et al. (2009) in a similar simulation model of the LCFS.

Table 2: Simulation Results

Assumptions	Policy Approach	Policy	Optimal Policy	Net Consumer Surplus Ranking	Producer Surplus Ranking	Normalized Social Welfare (Rank)
Carbon Damages=\$150/ton CO <sub>2</sub> , Elasticity of Cellulosic Ethanol=0.5	No Policy Equilibrium	None	-	5	8	98.82 (8)
	First-Best Carbon Tax	Tax	\$150/ton CO <sub>2</sub>	8	1	100 (1)
	Second-Best LCFS	LCFS	0.9520	2	6	99.23 (6)
	Second-Best LCFS with Credit Window	LCFS	0.2131	7	2	99.98 (2)
	Second-Best LCFS with Cellulosic Multiplier	Credit Window Price	\$1.945/gal	3	5	99.23 (5)
		LCFS	0.9510	1	7	99.22 (7)
	Second-Best RFS	RFS	0.2323	6	3	99.51 (3)
	Second-Best RFS with Credit Window	RFS	1	4	4	99.23 (4)
	Second-Best RFS with Cellulosic Multiplier	Credit Window Price	\$0.51/gal	4	4	99.23 (4)
		RFS	0.2383	4	4	99.23 (4)
		Cellulosic Multiplier	3.4	4	4	99.23 (4)
	Carbon Damages=\$150/ton CO <sub>2</sub> , Elasticity of Cellulosic Ethanol=3	No Policy Equilibrium	None	-	5	8
First-Best Carbon Tax		Tax	\$150/ton CO <sub>2</sub>	8	1	100 (1)
Second-Best LCFS		LCFS	0.9490	3	4	99.23 (4)
Second-Best LCFS with Credit Window		LCFS	0.2131	7	2	99.98 (2)
Second-Best LCFS with Cellulosic Multiplier		Credit Window Price	\$1.94/gal	2	5	99.23 (6)
		LCFS	0.9490	4	7	99.22 (7)
Second-Best RFS		RFS	0.2363	6	3	99.51 (3)
Second-Best RFS with Credit Window		RFS	1	1	6	99.23 (5)
Second-Best RFS with Cellulosic Multiplier		Credit Window Price	\$0.51/gal	1	6	99.23 (5)
		RFS	0.2423	1	6	99.23 (5)
		Cellulosic Multiplier	1.9	1	6	99.23 (5)

Notes: Net consumer surplus is equal to total consumer surplus minus emission damages. Social welfare is normalized so that the social welfare from the first-best carbon tax is equal to 100.

Table 3: Simulation Results

Assumptions	Policy Approach	Policy	Optimal Policy	Net Consumer Surplus Ranking	Producer Surplus Ranking	Normalized Social Welfare (Rank)	
Carbon Damages=\$50/ton CO <sub>2</sub> , Elasticity of Cellulosic Ethanol=0.5	No Policy Equilibrium	None	-	5	8	99.84 (8)	
	First-Best Carbon Tax	Tax	\$50/ton CO <sub>2</sub>	8	1	100 (1)	
	Second-Best LCFS	LCFS	0.9880	2	6	99.88 (6)	
	Second-Best LCFS with Credit Window	LCFS	0.2131	7	2	99.99 (2)	
	Second-Best LCFS with Cellulosic Multiplier	Credit Window Price	LCFS	\$0.67/gal	4	4	99.88 (5)
		Cellulosic Multiplier		1.5	1	7	99.88 (7)
	Second-Best RFS	RFS	0.1273	6	3	99.93 (3)	
	Second-Best RFS with Credit Window	Credit Window Price	RFS	\$0.185/gal	3	5	99.88 (4)
		Cellulosic Multiplier		0.1303			
				2.7			
	Carbon Damages=\$50/ton CO <sub>2</sub> , Elasticity of Cellulosic Ethanol=3	No Policy Equilibrium	None	-	5	8	99.84 (8)
		First-Best Carbon Tax	Tax	\$50/ton CO <sub>2</sub>	8	1	100 (1)
Second-Best LCFS		LCFS	0.9870	2	5	99.88 (6)	
Second-Best LCFS with Credit Window		LCFS	0.2131	7	2	99.99 (2)	
Second-Best LCFS with Cellulosic Multiplier		Credit Window Price	LCFS	\$0.665/gal	3	4	99.88 (5)
		Cellulosic Multiplier		1	4	6	99.88 (7)
Second-Best RFS		RFS	0.1283	6	3	99.93 (3)	
Second-Best RFS with Credit Window		Credit Window Price	RFS	\$0.19/gal	1	7	99.88 (4)
		Cellulosic Multiplier		0.1303			
				1.9			

Notes: Net consumer surplus is equal to total consumer surplus minus emission damages. Social welfare is normalized so that the social welfare from the first-best carbon tax is equal to 100.

## 6 Conclusion

The prevalence of fuel mandates such as the RFS and LCFS is increasing, with more states implementing or proposing similar programs. As with any policy which requires firms to adopt or produce new, unproven technologies, the risk of the policies costing more than originally anticipated or more than is socially optimal is non-trivial. As a result, cost containment provisions, especially hard caps on compliance credit prices, may play an important role in protecting the integrity of the programs in the short run.

In this paper, we summarize the effects of the two fuel mandates both with and without two general classes of cost containment provisions. We then study the potential gains from strategically setting each policy. While the second-best RFS and LCFS increase welfare relative to the no policy equilibrium, the second-best policy levels call for modest deployment of renewable fuels and only achieve around a quarter to a third of the efficiency gains which would be realized under a first-best policy. Adding a soft cap on credit prices implemented through a cellulosic fuel multiplier may modestly increase the efficiency of the programs, though the gains over the second-best policies alone are modest.

Importantly, we show there may be substantial welfare gains to setting a very stringent policy and a lower, hard cap on compliance credit prices. When both the fuel mandates and the hard cap on credit prices are set strategically, the second-best policy and hard cap can achieve around 60% of the efficiency gains of a first-best policy under a RFS, while a ‘technologically feasible’ LCFS with a hard cap on compliance costs may be nearly as efficient as a first-best policy. The efficiency of a RFS is limited by its inability to differentiate fuels based on their relative emission intensities.

Our framework contains a few key omissions, including: (1) the RFS being modeled as an overall biofuel mandate rather than in a nested structure; (2) the omission of other fuel markets such as diesel fuel, natural gas, and electricity; (3) the static nature of the model; and (4) the assumption that all costs and demand are certain. Interesting future research may extend along any of these dimensions.

The success of any cost containment mechanism intervening in compliance credit markets depends crucially on the existence of a robust and liquid compliance credit market. While the RIN credit market has been fairly developed since 2009, recent price spikes from early 2013 into the summer of 2013 have called some to question whether the market has behaved rationally. According to the LCFS reporting tool, as of October 2013 there have been on average only 18-25 transactions each month for LCFS credits. Both issues may call into question the viability and liquidity of each credit market to date. If either credit market is characterized by high transactions costs or a low amount of transactions such that there is not proper price discovery, the results discussed here are not applicable. Thus, our results depend crucially on regulators ensuring there are low transactions costs and that the market for compliance credits is liquid. To the extent that the markets are not, an immediate first step towards containing costs is to increase transparency and the ability of firms to trade credits before considering any provisions discussed here.

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