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Abstract

A low carbon fuel standard (LCFS) seeks to reduce greenhouse gas emissions by capping an industry's carbon emissions per unit of output. California has launched an LCFS for automotive fuels; others have called for a national LCFS. We show that this policy causes production of high-carbon fuels to decrease but production of low-carbon fuels to increase. The net effect of this may be an increase in carbon emissions. The LCFS may also reduce welfare, and the best LCFS may be no LCFS. We simulate the outcomes of a national LCFS, focusing on gasoline and ethanol as the high- and low-carbon fuels. For a broad range of parameters, we find that the LCFS is unlikely to increase CO_2 emissions. However, the surplus losses from the LCFS are quite large ($80 to $760 billion annually for a national LCFS reducing carbon intensities by 10 percent), and the average carbon cost ($307 to $2,272 per ton of CO_2 for the same LCFS) can be much larger than damage estimates. We propose an efficient policy that achieves the same emissions reduction at a much lower surplus cost ($16 to $290 billion) and much lower average carbon cost ($60 to $868 per ton of CO_2).

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1 Introduction

Low carbon fuel standards (LCFSs) are rapidly becoming an integral part of the national debate over how to reduce greenhouse gas emissions. On January 18th, 2007 California Governor Arnold Schwarzenegger signed an executive order launching a low carbon fuel standard to reduce the carbon intensity of fuels for light-duty vehicles. The standard, which limits carbon emissions per unit of output, allows fuel producers to achieve a given carbon emissions rate by flexibly altering their production of fuels.[1] Senators John McCain and Barack Obama have both called for a national low carbon fuel standard.[2] Other countries, states, and regions also have proposed low carbon fuel standards.[3] Despite this increasing prominence, this is the first paper to analyze the economics of low carbon fuel standards.

The political appeal of low carbon fuel standards has several components. First, federal resistance to the regulation of greenhouse gas emissions has limited states' options. In particular, the options for addressing carbon emissions from the transportation sector, which accounts for 28 percent of U.S. emissions (U.S. EPA 2006) are severely limited.[4] An LCFS might avoid these federal restrictions. Second, Pigouvian taxes, which can correct negative pollution externalities, have proven politically infeasible. An LCFS is not a tax. Third, cap and trade policies, which are more politically palatable, may be undermined by demand shocks. For example, the RECLAIM emissions market was almost destroyed by the California electricity crisis since it was argued that the rigid emissions limits contributed to electricity blackouts.[5] An LCFS, by regulating emissions rates rather than emissions, allows for higher emissions in years with higher demand. Finally, politicians are quite sensitive to the effects of policies on energy prices in general and on gasoline prices in particular. An LCFS certainly does not have a direct effect on prices, and one can imagine

[1]There is much ambiguity in the design of an LCFS, including: what output is covered (*e.g.,* light duty v. heavy duty vehicle fuel), how output is measured (energy v. miles), and how emissions rates are measured (*e.g.,* upstream v. downstream). These policy design issues are currently being debated for the California LCFS.

[2]Similarly, US Senators Dianne Feinstein (D-CA), Susan Collins and Olympia Snowe (both R-ME) have introduced a measure (S.1073) designed to reduce carbon emissions, which requires an increase in the percentage of alternative fuels.

[3]A current count includes: British Columbia, Washington, Oregon, Arizona, New Mexico, Minnesota, Illinois, the United Kingdom and the European Union.

[4]The Clean Air Act of 1970 stipulates that only the Environmental Protection Agency (EPA) is allowed to regulate fuel economy. California AB 1493, which caps greenhouse gas emissions from vehicles, is currently being challenged in the courts.

[5]Permits that are fully tradeable intertemporally can increase the flexibility of tradeable permits. In practice, permits are "bankable" but not "borrowable." Hybrid instruments can also increase the flexibility of tradable permits.

scenarios (and we will illustrate one) in which an LCFS has no effect on gasoline prices yet reduces carbon emissions.[6]

Despite this political appeal, we argue that the standards have a cost in terms of efficiency and effectiveness. In particular, we find that an LCFS can achieve the first best outcome only if the low-carbon fuel has no emissions. Moreover, we find that, contrary to the stated purpose, an LCFS can actually *raise* carbon emissions. Finally, we show that the second best LCFS—from a regulator's perspective—"under-taxes" all fuels and may require a nonbinding standard, *i.e.,* the optimal standard may be no standard at all.

The intuition behind these effects is that the LCFS acts as a tax on any fuel with a carbon intensity above the standard, but acts as a subsidy for any fuel with a carbon intensity below the standard. The first best outcome cannot be attained since it requires that any fuel emitting carbon should be taxed (not subsidized) in equilibrium. Carbon emissions can increase because compliance with the LCFS can be achieved by reducing the production of high carbon fuels *or* increasing production of low carbon fuels. In equilibrium, it is optimal for firms to do both. We show that it is possible that increases in carbon from ramping up production of the low carbon fuel can outweigh the reduction in carbon associated with decreasing output of the high carbon fuel.

We extend the theoretical analysis in a number of ways. First, we argue that the results under perfect competition also hold for firms with market power. In Section 4, we discuss meeting the LCFS by trading carbon, energy, or weighted emissions rates and show that trading can reduce compliance costs by allowing firms to equate the marginal production cost of each fuel across firms. Section 5 illustrates the surplus gains and losses to producers and consumers. Depending on the relative elasticities, producers and/or consumers can bear the burden of the LCFS. Incorporating gains from carbon trading shows that producers of low-carbon fuels are better off under an LCFS, while producers of high-carbon fuels are harmed.

Section 6 analyzes variants of the energy-based LCFS. We argue that feasible variants, which use different baselines, can have better incentives than the energy-based LCFS by increasing the implicit tax and reducing the implicit subsidy of the LCFS. In particular, a historical-baseline LCFS, which regulates carbon emissions relative to historic energy production, can attain the first-

[6] In initial policy discussions for implementing an LCFS in California, no mention was made of any effects on prices.

best emissions and fuel production. Analysis of these variants makes explicit the difficulties of finding a suitable baseline for the LCFS or for any other trading program. Section 7 analyzes the incentives under the different policies for technological innovation in carbon emissions rates and fuel economy.

To understand the likely impacts of an LCFS, Section 8 calibrates the theoretical model using a range of parameters representative of US supply and demand conditions for ethanol and gasoline. We find that an energy-based LCFS is unlikely to increase CO_2 emissions. In fact, we find that the CO_2 reductions can be surprisingly large. For example, an LCFS that reduces the carbon intensity by 10% reduces emissions by 45% for one set of parameters.[7]

While the CO_2 reductions can be significant, the energy-based LCFS is an expensive way to achieve these reductions. For the 10% reduction in carbon intensity, we find that the social surplus loss per ton of CO_2—the average cost of CO_2 reduction—ranges from \$307 to \$2,272 per ton. This implies that if the damage per ton of CO_2 is less than \$307, the LCFS reduces welfare. Since most damage estimates are less than this, our calculations imply that society would be better off without an LCFS compared to a standard that reduces the carbon intensity by 10%. In fact, if carbon damages are less than \$140, even a modest LCFS reducing carbon intensities by only 1% would never increase welfare in our simulations.

We compare these costs to the historical-baseline LCFS, which is equivalent to carbon trading and can attain the first best. The carbon cost under the historical-baseline LCFS, which attains the same CO_2 emissions reduction, are much lower: ranging from \$60 to \$868 per ton of CO_2. This historical-baseline LCFS corrects the perverse incentive for firms to internally *subsidize* ethanol production, taxing all fuels commensurate with their carbon content.

In our simulations, consumer surplus from energy consumption decreases for all but the most lenient standards, and producer surplus can increase or decrease. Accounting for carbon market transfers, surplus to ethanol producers always increases under an LCFS while surplus to gasoline producers always decreases. Carbon market transfers account for almost all of the gains to ethanol producers.

Our theoretical analysis is similar to Kwoka's (1983) study of an auto manufacturing monopolist

[7]The proposed LCFS in California calls for a 10% reduction in carbon intensities.

facing linear demands and a CAFE standard.[8] He shows that, under a CAFE standard, total vehicle sales can increase and fuel savings can be partially or fully offset. Our theoretical results are even stronger along several dimensions.[9] First, we demonstrate that rate regulation cannot be efficient. Second, we show that the optimal rate regulation may be nonbinding. Third, we show that the results are not due to market power, but rather are an optimal response to the policy. Fourth, our results hold for general supply and demand functions. Fifth, we illustrate the underlying supply and demand conditions which lead to the counterintuitive result. Finally, we analyze alternative baselines and trading.

While we analyze a low carbon fuel standard, our results are immediately applicable to any policy which regulates a rate when the true target of the policy is the level. The analysis is even applicable beyond environmental policy. For example, No Child Left Behind (NCLB), which requires a certain percentage of students to pass standardized tests, essentially regulates the test failure rate of public schools. Our analysis shows that NCLB places an implicit tax on low achieving students and a subsidy on high achieving students. If this tax leads to a reduction in the number of low achieving students taking the tests, then NCLB would lead to a decrease in the number of students passing the exams.[10] Although, public school administrators at the primary and middle school levels may have little scope for altering the mix of students taking the exams, our analysis illustrates the incentives these administrators face.

2 Efficient fuel production and carbon emissions

The model considers a negative externality, carbon emissions, associated with energy production. To illustrate the main theoretical effects, we focus on two fuels with different costs and carbon emissions rates. The theoretical analysis readily generalizes to multiple fuel sources.

[8] Helfand (1991) considers a number of regulatory instruments for regulating pollution including a standard expressed as emissions per unit output. As in our analysis, Helfand finds that the "constraint could lead to the perverse result that pollution increases." Her analysis does not, however, include our other theoretical results.

[9] An LCFS can be thought of as regulating the carbon efficiency of fuel. Khazzoom (1980) first identified the "rebound" or "take-back" effect of energy efficiency regulations, and Portney (2003) discusses the rebound effect in CAFE standards. Since motorists do not directly pay for carbon emissions, regulating carbon efficiency with an LCFS does not affect the cost of driving, and the LCFS does not have a rebound effect.

[10] Fiske and Ladd (2004) observe precisely this effect in post-apartheid South Africa. Although pass rates for matriculation exams increased following 1997, the total number of passes declined slightly over this period of time. The authors attribute part of this to a "variety of responses by individual schools to political pressure to raise their particular pass rates."

One fuel source, the high carbon fuel, *e.g.,* gasoline, has production costs $C_H(q)$ with $C'_H > 0$ and $C''_H > 0$ and carbon emissions rate β_H. A second fuel source, the low carbon fuel, *e.g.,* ethanol or hydrogen, has production costs $C_L(q)$ with $C'_L > 0$ and $C''_L > 0$ and emissions rate β_L. Assume $\beta_H > \beta_L \geq 0$ but $C_H(q) < C_L(q)$ for every relevant q. Further assume the quantities of each fuel source, q_H and q_L, are measured in some equivalent energy unit, *e.g.,* mmBtu, with $q_i \in \mathbb{R}_+$. Suppose a unit of carbon does τ dollars of damage, so the environmental damage from fuel i is $\tau\beta_i q_i$.

Let the benefit from consumption of energy be $U(q_H, q_L)$ with U increasing and concave. This function, which captures consumer surplus, is quite general and allows for a wide range of assumptions about substitutability of the fuels. Importantly, the marginal utilities, *i.e.,* the partial derivatives, capture the demands for the fuels.[11]

Efficient fuel production, consumption and carbon emissions in the model can be found from the following maximization problem:

$$\max_{q_H, q_L} \; U(q_H, q_L) - C_H(q_H) - C_L(q_L) - \tau(\beta_H q_H + \beta_L q_L). \tag{1}$$

Letting $MC_i = \frac{\partial C_i}{\partial q_i}$, the first order conditions can be written:

$$\frac{\partial U}{\partial q_i} = MC_i(q_i) + \tau\beta_i$$

for $i \in \{H, L\}$. Thus in the first best allocation, the marginal benefit of consumption equals the marginal social cost of production for each fuel.

As is well-known, perfectly competitive firms cannot in general achieve this efficient allocation, producing too much of any good which causes a negative externality. For prices p_i, the inefficiency arises in this model since firms produce such that $p_i = MC_i(q_i)$, but ignore the marginal social damage, $\tau\beta_i$. Because $p_i = \frac{\partial U}{\partial q_i} < MC_i(q_i) + \tau\beta_i$ in equilibrium, too much of each good is produced. This over-production could be corrected with market mechanisms such as Pigouvian taxes, here $\tau\beta_i$, or a system of tradable permits. Importantly, the Pigouvian taxes, which internalize the externality, impose a positive carbon tax on production of each fuel with a lower Pigouvian tax on the low carbon fuel.

[11] This formulation assumes additive separability from other goods. Income effects could be easily incorporated at the cost of additional notation.

3 An energy-based low carbon fuel standard

Consider a low carbon fuel standard expressed as a limit on the emissions per energy unit of fuel produced. To emphasize the tradeoffs between production of the two fuels, we focus on a single, representative, price-taking firm which produces both fuels. The analysis is easily extended to symmetric price-taking firms. Firms that are not price takers are analyzed in the section on market power, and asymmetric firms are discussed in the section on trading.

Let σ be the low carbon fuel standard, for example, in tons of CO_2 per mmBtu. The LCFS constraint facing our representative firm is:

$$\frac{\beta_H q_H + \beta_L q_L}{q_H + q_L} \leq \sigma. \tag{2}$$

Note that since the constraint implies that the weighted average of β_H and β_L must be less than σ, the constraint set is empty if $\sigma < \beta_L$. Similarly, the constraint set contains the entire positive orthant if $\sigma > \beta_H$.[12] In what follows, we assume that $\beta_L \leq \sigma \leq \beta_H$.

If we write the constraint as $\beta_H q_H + \beta_L q_L \leq \sigma(q_H + q_L)$, the Lagrangian for the firm's profit maximization can be written:

$$\max_{q_H, q_L} \; p_H q_H + p_L q_L - C_H(q_H) - C_L(q_L) + \lambda[\sigma(q_H + q_L) - \beta_H q_H - \beta_L q_L] \tag{3}$$

where λ is the shadow value of the LCFS constraint. The firm's first order conditions are:

$$p_i = MC_i(q_i) + \lambda(\beta_i - \sigma), \tag{4}$$

and:

$$\lambda[\sigma(q_H + q_L) - \beta_H q_H - \beta_L q_L] = 0, \tag{5}$$

where $\lambda \geq 0$. The first condition is that the firm equates price and marginal opportunity cost, where the opportunity cost includes the production cost as well as the effect on the LCFS constraint. The second condition, [5], is the complementary slackness condition which states that either the shadow value of the constraint is zero or the LCFS constraint binds. Since [4]-[5] characterize supply, and demand for fuel i is characterized by $p_i = \frac{\partial U}{\partial q_i}$, we have:

[12] Intuitively, if the standard is stricter than the lowest emissions rate, it is impossible to meet. Alternatively, if the standard is weaker than the highest emissions rate, then it is not binding.

Characterization of the energy-based LCFS equilibrium

If the LCFS binds, the LCFS equilibrium (q_H^e, q_L^e, λ^e) is characterized by:

$$\frac{\partial U(q_H^e, q_L^e)}{\partial q_i} = MC_i(q_i^e) + \lambda^e(\beta_i - \sigma)$$

for $i \in \{H, L\}$ and the constraint equation $\sigma(q_H + q_L) = \beta_H q_H + \beta_L q_L$.

The LCFS equilibrium introduces a wedge, $\lambda^e(\beta_i - \sigma)$, between marginal benefit, *i.e.,* demand, and marginal cost, *i.e.,* supply. Intuitively, this LCFS wedge can be analyzed like any tax wedge. To analyze this wedge, note that $\beta_H - \sigma \geq 0$ and $\beta_L - \sigma \leq 0$ since the standard is between the two emissions rates. For fuels with emissions rates higher than the standard, the LCFS wedge is nonnegative. Thus the high carbon fuel is *taxed* in the LCFS equilibrium. However, for fuels with emissions rates lower than the standard, the LCFS wedge is nonpositive, and the low carbon fuel is *subsidized* in the LCFS equilibrium.[13] This leads to our first result:[14]

Proposition 1 *The energy-based low carbon fuel standard cannot achieve the efficient allocation of fuel production and carbon emissions if $\beta_L > 0$. If $\beta_L = 0$, the efficient allocation can be attained (by setting $\sigma = 0$) iff $\partial U(0, q_L^*)/\partial q_H \leq MC_H(0) + \tau\beta_H$ (i.e., it is optimal only for fuel 2 to be produced).*

Proposition 1 follows since production of each fuel causes a negative externality. The efficiency conditions show that marginal utility should be above the marginal production cost for each fuel. However, with a standard, the firm faces an additional incentive to produce the low carbon fuel. Namely, increasing production of the low carbon fuel means the firm need not decrease production of the high carbon fuel as severely. This additional incentive means that the low carbon fuel is produced so that its price (equal in equilibrium to its marginal utility) is less than its marginal cost. This is not efficient. In short, the carbon in the low emissions fuel faces a negative price even though it produces the same damages as the carbon in the high emissions fuel, which faces a positive carbon price.

The second part of the proposition follows since if one fuel has zero emissions and production of the other fuel is socially inefficient, then setting the LCFS to zero can prohibit production of the high carbon fuel.

[13]More precisely, we can define $\lambda^e(\beta_H - \sigma)$ as the *LCFS tax* and $\lambda^e(\sigma - \beta_L)$ as the *LCFS subsidy.*

[14]All proofs are in the appendix.

Since Proposition 1 shows that the energy-based LCFS generally cannot attain the first best, the question arises as to how effective the LCFS can be in reducing carbon emissions. This leads to our second result:

Proposition 2 *The energy-based low carbon fuel standard may either increase or decrease carbon emissions and may either increase or decrease total energy production. If the LCFS increases emissions, then it increases energy. Similarly, if the LCFS reduces energy, then it reduces emissions.*

Proposition 2 follows for two separate reasons, which are reflected in the two independent proofs of the proposition. The first proof uses an example which shows that the LCFS can increase carbon emissions and energy, for a given standard, depending on the relative slopes of the marginal benefit and marginal cost curves. The second proof uses an example which shows that the LCFS can increase carbon emissions if the standard is not stringent enough.

The first proof of Proposition 2 follows because a given tax or subsidy affects output more if demand and supply are more elastic. For example, if the standard is set at the average emissions rate $(\beta_H + \beta_L)/2$, then the tax and subsidy are exactly equal. If demand and supply of the high carbon fuel are relatively flatter than those of the low carbon fuel, then the tax decreases production of the high carbon fuel more than the subsidy increases production of the low carbon fuel. In this case, carbon emissions clearly decrease under the LCFS. However, if demand and supply of the low carbon fuel are relatively flatter, then the tax decreases production of the high carbon fuel less than the subsidy increases production of the low carbon fuel. If the difference in relative slopes is large enough, the resulting large increase in low carbon fuel can lead to an increase in carbon emissions despite the lower emissions rate of the low carbon fuel.

The first proof might suggest that the energy-based LCFS only has perverse effects when the slopes of the marginal benefit and marginal cost curves are dramatically different. However, as shown in the second proof, the energy-based LCFS can lead to an increase in carbon emissions—even when the slopes are identical—if the standard is not set sufficiently tight. This follows because the relative sizes of the tax and subsidy depend on the stringency of the LCFS standard. If the standard is set relatively tight, *i.e.,* close to β_L, then the subsidy is smaller than the tax. In this case, production of the low carbon fuel increases less than production of the high carbon fuel decreases, and the LCFS decreases carbon emissions. However, if the standard is relatively lax, *i.e.,* close to β_H, then the subsidy is larger than the tax. In this case, production of the low carbon fuel increases more than production of the high carbon fuel decreases. Under certain conditions, the relative increase can be large enough that the LCFS can increase carbon emissions without differences in the relative slopes.[15]

The necessary conditions developed in Proposition 2 are quite intuitive. Since an LCFS reduces the carbon intensity of fuel, if it increases carbon emissions then energy must have increased. Similarly, if the LCFS reduces energy, then it must also reduce carbon emissions. This proposition also points to an interesting possibility: an LCFS could reduce carbon emissions while slightly increasing energy production.

3.1 The second best energy-based LCFS

Propositions 1 and 2 show that an energy-based low carbon fuel standard is not efficient and may even increase carbon emissions. However, if this is the only feasible policy option, the regulator may prefer to use the policy tool. This section analyzes the best energy-based LCFS a regulator could choose. Since any LCFS is not efficient, we call this the *second best* standard.

If the regulator can only determine the level of the standard, but not firms' responses to the standard, the LCFS equilibrium is as characterized above, where $(q_H^e,\, q_L^e,\, \lambda^e)$ depends on σ. The regulator's second best problem is:

$$\max_{\sigma}\; U(q_H^e, q_L^e) - C_H(q_H^e) - C_L(q_L^e) - \tau(\beta_H q_H^e + \beta_L q_L^e).$$

with $\beta_L \leq \sigma \leq \sigma^0$ where σ^0 is the carbon intensity in the unregulated equilibrium.[16] Here the regulator, whose only policy tool is the energy-based LCFS, puts equal weight on consumer surplus, producer surplus, and environmental damages.

The first order necessary conditions for the regulator's problem are:

$$\left(\frac{\partial U}{\partial q_H} - MC_H(q_H) - \tau\beta_H\right)\frac{dq_H^e}{d\sigma} + \left(\frac{\partial U}{\partial q_L} - MC_L(q_L) - \tau\beta_L\right)\frac{dq_L^e}{d\sigma} \geq 0,$$

and $\sigma^0 - \sigma^* \geq 0$ plus the complementary slackness condition.[17] Substituting in the firm's optimality

[15] A standard close to β_H may not be binding, so even a relatively lax, binding standard may imply a larger implicit tax than subsidy.

[16] Formally, if we let q_i^0 be the equilibrium production of fuel i in the absence of regulation, then the carbon intensity in the unregulated equilibrium, *i.e.,* most lax binding standard, is $\sigma^0 = (\beta_H q_H^0 + \beta_L q_L^0)/(q_H^0 + q_L^0)$.

[17] Since the constraint imposed on the regulator by the LCFS equilibrium is highly nonlinear, care must be taken to ensure that this necessary condition is indeed sufficient.

conditions shows that the FOC for an interior solution can be written

$$[\lambda^e(\beta_H - \sigma^*) - \tau\beta_H]\frac{dq_H^e}{d\sigma} = -[\lambda^e(\beta_L - \sigma^*) - \tau\beta_L]\frac{dq_L^e}{d\sigma}. \tag{6}$$

This equation says that the differences between the implicit tax/subsidy, $\lambda^e(\beta_i - \sigma^*)$, and the optimal taxes, $\tau\beta_i$, weighted by the changes in output should be equal at the optimal LCFS. By rearranging, this equation can be written:

$$(\lambda^e - \tau)\frac{d(\beta_H q_H^e + \beta_L q_L^e)}{d\sigma} = \lambda^e \sigma^* \frac{d(q_H^e + q_L^e)}{d\sigma} \tag{7}$$

which relates the marginal change in carbon emissions from a change in the standard with the marginal change in energy. We can now state the following proposition:

Proposition 3 *The second-best optimum may have $\sigma^* = \sigma^0$. At an interior solution, i.e., if $\sigma^* \in (\beta_l, \sigma^0)$ the second best optimum has:*
i) $\frac{d(\beta_H q_H^e + \beta_L q_L^e)}{d\sigma} > 0$,
ii) $\lambda > \tau$ *if and only if* $\frac{d(q_H^e + q_L^e)}{d\sigma} > 0$,
iii) $\lambda^e(\beta_L - \sigma^*) < \tau\beta_L$ *if* $\beta_L > 0$, *and*
iv) $\lambda^e(\beta_H - \sigma^*) < \tau\beta_H$ *if* $\beta_L > 0$, $\frac{dq_H^e}{d\sigma} > 0$, *and* $\frac{dq_L^e}{d\sigma} < 0$.

Proposition 3 first shows that it may be optimal to choose a nonbinding energy-based LCFS. This result has a strong implication, namely: under these conditions, any energy-based LCFS would decrease surplus relative to imposing no LCFS regulation.

For an interior solution, Proposition 3 derives several results about the optimal LCFS. First, relaxing the optimal standard cannot reduce emissions. This is intuitive since otherwise the regulator would presumably relax the standard. Second, the optimal λ is greater than τ if and only if tightening the standard reduces energy. With carbon trading, the regulator can attain the first best by comparing the shadow value of the carbon constraint with the marginal damages. This result shows that the second best cannot be attained by a simple comparison of the shadow value of the LCFS constraint and the marginal damages. The third result, that the implicit tax/subsidy on the low carbon fuel is less than the optimal tax, is unsurprising since the implicit tax is negative. The fourth result, shows that the optimal standard also under-taxes the high carbon fuel in the intuitive case where the standard decreases high carbon fuel, but increases low carbon fuel. Thus, the optimal LCFS "under-taxes" both fuels.[18]

[18] The appendix shows that $\frac{dq_H^e}{d\sigma} < 0$ and $\frac{dq_L^e}{d\sigma} > 0$ lead to a contradiction, *i.e.,* tightening the standard cannot lead to more high carbon fuel but less low carbon fuel. However, other sign combinations are possible.

3.2 Graphical illustration of the propositions

To illustrate Propositions 1 and 2, consider the function $U(q_H, q_L) - C_H(q_H) - C_L(q_L)$. By assumption the function is concave and has a unique global maximum. Define the *iso-surplus curves* as the level curves of this function, which are illustrated by circles in Figure 1. The unconstrained maximum of the function is shown by point A. By simple inspection of the first order conditions, this maximum is the (inefficient) perfectly competitive equilibrium which would result without regulation of the externality.

Now consider optimization of this function subject to the constraint $\beta_H q_H + \beta_L q_L \leq C^*$. This constraint set requires total carbon emissions to be less than C^*. If we define an *iso-carbon line* for C^* as the locus of points with carbon emissions C^*, then the constraint set is the area below this iso-carbon line.[19] The constrained optimum is point B. If C^* is chosen such that the shadow value of the constraint equals τ, this constrained optimum is the efficient outcome—seen again by simple inspection of the FOCs.

Finally, consider optimization of this function subject to the LCFS constraint $\beta_H q_H + \beta_L q_L \leq \sigma(q_H + q_L)$. This constraint set is the area above and to the left of the line $q_L = \frac{\beta_H - \sigma}{\sigma - \beta_L} q_L$. Again by simple inspection of the FOCs, this optimum, given by point C, is the LCFS equilibrium. Since points B and C are different, the LCFS is not efficient. This inefficiency is the main result in Proposition 1.[20]

The first proof of Proposition 2 is illustrated in Figures 2 through 5. Figures 2 and 3 show an LCFS that is effective in reducing carbon emissions while Figures 4 and 5 show an LCFS that increases carbon emissions. In Figure 2, the iso-surplus curves are illustrated along with the unconstrained maximum, A. The iso-carbon line, $\beta_H q_H + \beta_L q_L = K$, shows the locus of points with the same carbon emissions as the unconstrained maximum. Thus points below the iso-carbon line decrease carbon emissions while points above the iso-carbon line increase emissions. The LCFS equilibrium is illustrated by point B. As illustrated, the elliptical iso-surplus curves lead to an LCFS optimum where carbon emissions are lower than in the unconstrained optimum.

[19] We can think of C^* as a cap on total carbon emissions. The constraint set is then all feasible allocations under a cap and trade program.

[20] Figure 1 also illustrates an additional problem with the LCFS. Namely, the efficient allocation of fuel production may itself violate the LCFS constraint.

These elliptical iso-surplus curves arise because of differences in the marginal surplus cost of increasing the low carbon fuel above the unconstrained optimum relative to decreasing the high carbon fuel below the unconstrained optimum. With the relative slopes of the marginal benefit and marginal cost curves illustrated in Figure 3, there is a larger surplus loss from increasing q_L than from decreasing q_H by the same amount. These relative slopes generate elliptical iso-surplus curves as in Figure 2. Figure 3 also illustrates the tax, $\lambda^e(\beta_H - \sigma)$, and subsidy, $\lambda^e(\sigma - \beta_L)$, wedges. As illustrated the tax decreases production of the high carbon fuel by more than the subsidy increases production of the low carbon fuel, and carbon emissions decrease.

Figures 4 and 5 show an LCFS that *increases* carbon emissions. Again the iso-surplus curves in Figure 4 are elliptical, but now a decrease in q_H reduces surplus relatively more than an increase in q_L does. Here the LCFS optimum at C leads to an increase in carbon emissions since C is above the iso-carbon line, $\beta_H q_H + \beta_L q_L = K$. The relative slopes of corresponding marginal benefit and marginal cost curves are illustrated in Figure 5. Here the slopes of the marginal benefit and marginal cost curves of the low carbon fuel are flatter than the corresponding slopes of the high carbon fuel. Thus the LCFS subsidy increases production of the low carbon fuel more than the LCFS tax decrease production of the high carbon fuel. In this case, the increase in q_L is large enough that it leads to an increase in total carbon emissions despite the lower emissions rate of the low carbon fuel.

Figures 6 and 7 illustrate the second proof of Proposition 2 which shows that the energy-based LCFS can lead to an increase in carbon emissions—even when the slopes of the marginal benefit and marginal cost curves are identical—if the standard is not set sufficiently tight. In Figure 6, the iso-surplus curves are circles, which implies that the (linear) marginal benefit and marginal cost curves of the two fuels have the same slopes. With iso-surplus circles, the gradient of the surplus function, which is tangent to the iso-surplus circles, always points to the unconstrained maximum allowing easy comparison of carbon emissions with and without the LCFS constraint. In particular, if the gradient vector at the LCFS optimum is steeper (flatter) than the isocarbon line, then emissions are increased (decreased) by the standard. In Figure 6, the unconstrained optimum is at A, and the points B, C, and D illustrate the LCFS equilibria subject to progressively more stringent LCFS standards. At point B the gradient vector is steeper than the iso-carbon line, which implies that carbon emissions are higher under the LCFS. At C, the standard is such that the border of the LCFS constraint and the isocarbon line are perpendicular, *i.e.*, , $(\frac{-\beta_H}{\beta_L})\frac{\beta_H-\sigma}{\sigma-\beta_L} = -1$

or $\sigma = \frac{\beta_H^2+\beta_L^2}{\beta_H+\beta_L}$. This implies that the gradient vector and iso-carbon line have the same slope at C, and that C is on the iso-carbon line, *i.e.,* , emissions are unchanged by the LCFS. Under a more stringent standard, as illustrated by D, the gradient vector is flatter than the isocarbon line, which indicates that the standard decreases carbon emissions.

Figure 7 illustrates point B where the standard increases carbon emissions. This standard is not very stringent, *i.e.,* σ is closer to β_H than to β_L, and the LCFS tax on the high carbon fuel is smaller than the subsidy for the low carbon fuel. Thus, the firm optimally increases production of the low carbon fuel more than it decreases production of the high carbon fuel. If the increase in production is relatively large, the modest LCFS can increase carbon emissions.[21]

The second best LCFS is illustrated in Figure 8. Here the iso-surplus circles are illustrated by the dashed circles, and the unregulated optimum is point A. The social indifference curves are illustrated by the solid ellipses and attain a maximum at the efficient allocation, point B.[22] The locus of LCFS equilibria with different standards is illustrated by the curve connecting points A and D.[23] Point C is the LCFS equilibrium on the highest social indifference curve and is, thus, the second best allocation. In this example, a modest LCFS is second best. The proof of Proposition 3 describes an example in which a nonbinding LCFS is second best.

3.3 Market power

Our results assume perfect competition in both markets, but could easily be extended to alternative models of firm conduct. While market power is unlikely to change our main results, it has two effects in the model. For one, market power tends to mitigate the negative externality associated with carbon. Market power is itself a market failure. In the absence of a negative externality, market power leads to under-consumption of the good. In the presence of a negative externality, whether a good is under- or over-consumed depends on the size of each market failure. If the mark up for fuel j equals $\tau\beta_j$, then the market outcome is first best.[24] Here points A and B coincide in Figure 1. As mark ups are reduced from this level, point B moves northwest.

[21] In Figure 6, a modest (binding) standard increases carbon emissions if the unconstrained optimum, A, is below the ray through the origin which is perpendicular to the iso-carbon line.

[22] Including the environmental costs changes the circles to ellipses since increasing q_H has a greater environmental cost than increasing q_L by the same amount.

[23] Point A is the equilibrium with a nonbinding LCFS, and point D is the equilibrium with a standard equal to β_L.

[24] It is important to note that for this result, the relevant mark up is the sum of mark ups over each facet of the fuel's production. This includes extraction/feedstock growth, refining and retail.

While market power does not change Proposition 2, asymmetric levels of market power across the two fuels would affect the likelihood an LCFS would lead to an increase or decrease in carbon. Market power ultimately drives a wedge between demand and marginal revenue.[25] With linear demand, market power steepens the marginal revenue curve; whether an LCFS increases or decreases carbon then depends on the relative slopes of the marginal revenue and marginal cost curves across the two fuels. To illustrate this point, consider a monopolist operating in these two markets. The firm's first order condition for fuel i is:

$$\frac{\partial U(q_H^e, q_L^e)}{\partial q_i} + \frac{\partial^2 U(q_H^e, q_L^e)}{\partial q_i^2} q_i + \frac{\partial^2 U(q_H^e, q_L^e)}{\partial q_H \partial q_L} q_{-i} = MC_i(q_i^e) + \lambda^e(\beta_i - \sigma),$$

where $-i$ represents fuel other than i. Comparing this set of first order conditions with those under perfect competition, we see that the left hand side of the first order condition replaces the marginal utility for fuel i with the marginal revenue associated with the fuel.

It is difficult to speculate as to the relative levels of market power in gasoline and ethanol refining. Market power concerns are common in gasoline refining, but given the small amount of ethanol currently consumed may not be vocalized for ethanol. A recent FTC study of the ethanol market reports an HHI range of 499 to 1613, depending on whether a firm is defined as a producer or marketer and whether capacity or production is used.[26] These calculations assume the relevant market is national; in the gasoline refining market, the FTC has traditionally viewed the relevant market to be smaller than a PADD, where PADD-level HHIs range from 1000 to 2000.[27] Applying a consistent market size assumption increases the estimated HHI for ethanol.

Given this range and the likelihood that the ethanol industry is in a state of change, we leave the issue of relative market power in the two industries for future work.

4 Trading

If firms with different production costs must each meet the same low carbon fuel standard, then trading can potentially reduce compliance costs. Policymakers can take advantage of the cost savings from trading in a number of ways. For one, reducing the cost of compliance might increase the

[25]Here, the relevant market power is at the refining and retail levels, since the LCFS is set at the refining level. Upstream market power simply corresponds to a shift in the marginal cost curves.

[26]Available at: http://www.ftc.gov/reports/ethanol05/20051202ethanolmarket.pdf.

[27]See, Moss (2007).

support of legislation among fuel producers. Alternatively, for a given level of costs, policymakers can increase the stringency of the standard by allocating production more efficiently.

To illustrate trading, extend the model to two different (types of) firms, A and B, with different marginal production costs. Suppose that firms trade "low carbon energy" where x_j is the (net) quantity of low carbon energy demanded by firm $j \in \{A, B\}$, β_x is the emissions rate of low carbon energy with $\beta_x < \sigma$,[28] and p_x is its price. Firm j's profit maximization is now:

$$\max_{q_{Hj}, q_{Lj}, x_j} \; p_H q_{Hj} + p_L q_{Lj} - C_{Hj}(q_{Hj}) - C_{Lj}(q_{Lj}) - p_x x_j + \lambda_j[\sigma(q_{Hj} + q_{Lj} + x_j) - \beta_H q_{Hj} - \beta_L q_{Lj} - \beta_x x_j].$$

This maximization is identical to [3] except the firm can also purchase (or sell) low carbon energy at cost $p_x x_j$, but must incorporate additional emissions $\beta_x x_j$ and additional energy x_j in its LCFS constraint. The firm's FOCs for energy are $p_i = MC_{ij}(q_{ij}) + \lambda_j(\beta_i - \sigma)$, and its FOC for low carbon energy is $p_x = \lambda_j(\sigma - \beta_x)$. We show in the appendix that the firm's net demand for low carbon energy is downward sloping, *i.e.,* $dx_j/dp_x < 0$. The trading equilibrium for two firms (taking energy prices as given) is then characterized by the six FOCs, the two LCFS constraints, and market clearing in low carbon energy, *i.e.,* $x_A + x_B = 0$.

Three points are worth noting. First, by writing the firm's LCFS constraint with trading as $(\beta_H - \sigma)q_{Hj} + (\beta_L - \sigma)q_{Lj} = (\sigma - \beta_x)x_j$, it is easy to show that the market clearing condition implies $(\beta_H - \sigma)(q_{HA} + q_{HB}) + (\beta_L - \sigma)(q_{LA} + q_{LB}) = 0$. Thus with trading, the LCFS constraint holds for the market, even though it need not hold for any single firm. Second, the firms' first order conditions for low carbon energy purchases imply that $\lambda_A = \frac{p_x}{\sigma - \beta_x} = \lambda_B$. The first order conditions for energy then imply that $MC_{iA}(q_{iA}) = MC_{iB}(q_{iB})$. Thus trading equates equilibrium marginal production costs for each fuel across firms with different costs. Finally, the shadow value of the LCFS constraint is $\lambda_j = \frac{p_x}{\sigma - \beta_x}$. Since the units of the numerator are, for example, dollars per mmBtu, and the units of the denominator are CO_2 tons per mmBtu, the shadow value of the LCFS constraint is simply the price of carbon, *i.e.,* the units are dollars per CO_2 ton.

Since the shadow value of the constraint is the price of carbon, a question arises as to whether the firms could equivalently trade carbon emissions permits.[29] If p_c is the price of a carbon permit and c_j is firm j's net demand for carbon permits, then firm j's profit maximization with carbon

[28] If $\beta_x > \sigma$, the traded commodity would be "high carbon energy" and would have a negative price.

[29] This might be particularly useful if the program were eventually subsumed into a global carbon trading framework such as Kyoto.

trading would be:

$$\max_{q_{Hj},q_{Lj},c_j} \; p_H q_{Hj} + p_L q_{Lj} - C_{Hj}(q_{Hj}) - C_{Lj}(q_{Lj}) - p_c c_j + \lambda_j[\sigma(q_{Hj}+q_{Lj}) - \beta_H q_{Hj} - \beta_L q_{Lj} + c_j]. \quad (8)$$

As above, this maximization includes purchases of carbon permits, and the LCFS constraint subtracts permitted emissions, c_j, from the numerator. It is easy to show that with trading the LCFS constraint again holds for the market and marginal production costs are equal across firms. Moreover, $p_c = \lambda_j$, so the shadow value of the constraint is simply the price of a carbon permit.

Since the carbon permits and low carbon energy trading equilibria are both characterized by marginal production costs equal across firms and the LCFS constraint holding for the market, it follows that the two equilibria lead to identical energy production profiles. Moreover, the transfers are identical since $(\sigma - \beta_x)x_j = (\beta_H - \sigma)q_{Hj} + (\beta_L - \sigma)q_{Lj} = c_j$ and $\frac{p_x}{\sigma - \beta_x} = \lambda_j = p_c$. Since trading low carbon energy with $\beta_x = 0$ is equivalent to trading energy, then it follows that the equilibria resulting from trading (*i*) carbon emissions permits, (*ii*) low carbon energy, or (*iii*) energy are equivalent.

Trading is equivalent to minimizing production costs subject to a market LCFS constraint since in equilibrium only the market LCFS constraint is relevant. Thus trading reduces (cannot increase) production costs. Note that cost savings from trading could be essentially zero, if firms are nearly identical. On the other hand, gains from trading could be quite large if there are substantial cost differences or economies of scale. The magnitude of gains from trade is thus an empirical question.

5 Distributional effects of the LCFS

Since the LCFS imposes an implicit tax on the high carbon fuel and an implicit subsidy on the low carbon fuel, the distributional analysis is similar to tax incidence analysis. However, unlike with a tax imposed by the government, the LCFS tax/subsidy transfers occur within firms. To analyze the surplus to producers of high carbon fuel separately from the surplus to low carbon fuel, we utilize the carbon permit trading framework developed above.[30]

First, consider the changes in consumer surplus from energy consumption under an LCFS. Figure 9 illustrates the supply and demand curves for the low and high carbon fuels. Since the

[30] Even within a large energy firm, low carbon and high carbon fuel production would likely be in separate accounting centers.

LCFS subsidizes the low carbon fuel, the quantity increases and its price drops. Thus, consumer surplus from the low carbon fuel increases by Area(D+E) with an LCFS. Since the LCFS taxes the high carbon fuel, the consumer surplus from the high carbon fuel decreases by Area(W+X).

Consumer surplus, which changes by Area(D+E−W−X), can either increase or decrease with an LCFS. Note that if the demand for the high carbon fuel is perfectly elastic, then Area(W+X)=0, and consumers do not bear any of the burden from the LCFS. Conversely, if supply of the low carbon fuel is perfectly inelastic, then Area(D+E)=0, and consumers are worse off under the LCFS.

Now consider changes in producer surplus. The LCFS tax decreases production of the high carbon fuel and increases its price. Thus producer surplus from the high carbon fuel would increase by Area(W−Z).[31] However, this firm (division) would not be in compliance with the LCFS and would need to purchase $(\beta_H - \sigma)q_H$ carbon permits at an equilibrium price of $p_c = \lambda$ to come into compliance. Since this expenditure on permits is equal to Area(W+Y), producers of the high carbon fuel are worse off by Area(Y+Z) under the LCFS. Note that producers of the high carbon fuel cannot be better off under the LCFS.

For the low carbon fuel, the implicit LCFS subsidy increases its production and decreases its price. Thus producer surplus from the low carbon fuel would decrease by Area(C+D+E). But this firm (division) would exceed the standard and could still sell $(\sigma - \beta_L)q_L$ carbon permits at a price of $p_c = \lambda$ and remain in compliance. Since the revenue from permit sales is Area(A+B+C+D+E), producer surplus from the low carbon fuel increases by Area(A+B) under the LCFS, and producers of the low carbon fuel cannot be worse off under the LCFS.[32]

Total producer surplus, which changes by Area(A+B−Y−Z), can either increase or decrease with an LCFS. For example, if the supply of the low carbon fuel is perfectly inelastic, Area(A+B) is zero, and producers are worse off. Conversely, if supply of the high carbon fuel is perfectly elastic, then Area(Y+Z)=0, so producers are better off with the LCFS. Note that in this case, the burden of the LCFS is borne entirely by the consumers of the high carbon fuel.

Combined consumer plus producer surplus decreases with the LCFS by Area(C+X+Z), *i.e.,* the usual deadweight loss. Whether this loss in surplus from production and consumption is efficient depends on the environmental costs. Figure 10 illustrates the marginal benefit and private

[31] This is the increase in profit that a monopolist would attain by restricting output by an equal amount.

[32] Since revenues and expenditures on carbon permits are equal, Area(W+Y)=Area(A+B+C+D+E).

marginal cost of each fuel along with its social marginal cost and the LCFS tax or subsidy.[33] With the LCFS, production of the high carbon fuel decreases, and the deadweight loss decreases by Area(U). However, production of the low carbon fuel increases, and deadweight loss from the low carbon fuel increases by Area(F+G). Thus, the efficiency benefit of the LCFS is given by Area(U−F−G). The LCFS can either increase or decrease efficiency. If demand for the high carbon fuel is perfectly inelastic, then Area(U)=0, and any LCFS decreases efficiency. This illustrates the second part of Proposition 3. Conversely, if demand for the low carbon fuel is perfectly inelastic, then Area(F+G)=0, and any LCFS increases efficiency.

6 Alternative baselines

The energy-based LCFS limits carbon emissions per unit of current energy production, *i.e.,* limits carbon emissions as a fixed factor of the energy baseline. However, an alternative low carbon fuel standard could use some other baseline. This section analyzes LCFSs using fuel economy, historical energy production, a rolling average of energy production, and fixed proportions of total energy production as baselines.

6.1 Fuel-economy LCFS

One alternative definition of a low carbon fuel standard, the fuel-economy LCFS, is based on carbon per transportation mile. While the energy-based LCFS treats each mmBtu of energy the same, the fuel-economy LCFS recognizes that the energy in some fuels can be converted more easily into miles driven; for example, hydrogen fuel cell or battery electric vehicles can achieve higher miles per mmBtu than conventional gasoline vehicles.

To analyze a fuel-economy LCFS, let γ_i be the mileage of fuel i expressed as, for example, miles per mmBtu. The fuel-economy standard, $\tilde{\sigma}$, is the ratio of carbon to miles driven, and the constraint becomes

$$\frac{\beta_H q_H + \beta_L q_L}{\gamma_H q_H + \gamma_L q_L} \leq \tilde{\sigma},$$

which is equivalent to $q_L \geq \frac{\beta_H - \gamma_H \tilde{\sigma}}{\gamma_H \tilde{\sigma} - \beta_L} q_H$. Let $\frac{\beta_i}{\gamma_i}$ be the *fuel-economy adjusted emissions rate* for fuel i—measured, for example, in CO_2 tons per mile. As with the energy-based LCFS, the fuel-

[33] The social marginal cost simply increments the private marginal cost by the marginal damages, $\tau\beta_i$, which are higher for the high carbon fuel.

economy LCFS is unattainable if $\tilde{\sigma} < \min\{\frac{\beta_H}{\gamma_H}, \frac{\beta_L}{\gamma_L}\}$ and is nonbinding if $\tilde{\sigma} > \max\{\frac{\beta_H}{\gamma_H}, \frac{\beta_L}{\gamma_L}\}$. Thus, a relevant standard must lie between the two fuel-economy-adjusted emissions rates, and the boundary of the constraint is an upward sloping ray through the origin. This constraint set is mathematically very similar to the constraint set for the energy-based LCFS, except that the "low carbon fuel" is now the fuel with the lower fuel-economy adjusted emissions rate. Since $\beta_H > \beta_L$ does not imply that $\frac{\beta_H}{\gamma_H} > \frac{\beta_L}{\gamma_L}$, the equilibrium and the distributional effects of the fuel-economy LCFS may be very different from the energy-based LCFS.

If we write the constraint as $\beta_H q_H + \beta_L q_L \leq \tilde{\sigma}(\gamma_H q_H + \gamma_L q_L)$, the firm's first order conditions can be written

$$p_i = MC_i + \tilde{\lambda}(\beta_i - \tilde{\sigma}\gamma_i) \tag{9}$$

where $\tilde{\lambda}$ is the shadow value of the constraint. Since the standard must lie between the fuel-economy-adjusted emissions rates, the LCFS again taxes one fuel and subsidizes the other fuel. Using the fuel-economy-adjusted emissions rates, the analysis of the fuel-economy LCFS is identical to the energy-based LCFS. In particular, the fuel-economy LCFS cannot attain the efficient fuel production and carbon emissions, and it may or may not reduce carbon emissions.

6.2 Historical-baseline LCFS

A second alternative baseline would be to base each firm's baseline on historic energy production.[34] For example, the firm's baseline could be energy produced in 2003, or the average energy production between 2001 and 2004. If we let $\bar{q}_H$ and $\bar{q}_L$ be the firm's historic production of energy, the LCFS constraint becomes:

$$\frac{\beta_H q_H + \beta_L q_L}{\bar{q}_H + \bar{q}_L} \leq \sigma.$$

Two points are relevant for the analysis. First, any σ is feasible, *i.e.,* the standard is not bounded below by the lower emissions rate. Any standard, no matter how stringent, can be met by simply reducing output. Second, the slope of the boundary of the constraint set is negative. Thus the constraint set looks like the constraint set from a carbon cap and trade program.

Since historic production is exogenous to the firm's production decisions, the firm's FOC is now:

$$p_i = MC_i(q_i) + \lambda\beta_i$$

[34] Pizer (forthcoming) advocates regulating carbon intensity targets where the baseline is GDP. This is similar to the historical baseline LCFS because the denominator is exogenous to any firm, and firms treat the standard similar to a cap on carbon emissions.

where λ is the shadow value of the historical-baseline LCFS constraint. Since $\lambda \geq 0$, production of both the high and low carbon fuels are taxed. In fact, if the standard is chosen such that $\lambda = \tau$, then the historical-baseline LCFS can attain the efficient fuel production and carbon emissions. Moreover, any standard reduces carbon emissions.

The historical-baseline LCFS is surprisingly like carbon trading. Indeed, the historical-baseline LCFS is equivalent to carbon trading in the sense that any emissions reduction that could be attained by carbon trading can be attained at the same cost by the historical-baseline LCFS and vice versa. This LCFS can even incorporate banking, if firms are allowed to use emissions reductions from an earlier year to meet the current year LCFS. Clearly, the historical-baseline LCFS has many desirable properties.

6.3 Rolling-average LCFS

Although the historical-baseline LCFS is desirable, it is highly dependent on the baseline chosen. This is likely to make agreement on a baseline year or years very difficult, since the baseline years essentially set allowable carbon emissions for the life of the program. On the other hand, if firms anticipate the baseline years, they may have an incentive to overproduce during these years. A final difficulty with the historical-baseline LCFS is that over time allowable emissions may be very different than actual emissions. With liquid trading, this does not reduce efficiency, but it may represent a large windfall profit for a firm which had planned to cease fuel production regardless of the LCFS.

If firms are allowed to build their own baseline over a period of years, these difficulties can be mitigated. We call such an LCFS the *rolling-average LCFS*. For concreteness, we analyze a baseline which is the average energy production of the preceding five years. The analysis is easily extended to analyze a longer baseline period or a baseline period which ends at some other time.

Let q_{it} be production of fuel i at time t. If the baseline for the LCFS is averaged over the last 5 years, the LCFS constraint is:

$$\frac{\beta_H q_{Ht} + \beta_L q_{Lt}}{0.2(q_{H(t-5)} + ... + q_{H(t-1)}) + 0.2(q_{L(t-5)} + ... + q_{L(t-1)})} \leq \sigma_t.$$

where σ_t is the rolling-average LCFS in year t. For a myopic firm, this constraint set looks identical to the constraint set for the historical-baseline LCFS. In addition, note that any standard is feasible, since even a very stringent standard can be met by simply reducing current production.

A forward looking firm has an incentive to increase current production in order to make its LCFS constraints in the future less strict. Analysis of this incentive requires extending the model to multiple time periods. If the discount factor is δ, the forward looking firm's FOC for optimal production at time 0 is:

$$p_{i0} = MC_i(q_{i0}) + \lambda_0\beta_i - 0.2(\delta\lambda_1\sigma_1 + ... + \delta^5\lambda_5\sigma_5).$$

where λ_t is the shadow value of the LCFS constraint in year t.[35] Note that the marginal benefit of increasing current production has two components. First is the current price, and second is the effect on all the future constraints. Since λ_t is the shadow value of the constraint in year t, the future benefit in year t of increasing current production by one unit is $0.2\lambda_t\sigma_t$. Averaging this future benefit across five years and discounting gives $0.2(\delta\lambda_1\sigma_1 + ... + \delta^5\lambda_5\sigma_5)$.

In the stationary solution, where $\sigma_t = \sigma$ and hence $\lambda_t = \lambda$, the FOC becomes:

$$p_{i0} = MC_i(q_{i0}) + \lambda[\beta_i - 0.2\sigma(\delta + ... + \delta^5)].$$

First, note that if $\delta = 1$, the first order condition is $p_{i0} = MC_i(q_{i0}) + \lambda(\beta_i - \sigma)$ which is identical to the FOC for the energy-baseline LCFS. In this case, the standard cannot attain the first best and may or may not decrease carbon emissions. At the other extreme, with $\delta = 0$, the FOC is identical to the FOC for the historical-baseline LCFS. In this case, the standard can attain the first best, and any standard decreases carbon emissions.

With $\delta \in (0, 1)$, the standard cannot attain the first best.[36] The standard taxes production of the high carbon fuel, and may either tax or subsidize production of the low carbon fuel.[37] If the standard subsidizes production of the low carbon fuel, carbon emissions may or may not increase. Note that the incentives with this standard are better than the incentives with the energy-based LCFS since $\lambda[\beta_i - 0.2\sigma(\delta + ... + \delta^5)] > \lambda(\beta_i - \sigma)$, *i.e.,* the rolling-average LCFS tax is higher and the subsidy is smaller than under the energy-based LCFS.

Although the rolling-average LCFS does not have all the desirable efficiency properties of the historical-baseline LCFS, it is potentially more feasible politically since it can lessen disagreement over the baseline period and will accurately reflect current production. The efficiency of the rolling-average LCFS can be improved by lengthening the averaging window or shifting the averaging

[35] As above, both sides of the constraint equation have been multiplied by the denominator of the LHS.

[36] The proof of Proposition 1 holds for any k where the LCFS tax/subsidy is $\lambda(\beta_i - k)$.

[37] This LCFS taxes production of the low carbon fuel iff $\beta_L > 0.2\sigma(\delta + ... + \delta^5)$.

window further into the past, since these both increase the LCFS tax and decrease the LCFS subsidy.

6.4 Fixed-proportion LCFS

One advantage of the energy-based LCFS is that it allows for higher carbon emissions in a year in which demand is unexpectedly high. Although the historical-baseline and rolling-average LCFSs may have better static efficiency properties, they do not have this flexibility to allow additional carbon emissions in a year with high demand.[38] The fixed-proportion LCFS uses a firm's incentive to free ride to reduce the incentive to overproduce the low carbon fuel while still allowing carbon emissions to respond to current demand conditions.

The fixed-proportion LCFS has a baseline which is a fixed proportion of current production by all other firms.[39] Suppose firm j would hypothetically produce the fraction α_{jt} of total energy production. If the firm is assumed to produce this proportion, then this proportion can be used to define the fixed-proportion LCFS for year t by the constraint:

$$\frac{\beta_H q_{Ht} + \beta_L q_{Lt}}{\frac{\alpha_{jt}}{1-\alpha_{jt}}(Q_{\sim 1t} + Q_{\sim 2t})} \leq \sigma_t.$$

where $Q_{\sim it}$ is production of fuel i by all other firms in year t and α_{jt} is the fixed-proportion. Note that $\frac{\alpha_{jt}}{1-\alpha_{jt}}(Q_{\sim 1t} + Q_{\sim 2t}) = q_{Ht} + q_{Lt}$, so the denominator of the constraint would be equal to the denominator for the energy-based LCFS if production were equal to the hypothetical production.

To analyze the firm's incentives, we again turn to a dynamic model to capture the effects of current production on future constraints. The firm's FOC in year t is now:

$$p_{it} = MC_i(q_{it}) + \lambda_t \beta_i - \delta \lambda_{t+1} \sigma_{t+1} [Q_{\sim 1(t+1)} + Q_{\sim 2(t+1)}] \frac{d}{dq_{it}} \left(\frac{\alpha_{j(t+1)}}{1 - \alpha_{j(t+1)}} \right)$$

The marginal benefit of increasing production in year t again has two component: the current price and the relaxing of the next year's LCFS constraint. First, note that if the proportions are fixed, based on some historic baseline period, then $\frac{d}{dq_{it}} \left(\frac{\alpha_{jt}}{1-\alpha_{jt}} \right) = 0$. In this case, the first order condition becomes $p_{it} = MC_i(q_{it}) + \lambda_t \beta_i$, which is the FOC for the historical-baseline LCFS. Since production

[38] Permits, which are fully tradable intertemporally, can smooth out shocks to demand. However, most permits are bankable but not "borrowable."

[39] This is similar in spirit to a Vickery auction, which links a player's payoffs to the bids of other players and eliminates the incentive to manipulate his/her own bid.

from both fuels is taxed, this LCFS can attain the first best and decreases carbon emissions. Note that in contrast to the historical-baseline LCFS, the fixed-proportion LCFS does allow for higher carbon emissions in a year with high demand.

If the proportion is allowed to vary during the program, then increasing current production does change the future standard. If the allowed proportion is simply the fraction of total production in the prior year, then $\frac{d}{dq_{it}}\left(\frac{\alpha_{j(t+1)}}{1-\alpha_{j(t+1)}}\right) = \frac{1}{Q_{\sim 1t}+Q_{\sim 2t}}$. The firm's FOC is then:

$$p_{it} = MC_i(q_{it}) + \lambda_t\beta_i - \delta\lambda_{t+1}\sigma_{t+1}\frac{Q_{\sim 1(t+1)} + Q_{\sim 2(t+1)}}{Q_{\sim 1t} + Q_{\sim 2t}}.$$

which in the stationary solution is simply $p_{it} = MC_i(q_{it}) + \lambda(\beta_i - \delta\sigma)$. This FOC is equivalent to the 1-year rolling-average LCFS. As with the rolling-average LCFS, this LCFS cannot attain the second best and may or may not decrease carbon emissions. Similarly, the incentives are better with a longer average and more distant window. However, unlike the rolling-average LCFS, the fixed-proportion LCFS does allow for current carbon emissions to increase in years with higher demand.

7 The incentive to innovate

Reducing greenhouse gas emissions to recommended levels at a reasonable cost will require technological innovation. Thus, the incentive to innovate under each policy is a crucial component across which the policies should be compared. In this section, we analyze the incentive to reduce carbon emissions rates and to increase fuel economy (mileage) under the various proposals. This incentive, *i.e.,* the marginal benefit of innovation, could then be compared with the marginal cost of innovation to determine an optimal level.

7.1 Carbon emissions rates

The unregulated equilibrium does not depend on β_i. Thus there is no incentive to reduce carbon emissions in the absence of regulation. On the other hand, the efficient incentive to reduce carbon emissions can be found from the Lagrangian for the optimization in [1]. The efficient incentive, *i.e.,* the marginal benefit of decreasing β_i, is $-dL/d\beta_i = -\partial L/\partial\beta_i = \tau q_i^*$ by the envelope theorem.[40]

[40]The intuition is that reducing the emissions rate by one ton per mmBtu reduces damages by τ for each mmBtu and q_i^* mmBtu's are produced.

Thus the emissions rate should be reduced further as long as the marginal cost of reducing β_i is less than τq_i^* and emissions rates are too high in the unregulated equilibrium.

To analyze the firm's incentive to reduce carbon emissions, we consider the most general version of the producer's optimization problem in [8]. Again, by the envelope theorem, the incentive to reduce the carbon emissions rate for fuel i for the various low carbon fuel standards is λq_i.[41] This incentive can either be correct, too large, or too small. For the historical-baseline LCFS, the first best can be attained. In this case, the incentive is correct since $\lambda = \tau$. For the energy-based LCFS, the shadow value of the constraint is zero when the constraint is σ^0. Since the shadow value is continuous in σ, for a small constraint the incentives to reduce each emissions rate can be too small, *i.e.,* $\lambda^e q_H^e < \tau q_H^*$ and $\lambda^e q_L^e < \tau q_L^*$.[42] On the other hand, if the constraint is set such that $\lambda^e(\beta_H - \sigma) = \tau\beta_H$, then $\lambda^e > \tau$, $q_H^e = q_H^*$, and $q_L^e > q_L^*$. In this case, the incentives to decrease the carbon emissions rates are too great for both fuels.

With the other LCFS variants, the incentives generally can be either too large or too small. Thus analysis of the incentives to reduces carbon emissions rates is mainly an empirical question.

7.2 Fuel economy/mileage

As with the incentive to improve emissions rates, the incentive to improve mileage can be found from the various Lagrangians. First note that fuel economy affects the consumer surplus from energy usage. To make this explicit, assume that consumers only care about miles driven so $U = U(\gamma_H q_H + \gamma_L q_L)$.[43] Now the benefit of increased mileage from fuel i, $dL/d\gamma_i$, is given by $U'(\cdot)q_i$.

The efficient incentive is $U'(.)q_i^*$, *i.e.,* the marginal utility of an additional mile per mmBtu. The incentive under the energy-based LCFS is $U'(.)q_i^e$. Note that this incentive could be too high or two low depending on fuel production. With the fuel-economy LCFS, the incentive is $U'(.)q_i^e + \lambda\sigma q_i^e$. Note that this has an additional incentive for fuel economy, namely the benefit of relaxing the firm's LCFS constraint. Interestingly, this benefit would be hard to decentralize, since

[41] The marginal change in producer surplus for a change in β_i is $q_H * dp_H/d\beta_i + q_L * dp_L/d\beta_i - c * dp_c/d\beta_i - \lambda q_i$. The price taking assumption implies that the firm's incentive is simply λq_i.

[42] This would require a constraint that is lax enough such that $\lambda < \tau \min\{\frac{q_H^*}{q_H^0}, \frac{q_L^*}{q_L^0+\epsilon}\}$.

[43] In other words, the consumer likes a Prius because she can drive further, but doesn't get any additional utility from the higher mileage by itself, *i.e.,* there is no "warm glow."

it is a positive externality. In other words, the firms get an external benefit from the customer's fuel economy purchase decision.

8 Simulations

To investigate the economic significance of our results, we numerically simulate the model using a range of parameters representative of the U.S. market for gasoline in 2005.[44] The simulation, which is meant to capture relatively short-term adjustments, analyzes two representative firms: a gasoline producer and a low-carbon fuel producer, in this case ethanol.[45] A representative consumer demands fuel energy measured in units of gasoline gallon equivalents (gge) where gasoline and ethanol are assumed to be perfect substitutes.[46] Our analysis focuses on a range of parameters—rather than specific values—to describe the characteristics of the fuels and fuel market.[47] Appendix B discusses the parameters in more detail and describes the numerical solution algorithm.

Demand for transportation energy in gasoline gallon equivalents is a constant elasticity demand curve calibrated to U.S. gasoline consumption in the baseline year 2005. Demand for transportation energy is generally considered inelastic, so we assume demand elasticities range from 0.1 to 0.5, consistent with Espey (1998) and Hughes *et al.* (forthcoming).

Gasoline and ethanol supply are represented as constant elasticity supply curves with 2005 as the baseline year. We assume supply elasticities vary between 1.0 and 4.0 for ethanol and 0.5 and 2.0 for gasoline. These supply elasticities are consistent with Webb (1981) for ethanol and Dahl and Duggan (1996) for gasoline. These wide ranges reflect considerable uncertainty in the literature particularly about ethanol costs.

The CO_2 emissions rate of gasoline, 11.29 $KgCO_2e$ per gasoline gallon equivalent, comes from Wang (2007). We assume a carbon emissions rate for ethanol of 8.42 $KgCO_2e$ per gasoline gallon equivalent. Estimates of carbon emissions from ethanol production vary greatly, see Farrell *et al.*

[44] Following California, we focus on light-duty vehicles. However, an LCFS could easily include other segments of the transportation sector such as diesel fuel used in heavy-duty vehicles.

[45] Discussions with fuel refiners suggest that initial compliance strategies will center around blending more ethanol into the fuel supply.

[46] The assumption of perfect substitutes is correct if vehicles can use any mixture of ethanol and gasoline. Most current vehicles are limited to moderate blends of 10% - 20% ethanol, but "flex-fuel" vehicles can operate on much higher blends.

[47] In future work, we plan to develop more precise estimates of the relevant parameters.

(2006), including estimates higher than the emissions rate for gasoline. For this reason, we also analyze a range of ethanol emissions rates.

The LCFS standard, σ, is normalized by the 2005 carbon intensity of transportation fuel. Binding, attainable standards are thus in the interval [0.75,1), since 0.75 is the assumed normalized emissions rate of ethanol. The standards thus have a natural interpretation: *e.g.*, $\sigma = 0.9$ represents a 10% reduction in the carbon intensity of transportation fuel.

We investigate six scenarios. The first two scenarios vary the elasticities of supply and demand and are intended as upper and lower estimates of the welfare changes of the LCFS. The second two scenarios vary the relative supply elasticities of ethanol and gasoline while holding the demand elasticity at 0.3. These scenarios are intended as upper and lower estimates for CO_2 emissions reductions. The last two scenarios, which hold elasticities at intermediate ranges, vary the normalized ethanol emissions rate between 0.65 and 0.85. These scenarios capture the considerable uncertainty about the carbon emissions rate of ethanol. Specific parameter values for each scenario are reported in the respective tables.

Tables 1 through 6 summarize the results. The first column in each table presents the unregulated equilibrium, $\sigma = 1$. The LCFS standard becomes increasing strict moving from left to right. The equilibrium price and quantity for the unregulated scenario are the 2005 baseline values of \$2.27 per gasoline gallon equivalent and 117 billion gasoline gallon equivalents. For each value of σ, the change in social surplus is calculated as the sum of changes in tax revenue, producer and consumer surplus relative to the unregulated case. Finally, an implicit average cost of CO_2 is calculated as the change in social surplus divided by the change in emissions, relative to the unregulated equilibrium.

To provide context for our estimates, the tables also present simulations using the historical-baseline LCFS to attain the same reductions in CO_2 emissions implied by the LCFS. The resulting average cost of carbon, shadow values λ and energy prices, for the scenarios are presented at the bottom of each table. Because the cost of CO_2 under the historical-baseline LCFS is equivalent to the cost of CO_2 under a cap and trade system, these results enable a direct comparison between the energy-based LCFS and an efficient trading system.

Since the range of outcomes is primarily covered by the scenarios varying the elasticity ranges, we discuss Tables 1 and 2 in detail. Discussion of the remaining scenarios is more brief since these cases mainly support the major outcomes in Tables 1 and 2.

8.1 Elasticity range scenarios

Tables 1 and 2 present simulation results for the energy-based LCFS for relatively less and more elastic supply and demand curves. The less elastic scenario, shown in Table 1, assumes that the two supply elasticities and the demand elasticity take on the smallest values in their assumed ranges. This maximizes the costs of increases in ethanol production, maximizes the lost profit from decreases in gasoline production, and maximizes the consumer surplus loss for a given change in quantity. Since the LCFS requires a change in the quantities produced, as in a quota, the relatively inelastic supply and demands imply a large surplus cost of the LCFS. In the more elastic scenario in Table 2, elasticities take their largest values, and the surplus cost of the LCFS is smaller.

The simulation outcomes are largely as would be expected. For tighter standards: energy prices generally increase; energy production generally decreases; the fuel mix shifts to include more ethanol; CO_2 emissions fall; surplus losses are greater; and the shadow value of the constraint and average carbon cost are higher.

In most cases, energy production falls and energy prices increase with a tighter LCFS. However, Proposition 2 shows that it is possible for energy production to increase, and the 99% intensity standard in Table 2 does show a small increase in energy production (with a decrease in the energy price). This is perhaps the best case for the LCFS since carbon emissions actually fall slightly without affecting energy prices. However, this outcome is not very robust across our parameters and is unlikely to occur.

The shift in fuel mix is quite extreme. For a 90% intensity standard in Tables 1 and 2, the proportion of ethanol in the fuel supply would need to increase from the current 2% to approximately 40%. Since most current vehicles can only accept up to a 20% ethanol mix, our results suggest that attaining a 10% reduction in carbon intensities would require substantial expansion of the number of flex-fuel vehicles.[48]

CO_2 emissions fall in all cases in Tables 1 and 2. This suggests that CO_2 emissions are unlikely to increase with an LCFS despite the theoretical possibility identified in Proposition 2. In fact, we

[48] This suggests that our assumption of perfect substitutability between gas and ethanol may be invalid for the 90% standard. Future work will relax this assumption.

find that emissions reductions are likely to be substantial. The standard reducing carbon intensities by 10% leads to a reduction in CO_2 emissions of 20-25% across Tables 1 and 2.

Surplus decreases substantially for all scenarios. For the less elastic scenario, surplus changes range from -$9.7 billion to -$760 billion per year. Estimates are smaller, though still substantial, for the more elastic scenario and range from -$1.8 billion to -$81 billion per year. To put these numbers in perspective, annual *revenues* in the transportation energy market are only $265 billion in the unregulated case and these surplus losses range from 4% to 50% of implied transportation revenues across these two tables.

These substantial surplus losses are not shared equally. Consumers surplus decreases in every case except when the energy price decreases. The consumer surplus losses are large and account for a substantial proportion (sometimes over 100%) of the entire surplus cost. As described in Section 5, it is important to take into account carbon market transfers when analyzing surplus to gasoline and ethanol producers separately. After accounting for these carbon market transfers (which in many cases exceed the revenue from ethanol production), ethanol producers benefit quite handsomely. Surplus to ethanol producers increases substantially across all the scenarios. On the other hand, gasoline producers are harmed by the LCFS with surplus losses sometimes exceeding the entire surplus loss.

The shadow values of the LCFS constraint are quite large: ranging from $250 to $12,000 across Tables 1 and 2. As explained in Section 4, these shadow values are the price the firms would be willing to pay on the margin for an emissions permit for one ton of CO_2. These shadow values should be interpreted with caution, however, since Proposition 3 shows that these shadow values can optimally exceed CO_2 damages for the second-best energy-based LCFS.

Tol (2005), reviews 103 estimates of the damage cost of CO_2 emissions in 28 published studies.[49] The 90th percentile of these estimates is a damage cost of approximately $165 per ton, though the author argues that damage costs are unlikely to exceed $50 per ton.[50] Even taking the 90th percentile of damage estimates, social welfare increases only for the most lenient standard under

[49] It is not clear to the authors whether the marginal damage costs presented in Tol (2005) are in units of dollars per ton of CO_2 or dollars per ton of carbon. Therefore, we conservatively assume that the referenced values are in units of dollars per ton of CO_2.

[50] In addition, the distribution of damage costs presented in Tol (2005) is strongly right-skewed with mode, median and mean damage costs of $2 per $MTCO_2e$, $14 per $MTCO_2e$ and $93 per $MTCO_2e$, respectively.

our most optimistic assumptions about demand and supply elasticities.[51]

Finally, we compare these results with a historical-baseline LCFS that attains the CO_2 emissions reduction implied by the energy-based LCFS. As explained in Section 6, the historical-baseline LCFS is equivalent to carbon trading and thus attains the emissions reduction at least cost. The average carbon cost under the historical-baseline LCFS is significantly lower than under the energy-based LCFS. The less and more elastic scenario carbon costs range from \$16 to \$868 and \$2 to \$60 per ton. These costs range from 2-38% of the carbon costs from the energy-based LCFS for the same reduction in emissions. These results suggest that the carbon costs associated with an energy-based LCFS would be much larger than the costs associated with a cost-effective policy.

The simulations of the historical-baseline LCFS provide useful context since they show what could be attained under a cost effective policy. Note that the carbon costs under the historical-baseline LCFS may or may not be consistent with increasing welfare. At the 90th percentile of damages, \$165 per ton, reductions in CO_2 emissions of 20% would increase welfare under the more elastic scenario in Table 2. In fact, even higher reductions would be called for since the marginal cost of reductions after a 20% reduction is \$133. However, with these same damages, a 13% reduction in emissions would decrease welfare in the less elastic scenario in Table 1.

The comparison between the two LCFS policies highlights the inefficiencies of the energy-based LCFS. The higher CO_2 costs under the energy-based LCFS indicate a much larger surplus loss for an equivalent quantity of abatement.

8.2 Additional scenarios

Tables 3 and 4 summarize simulation results using more (less) elastic ethanol supply and less (more) elastic gasoline supply while holding the demand elasticity at an intermediate level. These results give guidance as to how CO_2 levels may be affected by an LCFS. For the upper-CO_2 scenario in Table 3, we choose parameter values within our ranges (namely more elastic ethanol supply and less elastic gasoline supply) that lead to small reductions in CO_2. For the lower-CO_2 scenario in Table 4, we choose the parameters which lead to large CO_2 reductions.

[51] There is considerable uncertainty about the true damages from carbon emissions. Factors such as the wide range of ecosystems that may be affected by climate change and the difficulty associated with evaluating both use and non-use values for the environment make this task extremely challenging. For this reason, we simply present the carbon cost, which can be compared with the relevant damages.

These two scenarios largely confirm the main results from the simulations in Tables 1 and 2. Namely, carbon emissions decrease with an energy-based LCFS, but the carbon cost is substantial. In all cases, the carbon costs are much larger than the carbon costs under the historical-baseline LCFS.

The upper CO_2 scenario in Table 3, does show one interesting outcome that does not occur in any other scenario. Under the 99% standard, carbon emissions actually increase by 0.1% even though the carbon intensity decreases by 1%. In this scenario, the supply of ethanol is particularly elastic while the gasoline supply is less elastic. Thus, it is optimal for firms to expand ethanol production relatively more than they decrease gasoline production; energy increases; and CO_2 emissions increase. Since CO_2 emissions increase only for these extremes of the supply elasticities and only for a modest standard, the results suggest that an LCFS is unlikely to increase CO_2 emissions.

Table 4 shows the other extreme where the LCFS if particularly effective in reducing CO_2 emissions. Here a standard reducing the carbon intensity by 10% reduces CO_2 emissions by 45%. Despite these large emissions reductions, the energy-based LCFS is still a costly way of attaining this emissions reduction which could be attained at less than half the cost with the historical-baseline LCFS.

Tables 5 and 6 test the sensitivity of the results to our assumptions about the carbon emissions rate of ethanol. Given the extensive controversy surrounding this emissions rate, we vary the normalized emissions rate between 0.65 in Table 5 and 0.85 in Table 6.

Again these scenarios confirm our main results: CO_2 emissions are unlikely to increase, and carbon costs are much larger than under a historical-baseline LCFS.

Several interesting results arise in these simulations. First, the surplus costs and energy prices are lower under the lower emissions rate. Second, the emissions reductions are higher when ethanol has a *higher* emissions rate. This result follows primarily from the output effect since energy output (and hence CO_2 emissions) is lower when ethanol has a higher emissions rate. Finally, surplus gains to ethanol producers are larger when they have a *higher* emissions rate. This follows again since prices are higher and a higher output of ethanol is required when the ethanol emissions rate is only slightly below the standard. This result suggests a rather perverse incentive: ethanol producers acting together may have an incentive to overstate the emissions rate of ethanol.

9 Conclusion

As states and the federal government seek policies for regulating greenhouse gas emissions, low carbon fuel standards will be part of the regulatory toolkit. Despite the increasing prominence of the standards in policy debates, this is the first work to analyze the economic effects and incentives of the LCFS. We find that an energy-based low carbon fuel standard (*i*) cannot be efficient, (*ii*) can decrease or *increase* carbon emissions, and (*iii*) can increase or *decrease* efficiency. In fact, a regulator's best option may be to choose a nonbinding LCFS even if the LCFS is its only policy option.

By illustrating the LCFS equilibrium, we show that the perverse effects of the LCFS depend on the slopes of the marginal utility and marginal cost curves as well as the magnitudes of the implied LCFS subsidy and tax. We show that the LCFS is more likely to increase carbon emissions if (*i*) supply and/or demand for the high carbon fuel are relatively steep, or (*ii*) the standard is relatively lenient and the unregulated equilibrium has a large proportion of high carbon fuel.

Analyzing the burden of the LCFS, we find that producers or consumers (but not both) can be better off under the LCFS. Producers can be better off with the LCFS if the reduction in production of the high carbon fuel (and subsequent price increase) increases profits enough to offset losses in low-carbon fuel production. Consumers can be better off if the lower prices on the low carbon fuel make up for the higher prices on the high carbon fuel. Incorporating the environmental costs, we find that the LCFS can decrease efficiency if the demand for the high carbon fuel is relatively inelastic.

Trading across firms can reduce compliance costs if firms have different marginal production costs. The equilibria that result from trading (including any transfers) are identical whether firms trade (*i*) carbon, (*ii*) low carbon energy, or (*iii*) energy. As in other Coase theorem results, trading minimizes total costs of production.

Because of the efficiency costs and potentially perverse effects of the energy-based LCFS, we explore other baselines for the LCFS. A fuel-economy LCFS is quite similar to the energy-based LCFS, but may change the low carbon fuel source and thus have quite different distributional effects. A historical-baseline LCFS can be efficient, but would not have flexibility to allow higher carbon in high demand years and would likely lead to disagreement over the baseline year or years.

The rolling-average and fixed-proportion LCFSs can reduce (but not eliminate) these difficulties but also may not be efficient.

We also theoretically analyze the incentives to improve carbon emissions rates and fuel efficiency. We find that the incentives can be either too large or too small depending on the standard. Interestingly, the fuel-economy LCFS introduces a positive externality from higher mileage which may be hard to decentralize.

To illustrate the economic significance of our theoretical results, we numerically simulate the model for a range of parameters representative of short-term adjustments in the U.S. markets for gasoline and ethanol. The functional forms for the simulation are chosen to rely on a minimal number of free parameters. Nonetheless, the main difficulty with our simulations is the lack of credible parameters from the literature. In particular, there is either little evidence or little agreement about the supply elasticities for ethanol and gasoline and about the carbon emissions rate of ethanol. For this reason, we assume broad parameter ranges to approximate the range of possible outcomes from an energy-based LCFS. In future work, we hope to develop more precise estimates of the relevant parameters and functional forms.

Despite the simplicity of our calculations, several results are clear. First, CO_2 emissions are unlikely to increase with adoption of an LCFS in the U.S., despite the theoretical possibility. In fact, we find quite large reductions in CO_2 emissions resulting even from modest regulation of the carbon intensity with an energy-based LCFS.

Despite these significant reductions in CO_2 emissions, an energy-based LCFS is an expensive way to reduce greenhouse gas levels. In fact, we find that the average carbon cost of the emissions reduction from the energy-based LCFS are at least twice as large, and under some circumstances, may be an order of magnitude higher than the average carbon cost from a cost-effective policy which attains the same CO_2 emissions reduction.

These high cost estimates suggest that an energy-based LCFS may not be efficient. In fact for some parameters and some estimates of carbon damages, our results suggest that it would be better to have no LCFS (or a nonbinding LCFS) then to adopt an energy-based LCFS.

Policy-makers concerns often extend beyond efficiency, and the distributional effects of an energy-based LCFS are also quite profound. We find that all of the burden of the energy-based

LCFS is borne by the consumers and by gasoline producers. In fact, after accounting for carbon market transfers, ethanol producers are better off in each scenario we analyze.

Other market failures such as: technology spillovers, learning by doing, an inability of private firms to privately appropriate all of the benefits from developing cleaner alternatives, etc., may suggest subsidizing renewable resources. If regulators lack direct policy instruments to address these other market failures, an energy-based LCFS, which subsidizes low-carbon fuels (primarily renewables), may be a second best policy instrument for addressing multiple policy goals with one instrument. Further analysis of multiple policy goals is beyond the scope of this paper. However, even the historical-baseline LCFS, which taxes all fuels and can be efficient, places a smaller tax on low carbon fuels, and thus implicitly subsidizes low carbon fuels precisely in proportion to their lower carbon emissions. Thus, it is not clear that an energy-based LCFS would be superior to a historical-baseline LCFS even in the presence of multiple policy objectives.

Adoption of any policy requires careful comparison of the costs and benefits of the policy along with the consideration of other policy options and any potentially unintended consequences. This paper lays out a framework for analyzing low carbon fuel standards. Explicit comparisons of an LCFS with other policies, such as a cap and trade program, depend on the details of the LCFS and the cap and trade program. However, given all the potential problems and excessive costs of an energy-based LCFS identified here, it is unlikely that an energy-based LCFS would be the preferred policy unless the range of alternative options were extremely limited.

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Figures and Tables

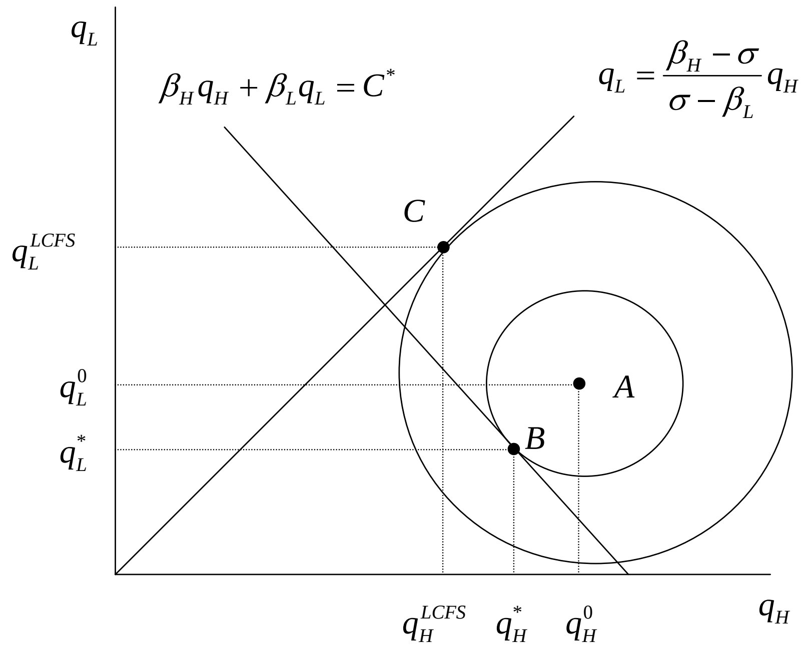

Figure 1: Iso-surplus curves with LCFS constraint and efficient carbon trading constraint

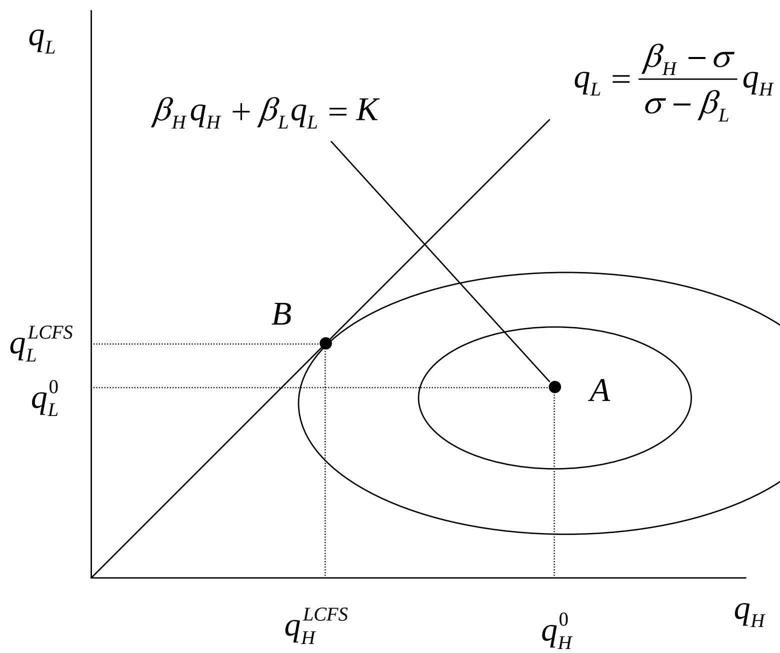

Figure 2: Iso-surplus curves with LCFS constraint and iso-carbon line where the LCFS decreases emissions.

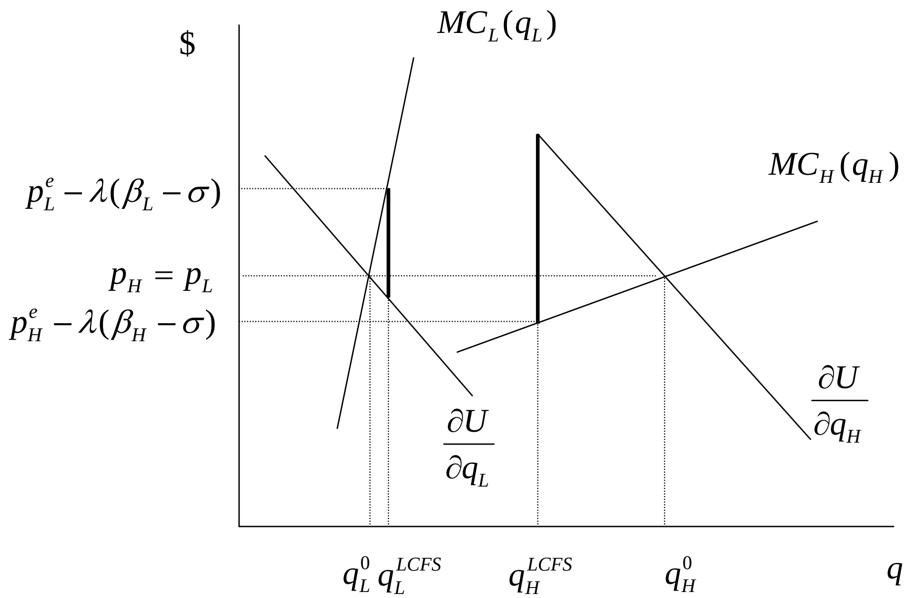

Figure 3: Marginal cost and marginal utility curves and LCFS subsidy/tax wedges where the LCFS decreases emissions. Here the supply of the high carbon fuel is flatter, so production of the high carbon fuel decreases relatively more, and emissions decrease.

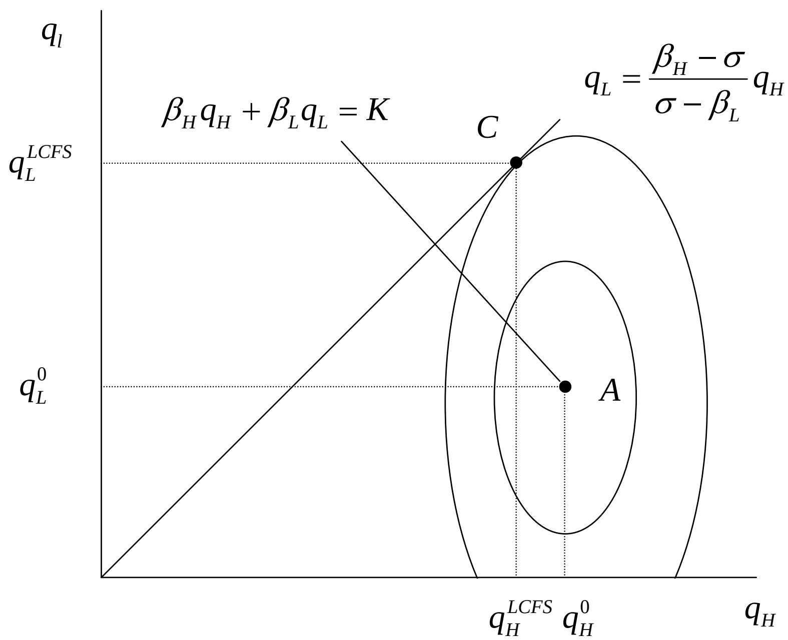

Figure 4: Iso-surplus curves with LCFS constraint and iso-carbon line where the LCFS increases emissions.

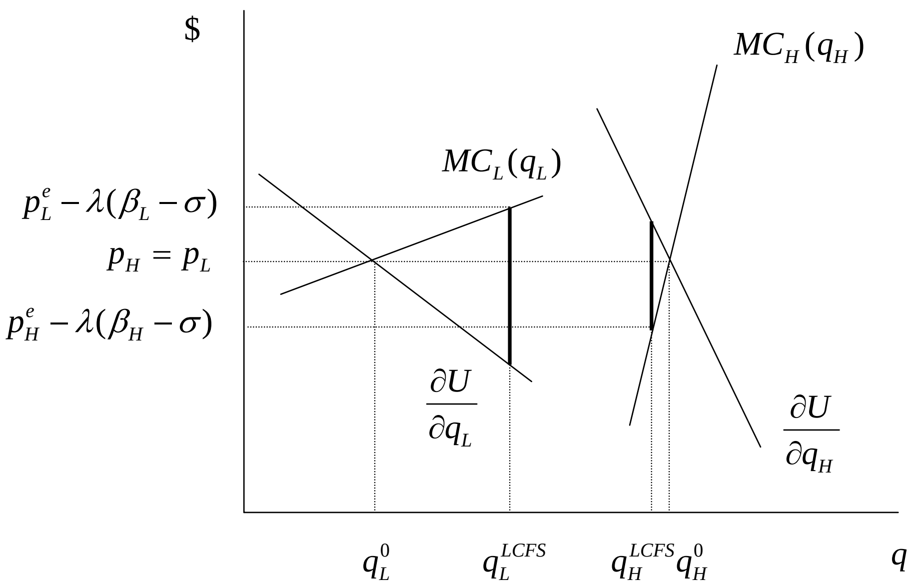

Figure 5: Marginal cost and marginal utility curves and LCFS subsidy/tax wedges where the LCFS increases emissions. Here the supply of the high carbon fuel is steeper, so production of the high carbon fuel decreases relatively less, and emissions increase.

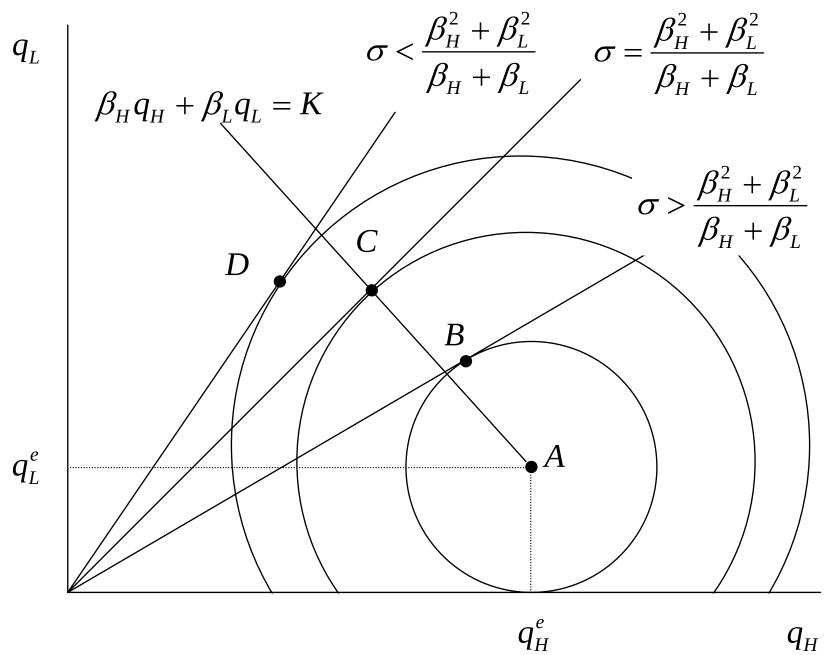

Figure 6: Iso-surplus curves and iso-carbon line with three different LCFS constraints. The first constraint (the most lenient constraint) causes carbon emissions to increase, the second causes emissions to stay the same, and the third causes emissions to decrease.

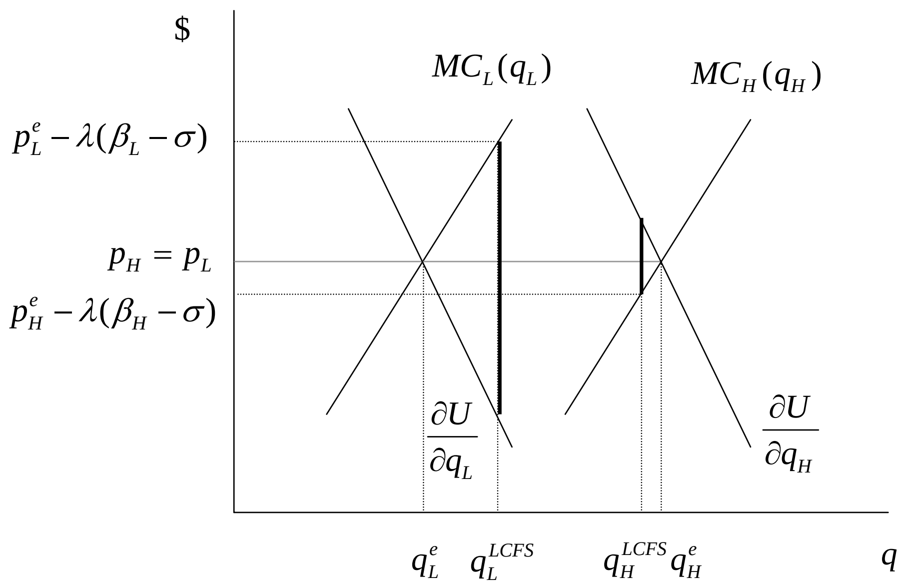

Figure 7: Marginal cost and marginal utility curves and LCFS subsidy/tax wedges for a lenient standard which increases emissions.

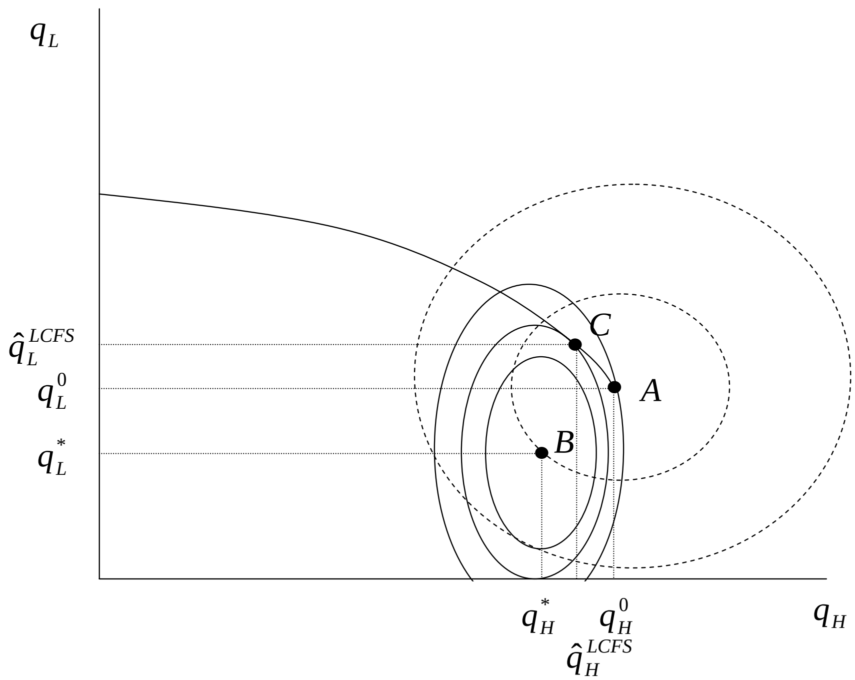

Figure 8: Illustration of the second best LCFS at C with locus of LCFS equilibria and social indifference curves.

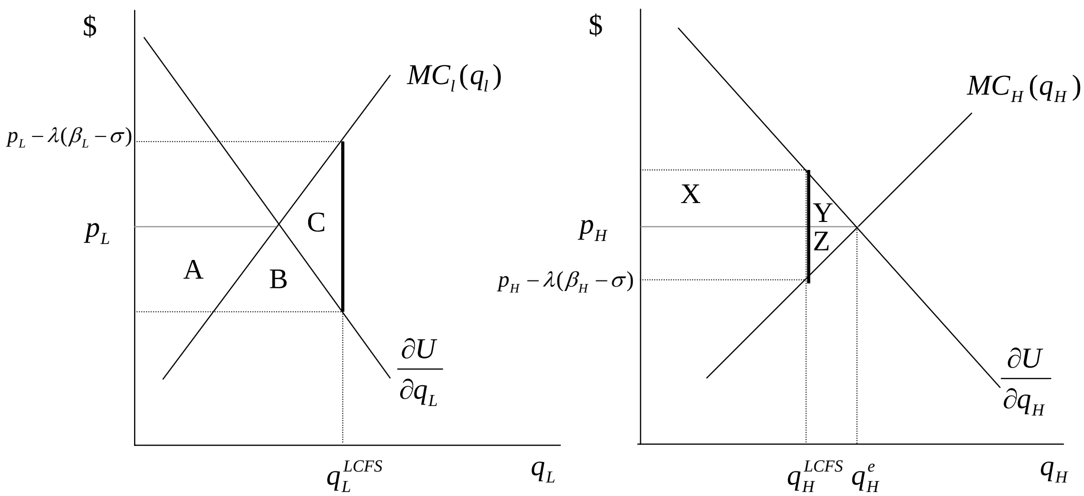

Figure 9: The distributional effects of an LCFS.

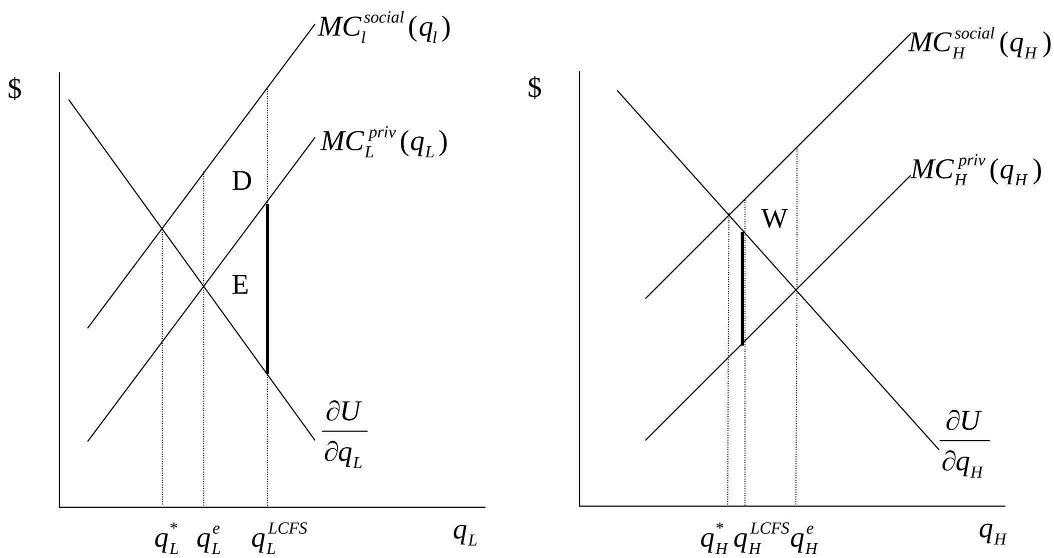

Figure 10: Changes in deadweight loss with an LCFS.

Table 1: Simulation results using least elastic parameter values implying the highest welfare changes

	LCFS Simulation Results: Less Elastic Scenario			
	$\sigma = 1$[i]	$\sigma = 0.99$	$\sigma = 0.95$	$\sigma = 0.90$
Equilibrium Price (\$/gge)[ii]	\$ 2.27	\$ 2.33	\$ 5.43	\$ 14.94
Equilibrium Fuel Quantity (billion gge)	117.00	116.66	107.20	96.89
Gasoline Quantity (billion gge)	114.44	109.54	83.88	56.87
Ethanol Quantity (billion gge)	2.56	7.12	23.32	40.02
Emissions (MMTCO_2e)	1313.96	99%	87%	75%
Δ CS (billion \$)		\$ (7.88)	\$ (352.69)	\$ (1,313.63)
Δ PS Gasoline - Transfers (billion \$)		\$ (19.37)	\$ (92.95)	\$ (129.28)
Δ PS Ethanol + Transfers (billion \$)		\$ 17.74	\$ 229.24	\$ 690.23
Carbon Market Transfer (from Gasoline to Ethanol)		\$ 28.18	\$ 353.63	\$ 817.44
Δ Tax Revenue (billion \$)		\$ (0.13)	\$ (3.77)	\$ (7.74)
Δ Surplus (billion \$)[iii]		\$ (9.65)	\$ (220.18)	\$ (760.41)
Shadow Value λ (\$/MTCO_2e)		\$ 1,468.34	\$ 6,752.45	\$ 12,124.13
Carbon Cost (\$/MTCO_2e)[iv]		\$ 569	\$ 1,293	\$ 2,272
		Historical Baseline LCFS		
Carbon Cost (\$/MTCO_2e)		\$ 16	\$ 245	\$ 868
Shadow Value λ (\$/MTCO_2e)		\$ 32.79	\$ 622.42	\$ 2,864.96
Equilibrium Price (\$/gge)		\$ 2.58	\$ 8.70	\$ 33.43

Notes: Assumed parameter values: Elasticity of demand, 0.1; Gasoline Supply Elasticity, 0.5; Ethanol Supply Elasticity, 1.0; Normalized Ethanol Emission Rate, 0.75.

[i] *σ = 1, represents the unregulated case with the LCFS standard normalized by the current carbon intensity.*

[ii] *The fuel quantity in gasoline gallon equivalents (gge) reflects the adjustment for the lower volumetric energy density of ethanol*

[iii] *Calculated as ($\Delta CS + \Delta PS + \Delta TR$)*

[iv] *Calculated as ($\Delta CS + \Delta PS + \Delta TR$)/($CO_2$ equivalent abatement)*

Table 2: Simulation results using most elastic parameter values implying the smallest welfare changes

	LCFS Simulation Results: More Elastic Scenario			
	$\sigma = 1$[i]	$\sigma = 0.99$	$\sigma = 0.95$	$\sigma = 0.90$
Equilibrium Price ($/gge)[ii]	$ 2.27	$ 2.26	$ 2.43	$ 2.87
Equilibrium Fuel Quantity (billion gge)	117.00	117.05	113.07	104.04
Gasoline Quantity (billion gge)	114.44	109.91	88.47	61.07
Ethanol Quantity (billion gge)	2.56	7.14	24.59	42.98
Emissions ($MMTCO_2e$)	1313.96	99%	92%	80%
Δ CS (billion $)		$ 0.25	$ (18.45)	$ (66.03)
Δ PS Gasoline - Transfers (billion $)		$ (3.33)	$ (17.68)	$ (32.19)
Δ PS Ethanol + Transfers (billion $)		$ 1.26	$ 9.97	$ 22.68
Carbon Market Transfer (from Gasoline to Ethanol)		$ 4.74	$ 38.39	$ 73.88
Δ Tax Revenue (billion $)		$ 0.02	$ (1.51)	$ (4.98)
Δ Surplus (billion $)[iii]		$ (1.81)	$ (27.67)	$ (80.52)
Shadow Value λ ($/$MTCO_2e$)		$ 246.19	$ 694.94	$ 1,020.41
Carbon Cost ($/$MTCO_2e$)[iv]		$ 144	$ 257	$ 307
	Historical Baseline LCFS			
Carbon Cost ($/$MTCO_2e$)		$ 2	$ 22	$ 60
Shadow Value λ ($/$MTCO_2e$)		$ 4.83	$ 45.65	$ 132.63
Equilibrium Price ($/gge)		$ 2.31	$ 2.68	$ 3.52

Notes: Assumed parameter values: Elasticity of demand, 0.5; Gasoline Supply Elasticity, 2.0; Ethanol Supply Elasticity, 4.0; Normalized Ethanol Emission Rate, 0.75.

[i] *$\sigma = 1$, represents the unregulated case with the LCFS standard normalized by the current carbon intensity.*

[ii] *The fuel quantity in gasoline gallon equivalents (gge) reflects the adjustment for the lower volumetric energy density of ethanol*

[iii] *Calculated as ($\Delta CS + \Delta PS + \Delta TR$)*

[iv] *Calculated as ($\Delta CS + \Delta PS + \Delta TR$)/($CO_2$ equivalent abatement)*

Table 3: Simulation results using least elastic gasoline supply and most elastic ethanol supply implying the smallest CO_2 reductions

	LCFS Simulation Results: Upper $CO2_e$ Scenario			
	$\sigma = 1$[i]	$\sigma = 0.99$	$\sigma = 0.95$	$\sigma = 0.90$
Equilibrium Price ($/gge)[ii]	$ 2.27	$ 2.18	$ 2.08	$ 2.40
Equilibrium Fuel Quantity (billion gge)	117.00	118.30	120.11	114.94
Gasoline Quantity (billion gge)	114.44	111.08	93.98	67.46
Ethanol Quantity (billion gge)	2.56	7.22	26.12	47.48
Emissions ($MMTCO_2e$)	1313.96	100.1%	98%	88%
Δ CS (billion $)		$ 9.65	$ 22.46	$ (15.99)
Δ PS Gasoline - Transfers (billion $)		$ (13.47)	$ (69.23)	$ (119.35)
Δ PS Ethanol + Transfers (billion $)		$ 1.28	$ 10.92	$ 26.17
Carbon Market Transfer (from Gasoline to Ethanol)		$ 5.42	$ 51.50	$ 109.02
Δ Tax Revenue (billion $)		$ 0.50	$ 1.19	$ (0.79)
Δ Surplus (billion $)[iii]		$ (2.03)	$ (34.66)	$ (109.97)
Shadow Value λ ($/$MTCO_2e$)		$ 278.73	$ 877.71	$ 1,362.94
Carbon Cost ($/$MTCO_2e$)[iv]		NA	$ 1,065	$ 723
		Historical Baseline LCFS		
Carbon Cost ($/$MTCO_2e$)		NA	$ 13	$ 69
Shadow Value λ ($/$MTCO_2e$)		$ (1.08)	$ 27.26	$ 145.57
Equilibrium Price ($/gge)		$ 2.26	$ 2.47	$ 3.42

Notes: Assumed parameter values: Elasticity of demand, 0.3; Gasoline Supply Elasticity, 0.5; Ethanol Supply Elasticity, 4.0; Normalized Ethanol Emission Rate, 0.75.

[i] *$\sigma = 1$, represents the unregulated case with the LCFS standard normalized by the current carbon intensity.*

[ii] *The fuel quantity in gasoline gallon equivalents (gge) reflects the adjustment for the lower volumetric energy density of ethanol*

[iii] *Calculated as ($\Delta CS + \Delta PS + \Delta TR$)*

[iv] *Calculated as ($\Delta CS + \Delta PS + \Delta TR$)/($CO_2$ equivalent abatement)*

Table 4: Simulation results using most elastic gasoline supply and least elastic ethanol supply implying the largest CO_2 reductions

	LCFS Simulation Results: Lower $CO2_e$ Scenario			
	σ = 1[i]	σ = 0.99	σ = 0.95	σ = 0.90
Equilibrium Price (\$/gge)[ii]	\$ 2.27	\$ 2.44	\$ 5.21	\$ 11.61
Equilibrium Fuel Quantity (billion gge)	117.00	114.45	91.14	71.66
Gasoline Quantity (billion gge)	114.44	107.47	71.32	42.06
Ethanol Quantity (billion gge)	2.56	6.99	19.82	29.60
Emissions (MMTCO_2e)	1313.96	97%	74%	55%
Δ CS (billion \$)		\$ (19.97)	\$ (299.59)	\$ (810.04)
Δ PS Gasoline - Transfers (billion \$)		\$ (5.09)	\$ (27.27)	\$ (39.21)
Δ PS Ethanol + Transfers (billion \$)		\$ 16.95	\$ 164.03	\$ 373.75
Carbon Market Transfer (from Gasoline to Ethanol)		\$ 26.08	\$ 243.92	\$ 430.50
Δ Tax Revenue (billion \$)		\$ (0.98)	\$ (9.95)	\$ (17.44)
Δ Surplus (billion \$)[iii]		\$ (9.10)	\$ (172.78)	\$ (492.94)
Shadow Value λ (\$/MTCO_2e)		\$ 1,385.19	\$ 5,478.39	\$ 8,632.92
Carbon Cost (\$/MTCO_2e)[iv]		\$ 219	\$ 506	\$ 836
		Historical Baseline LCFS		
Carbon Cost (\$/MTCO_2e)		\$ 13	\$ 148	\$ 388
Shadow Value λ (\$/MTCO_2e)		\$ 25.71	\$ 367.96	\$ 1,233.65
Equilibrium Price (\$/gge)		\$ 2.52	\$ 6.09	\$ 15.57

Notes: Assumed parameter values: Elasticity of demand, 0.3; Gasoline Supply Elasticity, 2.0; Ethanol Supply Elasticity, 1.0; Normalized Ethanol Emission Rate, 0.75.

[i] *σ = 1, represents the unregulated case with the LCFS standard normalized by the current carbon intensity.*

[ii] *The fuel quantity in gasoline gallon equivalents (gge) reflects the adjustment for the lower volumetric energy density of ethanol*

[iii] *Calculated as (ΔCS + ΔPS + ΔTR)*

[iv] *Calculated as (ΔCS + ΔPS + ΔTR)/(CO_2 equivalent abatement)*

Table 5: Simulation results using a lower ethanol intensity rating

	LCFS Simulation Results: Lower $CO2_e$ Ethanol			
	$\sigma = 1$[i]	$\sigma = 0.99$	$\sigma = 0.95$	$\sigma = 0.90$
Equilibrium Price (\$/gge)[ii]	\$ 2.27	\$ 2.25	\$ 2.41	\$ 2.94
Equilibrium Fuel Quantity (billion gge)	117.00	117.21	114.89	108.26
Gasoline Quantity (billion gge)	114.44	111.37	96.32	75.64
Ethanol Quantity (billion gge)	2.56	5.84	18.57	32.63
Emissions ($MMTCO_2e$)	1311.04	99%	93%	83%
Δ CS (billion \$)		\$ 1.60	\$ (16.42)	\$ (75.21)
Δ PS Gasoline - Transfers (billion \$)		\$ (4.14)	\$ (14.77)	\$ (14.60)
Δ PS Ethanol + Transfers (billion \$)		\$ 0.79	\$ 2.66	\$ 1.71
Carbon Market Transfer (from Gasoline to Ethanol)		\$ 3.70	\$ 32.13	\$ 65.23
Δ Tax Revenue (billion \$)		\$ 0.08	\$ (0.81)	\$ (3.36)
Δ Surplus (billion \$)[iii]		\$ (1.66)	\$ (29.34)	\$ (91.46)
Shadow Value λ (\$/$MTCO_2e$)		\$ 235.19	\$ 770.25	\$ 1,186.90
Carbon Cost (\$/$MTCO_2e$)[iv]		\$ 155	\$ 333	\$ 417
		Historical Baseline LCFS		
Carbon Cost (\$/$MTCO_2e$)		\$ 4	\$ 31	\$ 88
Shadow Value λ (\$/$MTCO_2e$)		\$ 7.17	\$ 64.86	\$ 196.22
Equilibrium Price (\$/gge)		\$ 2.33	\$ 2.84	\$ 4.09

Notes: Assumed parameter values: Elasticity of demand, 0.3; Gasoline Supply Elasticity, 1.0; Ethanol Supply Elasticity, 2.5; Normalized Ethanol Emission Rate, 0.65.

[i] *$\sigma = 1$, represents the unregulated case with the LCFS standard normalized by the current carbon intensity.*

[ii] *The fuel quantity in gasoline gallon equivalents (gge) reflects the adjustment for the lower volumetric energy density of ethanol*

[iii] *Calculated as ($\Delta CS + \Delta PS + \Delta TR$)*

[iv] *Calculated as ($\Delta CS + \Delta PS + \Delta TR$)/($CO_2$ equivalent abatement)*

Table 6: Simulation results using a higher ethanol intensity rating

	LCFS Simulation Results: Higher $CO2_e$ Ethanol			
	$\sigma = 1$[i]	$\sigma = 0.99$	$\sigma = 0.95$	$\sigma = 0.90$
Equilibrium Price ($/gge)[ii]	$ 2.27	$ 2.27	$ 3.18	$ 5.58
Equilibrium Fuel Quantity (billion gge)	117.00	116.91	105.71	89.27
Gasoline Quantity (billion gge)	114.44	106.72	68.94	29.11
Ethanol Quantity (billion gge)	2.56	10.18	36.78	60.16
Emissions ($MMTCO_2e$)	1316.90	99%	86%	69%
Δ CS (billion $)		$ (0.69)	$ (101.14)	$ (333.23)
Δ PS Gasoline - Transfers (billion $)		$ (26.01)	$ (190.01)	$ (379.77)
Δ PS Ethanol + Transfers (billion $)		$ 18.94	$ 179.18	$ 405.11
Carbon Market Transfer (from Gasoline to Ethanol)		$ 29.02	$ 249.86	$ 437.07
Δ Tax Revenue (billion $)		$ (0.04)	$ (4.34)	$ (10.67)
Δ Surplus (billion $)[iii]		$ (7.79)	$ (116.32)	$ (318.56)
Shadow Value λ ($/$MTCO_2e$)		$ 1,057.07	$ 3,024.74	$ 4,312.92
Carbon Cost ($/$MTCO_2e$)[iv]		$ 549	$ 624	$ 772
		Historical Baseline LCFS		
Carbon Cost ($/$MTCO_2e$)		$ 5	$ 74	$ 215
Shadow Value λ ($/$MTCO_2e$)		$ 9.56	$ 161.93	$ 561.39
Equilibrium Price ($/gge)		$ 2.35	$ 3.77	$ 7.86

Notes: Assumed parameter values: Elasticity of demand, 0.3; Gasoline Supply Elasticity, 1.0; Ethanol Supply Elasticity, 2.5; Normalized Ethanol Emission Rate, 0.85.

[i] *$\sigma = 1$, represents the unregulated case with the LCFS standard normalized by the current carbon intensity.*

[ii] *The fuel quantity in gasoline gallon equivalents (gge) reflects the adjustment for the lower volumetric energy density of ethanol*

[iii] *Calculated as ($\Delta CS + \Delta PS + \Delta TR$)*

[iv] *Calculated as ($\Delta CS + \Delta PS + \Delta TR)/(CO_2$ equivalent abatement)*

Appendices

A Proofs

A.1 Proof of Proposition 1.

Assume $\beta_L > 0$. Suppose the regulator sets the constraint such that $\lambda^e(\beta_H - \sigma) > \tau\beta_H$. But this implies that $\frac{\partial U}{\partial q_H} = p_H = MC_H(q_H^e) + \lambda^e(\beta_H - \sigma) > MC_H(q_H^e) + \tau\beta_H$. Thus efficiency could be increased by increasing q_H since the marginal benefit is greater than the social marginal cost. Similarly, the first best is not attained if $\lambda^e(\beta_H - \sigma) < \tau\beta_H$ since efficiency could be increased by decreasing q_H. Suppose instead the regulator sets the standard such that $\lambda^e(\beta_H - \sigma) = \tau\beta_H$.[52] In this case, q_H is set optimally conditional on q_L. However,

$$\frac{\partial U}{\partial q_L} = p_L = MC_L(q_L^e) + \lambda^e(\beta_L - \sigma) \leq MC_L(q_L^e) < MC_L(q_L^e) + \tau\beta_L \qquad (10)$$

since $\sigma \geq \beta_L > 0$. But now efficiency can be increased be decreasing q_L, so the first best is not attained.

Now assume $\beta_L = 0$. As above, the first best is not attained if $\lambda^e(\beta_H - \sigma) \neq \tau\beta_H$, so let $\lambda^e(\beta_H - \sigma) = \tau\beta_H$. If $\sigma > \beta_L$, first best is not attained since the first inequality in [10] would be strict. So let $\sigma = \beta_L = 0$. Note that this implies that $q_H^e = 0$ and $\lambda^e = \tau$. Producers set $q_H^e = 0$ iff $p_H \leq MC_H(0) + \tau\beta_H$ which is efficient iff $\frac{\partial U(0, q_L^*)}{\partial q_H} \leq MC_H(0) + \tau\beta_H$.

A.2 Proof of Proposition 2.

The proofs of Propositions 2 and 3 rely on examples with linear marginal costs $MC_H(q_H) = Bq_H$ and $MC_L(q_L) = 40 + q_L$ where $B \in \{0.5, 1, 2\}$ and with linear demand $D(p) = 1000 - 20p$ where the fuels are perfect substitutes, *i.e.*, $p_H = p_L = p$. Throughout assume $\beta_H = 1$ and $\beta_L = 0.75$. The first proof of Proposition 2 varies the relative slopes of the marginal cost curves and the second proof varies the stringency of the standard. Let q_i^0 be the output of the unregulated firm and q_i^e be the equilibrium output of the firm subject to the LCFS.

First proof:

[52] This may or may not be feasible.

This proof varies B. Begin with $B = 2$. The unregulated firm produces $q_H^0 = \frac{1040}{43}$, $q_L^0 = \frac{360}{43}$, at $p^0 = \frac{2080}{43}$ with carbon intensity of 0.936, carbon emissions 30.47, and energy of 32.56. Under an LCFS equal to the average intensities of the two fuels ($\sigma = 0.875$), $q_H^e = q_L^e = \frac{75}{4}$, $p^e = \frac{385}{8}$, and $\lambda = 85$. Since emissions are 32.81 and energy is 37.50, this LCFS increases carbon emissions and increases energy.

Now let $B = 0.5$. Here the unregulated firm produces such that $q_H^0 = \frac{2080}{23}$, $q_L^0 = \frac{120}{23}$, and $p^0 = \frac{1040}{23}$ with a carbon intensity of 0.986, carbon emissions of 94.35, and energy of 95.65. Under an LCFS of 0.875, $q_H^e = q_L^e = \frac{600}{17}$, $p^e = \frac{790}{17}$ and $\lambda = \frac{3920}{17}$. Here carbon emissions are 61.76 and energy is 70.59, and this LCFS reduces carbon emissions and reduces energy.

Second proof:

This proof varies σ. Let $B = 1$ so the slopes of the marginal costs are equal. The unregulated firm would produce $q_H^0 = \frac{520}{11}$, $q_L^0 = \frac{80}{11}$, at $p^0 = \frac{520}{11}$ with carbon intensity of 0.967 and carbon emissions 52.73. Under a lax, binding standard of 0.9, the LCFS equilibrium has $q_H^e = \frac{680}{19}$, $q_L^e = \frac{1360}{57}$, $p^e = \frac{2680}{57}$, and $\lambda = \frac{6400}{57}$, with carbon emissions of 53.68. This standard increases carbon emissions. Under a more stringent standard of 0.875, the LCFS equilibrium has $q_H^e = q_L^e = \frac{300}{11}$, $p^e = \frac{520}{11}$, and $\lambda = 160$, with carbon emissions of 47.73. This standard decreases carbon emissions.

Proof of assertions:

A binding LCFS must reduce the carbon intensity of fuel so

$$\frac{\beta_H q_H^e + \beta_L q_L^e}{q_H^e + q_L^e} < \frac{\beta_H q_H^0 + \beta_L q_L^0}{q_H^0 + q_L^0}.$$

If $\beta_H q_H^e + \beta_L q_L^e > \beta_H q_H^0 + \beta_L q_L^0$, it is easy to show that $q_H^e + q_L^e > q_H^0 + q_L^0$. Similarly, it is easy to show that $q_H^e + q_L^e < q_H^0 + q_L^0$ implies that $\beta_H q_H^e + \beta_L q_L^e < \beta_H q_H^0 + \beta_L q_L^0$.

A.3 Comparative statics of LCFS equilibrium

We analyze how the LCFS equilibrium changes with the standard. First, the total derivative of the constraint is,

$$\beta_H \frac{dq_H^e}{d\sigma} + \beta_L \frac{dq_L^e}{d\sigma} = q_H^e + q_L^e + \sigma\left(\frac{dq_H^e}{d\sigma} + \frac{dq_L^e}{d\sigma}\right) \tag{11}$$

which can be written,

$$(\beta_H - \sigma)\frac{dq_H^e}{d\sigma} + (\beta_L - \sigma)\frac{dq_L^e}{d\sigma} = q_H^e + q_L^e.$$

Since $\beta_H - \sigma \geq 0$ and $\beta_L - \sigma \leq 0$, it is easy to show that $\frac{dq_H^e}{d\sigma} \leq 0$ and $\frac{dq_L^e}{d\sigma} \geq 0$ leads to a contradiction. Other sign combinations cannot be ruled out by theory.

A.4 Proof of Proposition 3.

The proof of the first statement of the proposition follows from the linear example described in the proof of Proposition 2 where $B = 1$. Solving for the LCFS equilibrium with σ as a parameter,

$$q_H = \frac{200(33 - 92\sigma + 64\sigma^2)}{501 - 1120\sigma + 640\sigma^2} \quad \text{and} \quad q_L = \frac{-800(11 - 27\sigma + 16\sigma^2)}{501 - 1120\sigma + 640\sigma^2}$$

are the LCFS equilibrium quantities for an arbitrary $\sigma \in [3/4, 29/30]$. Integrating under the demand and supply curves and with $\tau = 20$, we have the social welfare function

$$W(\sigma) = 50(q_H + q_L) - (q_H + q_L)^2/2 - q_H^2/2 - 40q_L - q_L^2/2 - 20(q_H + .75q_L).$$

W has local maximums at $W(29/30) = 163.64$ and $W(3/4) = -95.24$. Thus social welfare is maximized when the standard is not binding and any binding standard decreases welfare.

The proof of i) follows since [11] can be substituted into [7] to derive

$$\tau \frac{d(\beta_H q_H^e + \beta_L q_L^e)}{d\sigma} = \lambda^e(q_H^e + q_L^e)$$

which implies that $\frac{d(\beta_H q_H^e + \beta_L q_L^e)}{d\sigma} > 0$.

The proof of ii) follows since [11] can be differently substituted into [7] to derive

$$(\lambda^e - \tau)(q_H^e + q_L^e) = \tau\sigma^* \frac{d(q_H^e + q_L^e)}{d\sigma}$$

which implies $\lambda^e > \tau$ iff $\frac{d(q_H^e + q_L^e)}{d\sigma} > 0$.

iii) follows trivially since $\lambda^e(\beta_L - \sigma^*) \leq 0 < \tau\beta_L$ if $\beta_L > 0$.

iv) follows from [6] since the right-hand side is positive from iii) and the assumption.

A.5 Details of trading equilibrium.

First we show that the net demand for low carbon energy is downward sloping. If S_{ij} is firm j's supply function for fuel i, then

$$(\sigma - \beta_x)x_j = (\beta_H - \sigma)q_{Hj} + (\beta_L - \sigma)q_{Lj}$$

$$= (\beta_H - \sigma)S_{Hj}\left(p_H - \frac{p_x}{\sigma - \beta_x}(\beta_H - \sigma)\right) + (\beta_L - \sigma)S_{Lj}\left(p_L - \frac{p_x}{\sigma - \beta_x}(\beta_L - \sigma)\right).$$

The first equation is simply the constraint and the second equation follows by substituting in the supply functions at the LCFS price. The derivative of this last equation w.r.t. p_x is negative which implies that $dx_j/dp_x < 0$.

B Simulation Details

B.1 Parameter Choice Details

Simulation parameters have been selected to approximate the U.S. market for transportation fuel as well as the emissions properties of gasoline and ethanol. The year 2005, is used as a baseline for all parameter values. Because the volumetric energy density of ethanol is lower than that of gasoline, ethanol volumes are converted to gasoline gallon equivalent units.

For convenience, the emissions rates for gasoline and ethanol as well as the LCFS standard are normalized by the 2005 carbon intensity of transportation fuel, which is calculated as the average of each fuel's emissions rate weighted by 2005 U.S. sales of gasoline and ethanol. The emissions rate for gasoline is taken from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET 1.7), Wang (2007). There is a great deal of uncertainty about the carbon intensity of ethanol production, Farrell (2006). While ethanol itself is a homogenous product, different production technologies and raw materials can result in large differences in "upstream" or production process emissions. In this analysis, we assume a normalized emissions rate for ethanol ranging from 0.85 to 0.65, which is comparable to estimates from current emissions models. For example, Unnasch et. al. (2007) predict normalized emissions rates for Midwest corn ethanol that range from approximately 0.51 to 1.24.

The constant elasticity demand curve for gasoline gallon equivalents is calibrated to 2005 U.S. average annual values using data from the U.S. Energy Information Administration (2007). The baseline price is the U.S. average retail price in 2005. Quantity is U.S. annual "Total Gasoline Wholesale/Resale Volume by all R&G" in gallons per year as reported by the U.S. Energy Information Administration (2007). For the four simulation scenarios we assume upper and lower estimates for the price elasticity of gasoline demand of 0.50 and 0.10. This range is consistent with previous studies of gasoline demand, such as Espey (1998) who reports a median long-run price elasticity of 0.43 and Hughes *et al.* (forthcoming) who report a short-run price elasticity of 0.08.

The constant elasticity supply curve for gasoline is calibrated to 2005 U.S. average annual values using data from the U.S. Energy Information Administration (2007) as described above. We assume lower and upper estimates for the elasticity of gasoline supply of 0.50 and 2.00, respectively. This range is consistent with previous studies of gasoline supply for example, Dahl and Duggan (1996). As prices are retail prices, producer revenue is calculated from retail price less the federal gasoline tax and weighted average state gasoline tax. Tax rates are taken from the Federal Highway Administration (2005). The tax on the blended fuel is equivalent to the current gasoline tax. Implicitly, this assumes that the current federal and state subsides for fuel ethanol are excluded.

The constant elasticity supply curve for ethanol is calibrated to 2005 U.S. ethanol production using data from the Renewable Fuels Association (2007). The baseline price per gasoline gallon equivalent is assumed to be equal to the baseline price of gasoline. We assume lower and upper estimates for the elasticity of ethanol supply of 1.0 and 4.0, respectively. This broad range reflects considerable uncertainty, but is consistent with Webb (1981) where the implied elasticity at relevant prices exceeds 3.5.[53]

B.2 Numerical Solution Algorithm

The numerical simulation, which allows considerable flexibility in functional forms, is implemented as follows. For an assumed initial price per gasoline gallon equivalent, P_{gge}, and shadow value, λ, the supply of gasoline and ethanol are calculated from the respective supply curves and the first order conditions in Equation 3. Equation 1 is then used to check for compliance with the LCFS standard. If the carbon intensity is greater than (less than) the standard, the shadow value, λ, is increased (decreased) until the LCFS standard is exactly met. The total supply of gasoline gallon equivalents (gasoline plus ethanol) is then checked against consumer demand at the assumed price P_{gge}. If demand is greater than (less than) supply, the price is increased (decreased). The model iterates on λ and P_{gge} until the LCFS standard is exactly met and the market for gasoline gallon equivalents clears.

[53] Webb estimates a linear supply curve for ethanol using relationships for corn supply and demand for distiller's dried grains. The minimum supply elasticity implied by this analysis is approximately 3.7.