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A Report on the Economics of California's Low Carbon Fuel Standard and Cost Containment Mechanisms

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A Report on the Economics of California's Low Carbon Fuel Standard & Cost Containment Mechanisms

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Prepared for: California Air Resources Board
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Executive Summary

California's Low Carbon Fuel Standard was created by Executive Order S-01-07 in 2007 by former Governor Arnold Schwarzenegger. The program is a key complimentary measure in meeting statewide reductions in greenhouse gas emissions required by California's Assembly Bill 32, the Global Warming Solutions Act of 2006. The program calls for large reductions in the carbon intensity of fuel sold in California over the next decade.

As with similar policies whose success depends on the development of new technologies in order for the policy's goals to be met, there is significant uncertainty as to how compliance may be achieved in coming years. Given the unpredictable nature of new technologies and the scale at which alternative fuels will need to be produced in order to maintain compliance across all obligated parties, there is reasonable concern regarding the potential for high and volatile costs of the program in coming years.

In this report, we study multiple issues related to the costs of the LCFS in the near future, and discuss provisions designed to contain compliance costs at reasonable levels. In addition, we discuss a number of other important issues such as concerns over market power in the state's fuel and credit markets, the role of dynamics and uncertainty on market outcomes, and incentives to innovate and invest in renewable fuels and their potential interactions with cost containment mechanisms.

We find that compliance costs may increase rapidly in the future if there are large differences in marginal costs between traditional fossil fuels and alternative, low carbon intensity fuels; or if there are capacity or technological constraints to deploying alternative fuels, particularly those with low carbon intensity. In the absence of readily available, low CI fuel alternatives, the fuel market will adjust along two dimensions to maintain compliance with the LCFS: (i) increase the use of cheaper fuels below the Standard such as ethanol derived from corn starch and sugarcane; or (ii) increase fuel prices and reduce fuel consumption to a level where the Standard is technologically feasible. Both options will be associated with high LCFS credit prices. Because firms are able to bank credits over time, anticipated high costs in the future may lead to higher costs in the present before any constraints bind on the industry.

The potential for compliance costs to increase rapidly in the near future motivates our recommendation to institute a hard cap on LCFS compliance credits through a mechanism such as an unlimited credit window or noncompliance penalty. Both mechanisms guarantee that compliance costs will never exceed either the credit window price or the non-compliance fee, and provide a clear and transparent alternative compliance strategy. Both proposals have the additional advantage of generating funds which may be used to increase investments in low CI fuel technologies. Importantly, neither mechanism will compromise the greenhouse gas reduction goals set by Assembly Bill 32.

California is a clear leader in enacting greenhouse gas policies in the United States and around the world. Extreme compliance costs in programs such as the LCFS may compromise greenhouse gas policies currently in place, as well as discourage the adoption of similar programs in other jurisdictions. As a result, instituting a hard cap on LCFS credit prices using a transparent containment mechanism as suggested in our report is imperative.

1 Introduction

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

Under the LCFS, obligated parties in California must reduce the weighted average carbon intensity of fuel sold in the state by pre-specified amounts each year. Obligated parties are defined as upstream producers and importers of gasoline and diesel fuel sold in the state.[1] The program is agnostic as to which fuels can be used to meet the Standard. As a result, the industry faces only technological and economic constraints in choosing the optimal fuel mix to comply with the program. For example, provisions are made such that electricity providers for plug-in vehicles as well as hydrogen fuel providers for hydrogen vehicles may generate credits under the LCFS which can be sold to regulated parties.[2]

In many respects, the LCFS is a first-of-its-kind regulation. Due both to the unprecedented nature of the program as well as to the uncertainty regarding the ability of the renewable fuel industry to produce volumes of low CI fuels necessary to meet the required reductions, it is difficult to predict market outcomes and compliance scenarios in the market in coming years. Any forecast of future economic outcomes under the LCFS requires knowledge of the availability of alternative fuels at different market prices, the cost of producing each fuel, long-run trends in alternative fueling infrastructure, consumer preferences for alternative fuel and alternative fuel vehicles, as well as many other unknowns. Several groups have studied potential future compliance scenarios under the LCFS including Boston Consulting Group (2012) and ICF International (2013). Some studies claim to predict future outcomes, however, their results should not be viewed as forecasts, but rather as case studies of potential outcomes because of the uncertainty regarding the development of low CI fuels.[3]

Because of the large degree of uncertainty regarding future compliance paths, there is concern that LCFS credit prices may become both costly and volatile. Volatile prices are a concern in similar compliance credit markets. Europe's Emissions Trading Scheme (ETS) has experienced high volatility in both phases of its program, with prices collapsing on a number of occasions due to the total cap on emissions being set too high relative to baseline industry emissions. In the United States, permit prices under California's Regional Clean Air Incentives Market (RECLAIM) sharply increased in the summer of 2000 from around $5,000/ton

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[1] Final Regulation Order, Section 95484.

[2] The full list of fuels which substitute for gasoline under the program is available at http://www.arb.ca.gov/fuels/lcfs/121409lcfs_lutables.pdf .

[3] As a case in point regarding technological uncertainty and policy outcome forecasts, a preceding and related program to the LCFS is the U.S. Renewable Fuel Standard (RFS2). Under the RFS2, fuels derived from cellulosic biomass were originally mandated to grow to 16 billion gallons by 2022. Thus far, actual cellulosic fuel production in the U.S. is far below mandated volumes. For example, in 2012, the RFS2 mandate originally required 100 million gallons of ethanol derived from cellulosic feedstock to be blended into the U.S. fuel supply. Actual production and fuel sold in the U.S. was essentially zero (Energy Information Agency, 2012). As a result, the compliance obligation for cellulosic biofuel has been reduced drastically and most compliance to date with the advanced biofuel portion of the law has been met through purchasing emergency credits and increasing imports of sugarcane ethanol from Brazil.

NO_x to over \$45,000/ton NO_x. Similar price swings have been seen in the EPA's Acid Rain Program and the Northeast states' Ozone Transport Commission NO_x program (Metcalf, 2009). More recently, the price of Renewable Identification Numbers (RINs) under the Environmental Protection Agency's RFS2 has experience large, volatile price swings since January 2013. The volatility is due mostly to concern over the coming 10% blend wall for ethanol in the U.S. gasoline market as well as uncertainty regarding the level at which the EPA will set the 2014 standard.

Volatility in compliance credit markets can undermine the underlying policy and obfuscate price signals for investors in low CI fuels. Economists have proposed a number of mechanisms aimed at limiting price volatility in compliance credit markets, many of which we consider in this report. The LCFS credit market is unique from other compliance credit markets, particularly cap and trade permit markets, in that the ARB does not directly control the number of credits. As a result, instituting safety valve mechanisms such as those proposed in cap and trade market come with unique design issues.

Instituting a cost containment mechanism may have a number of effects on the incentives the LCFS provides for innovation and investment in low CI technologies. By reducing volatility in the credit markets, incentives for innovation may be enhanced because the riskiness of investments in low CI technologies will be reduced (Jacoby and Ellerman, 2004; Burtraw et al., 2010). In March 2009 Dallas Burtraw, Senior Fellow at Resources for the Future, testified on price volatility in cap and trade markets before the U.S. House Committee on Ways and Means, stating that "...volatility in prices will undermine the incentive for new investment, slow technological change, and raise the long-run cost of climate policy." By establishing clearer price signals through cost-containment provisions, the ARB can reduce volatility in the LCFS credit market. This would facilitate long-run investment decisions by firms. Limiting volatility, however, may also have the adverse effect of reducing expected credit prices by limiting scenarios where credit prices would reach levels which have the highest payoffs to investors (Burtraw et al., 2010; Nemet, 2010). Thus, any cost containment mechanism should also consider complimentary measures to counteract reductions in incentives to invest in low CI fuels.

Overall, we strongly support the establishment of either a credit window where firms can purchase unlimited LCFS credits from the ARB to meet their compliance obligation, or for the ARB to institute a fixed non-compliance penalty on any net deficits incurred by firms in a given compliance year. Both policies place a hard cap on LCFS credit prices. Given emissions from fossil fuels will be covered under California's cap and trade program beginning in 2015, the emission targets established by AB 32 would not be compromised by a cap on LCFS credit prices. In addition, both options generate revenue which may be reinvested in low CI technologies, counteracting reductions in the incentive to innovate and invest.

Before proceeding with our report, a qualifying statement should be made regarding the intent of our analysis. We study qualitative features of the LCFS. In particular, through our modeling efforts we attempt to understand the direction which key economic variables such as fuel prices, LCFS credit prices, emissions, and fuel demand will move in response to the LCFS, the inclusion of alternative cost containment policies, and when taking into consideration other policies which affect the fuel industry in the state.

We refer to qualitative economic analysis in contrast to quantitative economic analysis. The two types of analyses differ in their purpose. Qualitative research of environmental policy seeks to establish an understanding of the effects of the policy on underlying economic variables. In contrast, quantitative research is typically conducted whenever the researcher has greater certainty about the economic system being studied and wishes to make specific recommendations as to the level at which an environmental policy should be set. The purpose of the current report is to understand how various cost containment mechanisms will affect the LCFS in California. Compliance with the LCFS may occur through an innumerable number of mechanisms depending on advancements in low CI technologies in years to come. Currently, there are around 90 fuel pathways representing 14 fuels which can be used to meet compliance under the program, and these fuels represent only those which are current proven technologies. By focusing on qualitative features of the LCFS, we are able to better determine the likely effects changes to the policy would have rather than actual prices or quantities of any of the many fuels which may be used.[4]

Currently, LCFS compliance is predominantly met through blending fuel ethanol into gasoline or, to a limited extent, biodiesel into diesel fuel. In a recent status review of the program, Yeh et al. (2013) find around 78% of credits generated under the program to date have been derived from conventional ethanol, with the second and third highest compliance credits generated by natural gas and biodiesel at 12% and 9%, respectively. In addition, Yeh et al. (2013) find status quo production will allow the industry to maintain compliance with the Standard only through 2013. Absent major technological breakthroughs, biofuels are likely to remain the main compliance pathway in the short term. As a result, we choose to focus on the near term where most compliance will be met through increased use of biofuels.

The report proceeds as follows. In section 2, we discuss the basic economics of the LCFS using a simple model with two inputs which are used to produce fuel. We also illustrate the effect of the LCFS on several market outcomes. In addition, we discuss the role of uncertainty and dynamics in the market, potential issues and implications of market power, interactions of the LCFS with the state's cap and trade program, and the incentives to innovate and invest in low CI fuel technologies provided by the Standard.

Section 3 uses the framework developed in section 2 to discuss a number of cost containment mechanisms proposed by the Air Resources Board (ARB) as well as other potential policies which may contain compliance costs. In addition, we discuss the potential to link the LCFS market to other cap and trade allowance markets, issues regarding the establishment of a price floor for LCFS credits, and the effect of cost containment mechanisms on emissions as well as the interaction of potential market power issues with a cap on LCFS credit prices.

Section 4 presents a numerical model developed to aid in our understanding of the likely effect of the LCFS and cost containment mechanisms. We calibrate the model so that it is similar to California's gasoline market in 2010. We then simulate a number of market outcomes under an LCFS with and without various cost containment mechanisms. In addition, we explore the interaction of the LCFS with the state's cap and trade program. Section 5 discusses directions for future research related to the LCFS compliance credit market, and section 6 concludes, summarizing key findings and key recommendations.

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[4] The sentiment of our modeling technique is not shared by social scientists alone. Indeed, it was Albert Einstein who stated the following in his work "On the Method of Theoretical Physics" published in *The Philosophy of Science*. "It can scarcely be denied that the supreme goal of all theory is to make the irreducible basic elements as simple and as few as possible without having to surrender the adequate representation of a single datum of experience."

2 The Economics of Renewable Fuel Policies

In this section we discuss the economics of the LCFS. The Low Carbon Fuel Standard is a form of an intensity standard. The environmental and energy economics literature has studied a number of features of policies similar to the LCFS. Historically, intensity standards have been used to regulate pollutants produced by industries by regulating the amount of emissions allowed per unit of output. In this section, we draw on insights from the academic literature as well as add our own contributions.

For ease of exposition, we focus on an industry with two inputs to production: a low emission, renewable input and a conventional input associated with higher emissions. We assume the inputs are perfect substitutes so that the quality of the final fuel does not change based on the input mix. For many renewable fuels such as ethanol and biodiesel, the energy content of the fuel is less than that of conventional fossil fuels.[5] We assume the inputs are perfect substitutes after being adjusted for their respective energy contents. Firms comply with the LCFS using many inputs, including credits generated outside traditional liquid fuels.[6] The two input case, however, yields important insights into the mechanisms through which the LCFS affects the market, which is helpful when extending the model to include more inputs and more complex functional forms. Where appropriate, we mention caveats and results from extending the model to incorporate more complicating features. The results from this and all subsequent sections are derived in greater rigor in the Technical Appendix.

2.1 The Economics of Pollution Externalities

Before discussing the economics of the LCFS, consider a competitive market in the absence of any policy intervention. Figure 1 graphs the initial equilibrium of our hypothetical market. In the figure as well as in all subsequent figures in this section, the blue line represents the downward sloping demand for final fuel, the red line represents the supply curve of conventional fuel, the green line represents the supply curve of renewable fuel, and the black line represents the total fuel supply curve.[7] The final fuel supply curve is the horizontal sum of the renewable and conventional fuel supply curves.[8]

The market equilibrium is the point where the total fuel supply curve crosses the total fuel demand curve. The equilibrium fuel price and quantities are shown by the dashed horizontal and vertical lines, respectively. The amount of conventional and renewable fuel supplied on the market is found where the horizontal dashed line intercepts the renewable and conventional marginal cost curves. This represents the quantities of each fuel which is supplied by the respective industries at the market clearing price. As can be seen, in the initial equilibrium the renewable fuel is expensive relative to the conventional fuel and as a result little is used in the final fuel supply. We refer to the scenario as the competitive market outcome.

If all costs of producing each fuel are fully reflected in the firms' marginal cost curves, the competitive market outcome will be socially optimal in the sense that both consumer and producer welfare will be

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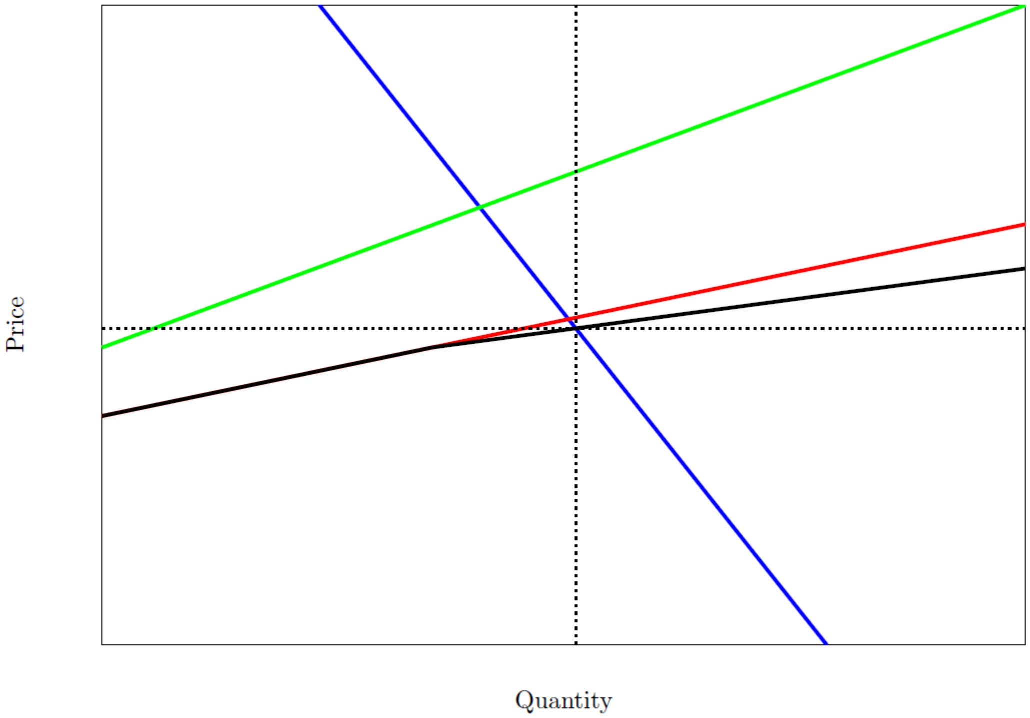
[5] A gallon of ethanol has around 70% of the energy content as a gallon of gasoline regardless of the feedstock from which ethanol is derived. A gallon of neat biomass-based diesel has around 95% of the energy content of conventional diesel fuel.

[6] We refer to conventional liquid fuels as gasoline, diesel and biofuels. The Low Carbon Fuel Standard regulates the carbon intensity of all transportation fuel, which includes electricity, hydrogen, compressed and liquefied natural gasoline, biogas, etc. In general, whenever we model the refining and blending industry, we treat credits generated from sources outside the

Figure 1: Competitive equilibrium with two inputs*



*The red and green lines represent the conventional and renewable private conventional marginal cost curves, respectively. The black line represents the total fuel supply curve which is the horizontal sum of the red and green lines. The blue line represents the final fuel demand curve.

maximized and a regulator cannot make one group better off without making the other worse off. If, however, the production or consumption of the final good creates additional costs which are not reflected in the private costs of producing the good, then sales and consumption in the market generate negative externalities.[9] In the case of transportation fuels, externalities due to greenhouse gas (GHG) emissions exist if fuel consumers and producers do not pay the costs of the environmental damages caused by greenhouse gases fuels emit.[10] If emissions such as GHG emissions are associated with damages which are not reflected in the market price when producers (consumers) make production (consumption) decisions, the competitive equilibrium will not be socially optimal. It is in this sense that economists refer to the initial equilibrium as

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conventional liquid fuel sector as exogenous to liquid fuel prices.

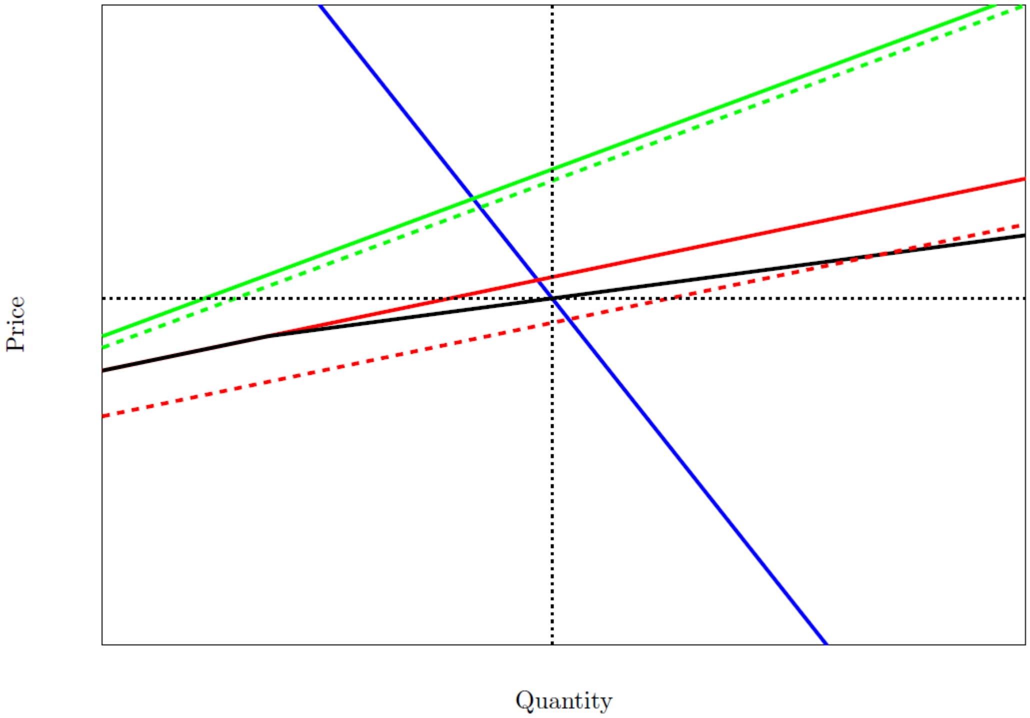
[7] In the report, we refer to the supply curve and marginal cost curve of fuels interchangeably. See Krugam and Wells (2009) chapters 12-13 for a general discussion of market supply curves.

[8] A market supply curve represents the amount of fuel which an industry is willing to supply for a given price. Thus, whenever we have multiple supply curves, the total fuel available on the market is the amount of renewable and conventional fuel which all firms in each respective industry are willing to supply at a given price. Thus, the market supply curve is equal to the horizontal rather than vertical sum of all firm and industry supply curves.

[9] Kolstad (2011) defines externalities as "[existing] when the consumption or production choices of a person or firm enter the utility or production function of another entity without that entity's permission or compensation."

[10] We refer to GHG emissions as the sole unpriced externalities for illustrative purposes. There are certainly other benefits of alternative fuels in reducing externalities related to local air pollutants. For an extensive discussion of externalities related to the transportation sector see Parry and Small (2005).

Figure 2: Potential Social Optimal Outcome*



*The red and green lines represent the conventional and renewable private conventional marginal cost curves, respectively. Solid lines represent social marginal cost curves while dashed lines represent private marginal cost curves. The black line represents the total fuel supply curve which is the horizontal sum of the solid red and green lines. The blue line represents the final fuel demand curve.

inefficient.

Whenever the cost of both inputs includes all costs, private and social, economists refer to the resulting market outcome as socially optimal. The equilibrium where all costs from production are included in the market supply curves is referred to as a first-best equilibrium. Figure 2 graphs an example of a first-best solution. In the figure, the dashed lines represent the private cost curves while the solid lines are the social marginal cost curves. The socially optimal outcome in Figure 2 shifts both the conventional and renewable marginal cost curves upward to account for the externalities from the production of each fuel. This will be true so long as both fuels are associated with greenhouse gas emissions. In our example, we assume conventional fuels are associated with higher damages than renewable fuels. As a result, the conventional fuel supply curve shifts upward more than the renewable fuel supply curve. The socially optimal equilibrium is the point where the adjusted total fuel supply curve equals the total fuel demand curve. We refer to this equilibrium as the socially optimal equilibrium.

Compared to the competitive market outcome, the market clearing fuel price is higher and total fuel demand decreases in the socially optimal equilibrium. In addition, the amount of renewable fuel blended increases in equilibrium. The socially optimal equilibrium can be achieved in a number of ways. The simplest policy is to tax both fuels by their respective marginal social damages. Alternatively, the government can institute a cap and trade program. If the cap on greenhouse gas emissions is set at the socially optimal emission level, the socially optimal outcome will be achieved.[11] In both cases, the policy prescription involves "internalizing the externality" of emissions from both fuels.

2.2 The Economics of the LCFS

California's Low Carbon Fuel Standard (LCFS) is an intensity standard which regulates the emissions per unit of fuel produced in the state. The Standard requires fuel producers to reduce the average carbon intensity of fuel sold in the state by 10% by 2020. The program assigns carbon intensity (CI) values to each fuel which are estimates of "life-cycle" emissions of fuels, and becomes more stringent each year from 2011-2020.[12]

Suppose CI factors are assigned such that the conventional fuel generates net deficits and the renewable fuel generates net credits under the LCFS. For example, suppose the conventional input has carbon intensity factor equal to 100 gCO_2e/MJ, the renewable input has an intensity factor equal to 50 gCO_2e/MJ, and the LCFS requires the average carbon intensity of fuel to be reduced by 10% so that the average intensity must be equal to 90 gCO_2e/MJ. In this example, for every MJ of renewable fuel produced firms will generate 40 gCO_2e of LCFS credits which they can sell on the credit market at the market clearing LCFS credit price. This makes production of renewable fuels more valuable, and shifts the renewable supply curve down. In contrast, conventional fuel producers will generate 10 gCO_2e deficits per MJ of fuel produced which they will need to account for by purchasing LCFS credits from other firms. This will make production per unit of fuel more expensive, shifting up the conventional supply curve.

Figure 3 illustrates the LCFS equilibrium. In order to meet the Standard, 20% of the final fuel supply must come from the renewable fuel and 80% must come from the conventional fuel. LCFS credit prices will adjust to the point where the Standard is just met by the industry. As shown in the technical appendix, the renewable supply curve shifts down by the amount of net credits generated per unit of fuel times the LCFS credit price. The conventional supply curve shifts up by the amount of net deficits generated times the LCFS credit prices.

Figure 3 illustrates the LCFS equilibrium for one combination of supply and demand curves. For each combination of curves, there exists a unique LCFS equilibrium. To examine how the LCFS equilibrium changes at different levels, we calculate the market clearing prices and quantities for many potential demand curves, illustrated in Figure 4. In the figure, the solid green, red and black lines represent the market clearing prices and quantities for the renewable, conventional and total fuel supply curves, respectively, after adjusting for net generation of deficits and credits for different levels of demand. The dashed green and red lines represent the private marginal cost curves of the renewable and conventional supply curves without

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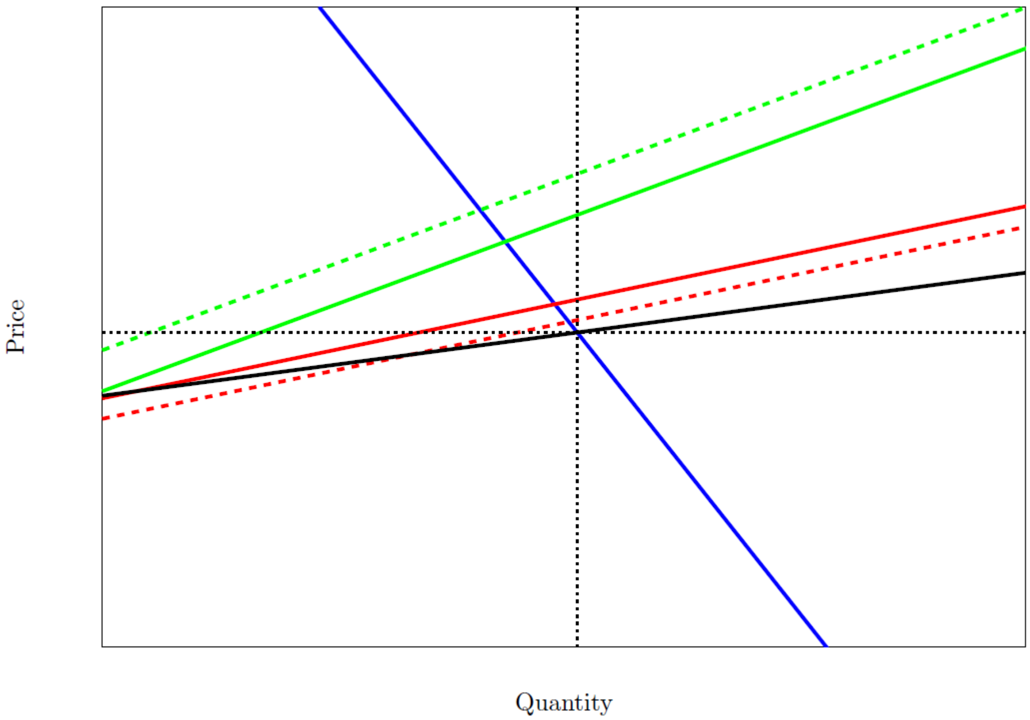
[11] Cap and trade programs and carbon taxes are equivalent whenever there is no uncertainty about market supply and demand curves, there are no transaction costs to trading cap and trade permits, and markets are perfectly competitive. For a comprehensive review of the regulatory history and design issues in cap and trade programs, see Tietenberg (2006).

[12] In the current report, we do not consider how carbon intensity factors are set. As discussed in Lemoine (2013), setting CI factors can be viewed as a strategic variable by regulators. In practice, the CI factors represent best guesses of actual emissions associated with each fuel. If, however, the regulator views the factors as strategic variables, Lemoine shows the 'best' CI standards in terms of maximizing social welfare may differ from the best guess of actual emissions.

Figure 3: LCFS Equilibrium with Two Inputs



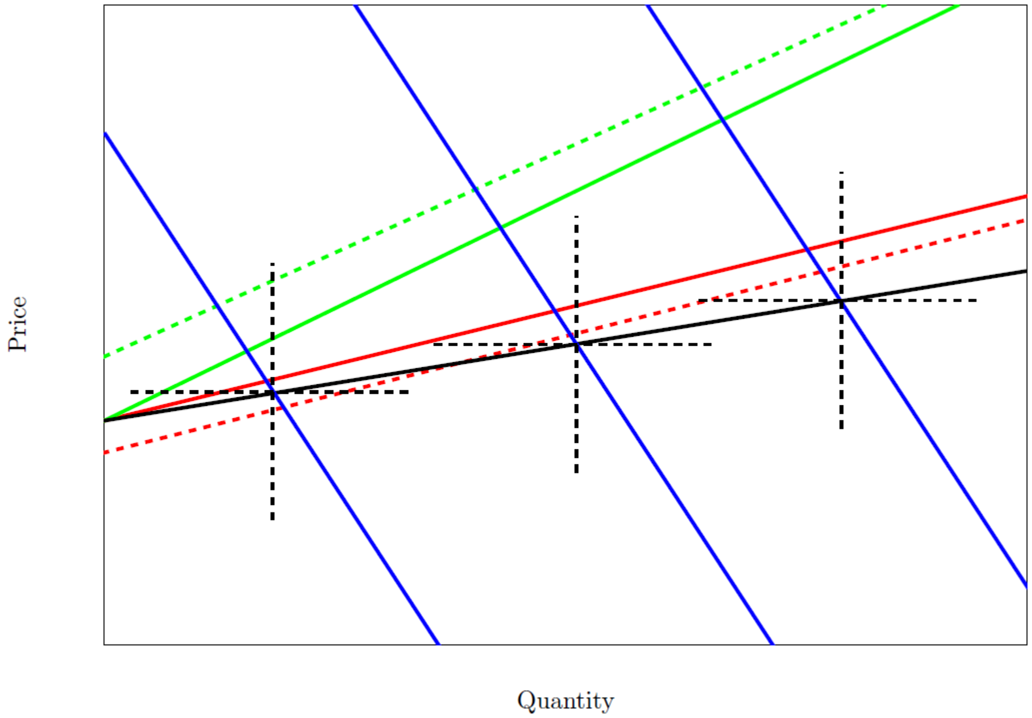
*The dotted red and green lines represent the conventional and renewable private marginal cost curves, respectively. Solid lines represent marginal cost curves after being adjusted for relevant LCFS credit and deficits. The black line represents the total fuel supply curve which is the horizontal sum of the solid red and green lines. The blue line represents the final fuel demand curve.

adjusting for generation of credits or deficits under the LCFS. The blue lines represent three demand curves used to calculate each equilibrium, and the equilibrium quantities and prices for each demand curve are illustrated by the black vertical and horizontal dashed lines. The vertical difference between the solid and dashed green (red) lines is equal to the value of the marginal net credits (deficits) in each equilibrium. Given that the marginal net credits are constant across demand levels, Figure 3 illustrates how LCFS credit prices decrease as demand increases with linear supply and demand curves.

Figure 4 illustrates the complicated nature of the LCFS. As shown in the Technical Appendix, it is difficult in general to determine how the LCFS will affect market clearing prices, quantities, compliance costs, and emissions. The effect of the LCFS on various market outcomes depends crucially on assumed functional forms of the supply and demand curves as well as the assigned CI levels to each fuel. This motivates the need to develop our numerical model in Section 4.

In general, an intensity standard such as the LCFS cannot achieve the first best equilibrium. In order to achieve the socially optimal equilibrium, the government can either institute a cap and trade program covering emissions from both renewable and conventional fuels, or institute a carbon tax on emissions from both fuels. In contrast, the LCFS makes fuels which generate credits (renewable fuels) cheaper and makes fuels which generate deficits (fossil fuels) more expensive. Thus, the LCFS equilibrium will never be able

Figure 4: LCFS Equilibria for Varying Demand Levels



*The solid green, red and black lines represent alternative LCFS market clearing quantities and prices of renewable, conventional and total fuels for varying demand levels, respectively. The dashed green and red lines represent marginal cost curves which are not adjusted for net generation of marginal credits and deficits for each market clearing quantity of renewable and conventional fuel. The dashed blue line represents sample levels of final fuel demand used to calculate each LCFS equilibrium. The LCFS equilibrium for each demand curve occurs where the dashed blue line intercepts the solid black line.

to achieve the first-best outcome.[13] Whenever a policy cannot replicate the first best outcome, economists refer to the policy as second (or third) best.

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[13] The intuition behind the result is discussed more thoroughly in the Technical Appendix as well as in Helfand (1991), Holland et al. (2007), Lapan and Moschini (2012), and Lemoine (2013).

2.3 LCFS Compliance Costs and LCFS Credit Prices

The cost of compliance under the LCFS is directly related to the price and availability of renewable fuels relative to conventional fossil fuels. In the two input case, compliance can only be achieved by increasing the amount of low CI fuel in the fuel supply. As a result, the key driver of compliance costs is the difference between the marginal costs of renewable and conventional fuel. As the difference between the two fuels become greater, compliance costs increase. If the last unit of fuel required to be purchased by regulated parties under the program is more expensive than traditional fossil fuel, the firms will require a high LCFS credit price to have an incentive to purchase the last unit of fuel. The LCFS credit price will adjust to the point where the marginal cost of the renewable fuel plus value of the credits generated by the renewable fuel is equal to the marginal cost of the conventional fuel minus the value of the deficits generated by the conventional fuel.

An extreme compliance scenario would arise if the renewable industry faced a technological or capacity constraint on production or distribution. Technological constraints arise whenever renewable fuels are available to be sold on the market; however, the necessary fueling infrastructure is not available. An example of such a constraint is the current blend wall in ethanol markets. Currently, ethanol is predominantly sold in 10% ethanol blends (E10) and 85% ethanol blends (E85). E10 can be distributed using traditional fueling infrastructure and can be used in all vehicles. E85 fuel, however, requires special fueling infrastructure as well as for vehicle owners to have flex fuel vehicles (FFVs). Without a substantial increase in the number of E85 fueling terminals and FFVs, ethanol is effectively constrained to 10% of the final fuel supply. In contrast, a capacity constraint exists whenever the production of renewable fuel cannot increase above a given level of production at any price. In both cases, the marginal cost curve of the renewable fuel will exhibit "hockey stick" shapes which are common in other energy markets such as electricity markets.[14]

Suppose the fuel industry faces a strict capacity constraint on renewable fuel production. Figure 5 graphs the competitive market equilibrium in this case. In the figure, the renewable fuel supply curve is the same as we previously assumed up to the capacity constraint, after which further production is not possible at any price. The total fuel supply curve is equal to the horizontal sum of the renewable and conventional supply curve. As can be seen, beyond the renewable capacity constraint the total supply curve consists only of the conventional fuel. As in our original example, the competitive market equilibrium involves the final fuel supply being met predominantly by the conventional fuel.

Suppose the government imposes an LCFS on the market. Whenever there are capacity constraints to renewable fuel production and there are no other compliance options, the LCFS can only be met up to a certain volume of final fuel sold in the state. In order to maintain compliance with the LCFS, however, the industry must reduce the total volume of fuel in the market to the point where compliance is achieved at the renewable capacity constraint.

The LCFS equilibrium with a binding renewable fuel capacity constraint is illustrated in Figure 6. As can be seen, whenever the renewable capacity is reached, the policy creates a capacity constraint on the overall fuel supply because compliance beyond a given level of fuel demand is impossible. Thus, once the constraint is reached the only means to maintain further compliance is to increase fuel prices and maintain

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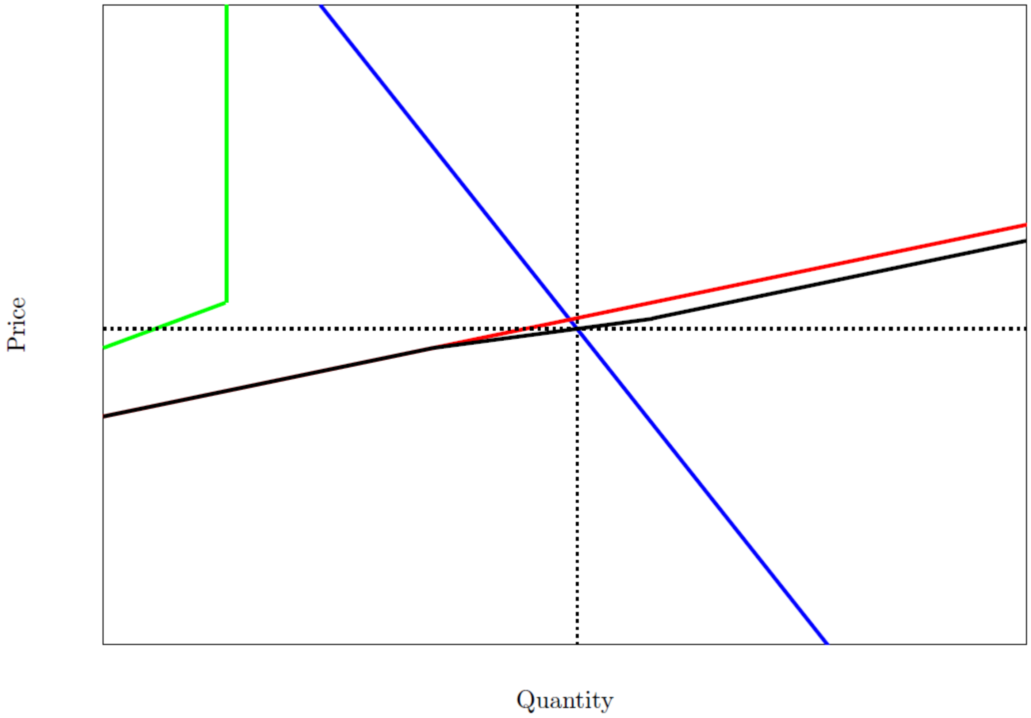
[14] For an example of an economic analysis studying an industry facing similar supply curves, see Borenstein et al. (2002).

Figure 5: Competitive Market Equilibrium with Capacity Constraints

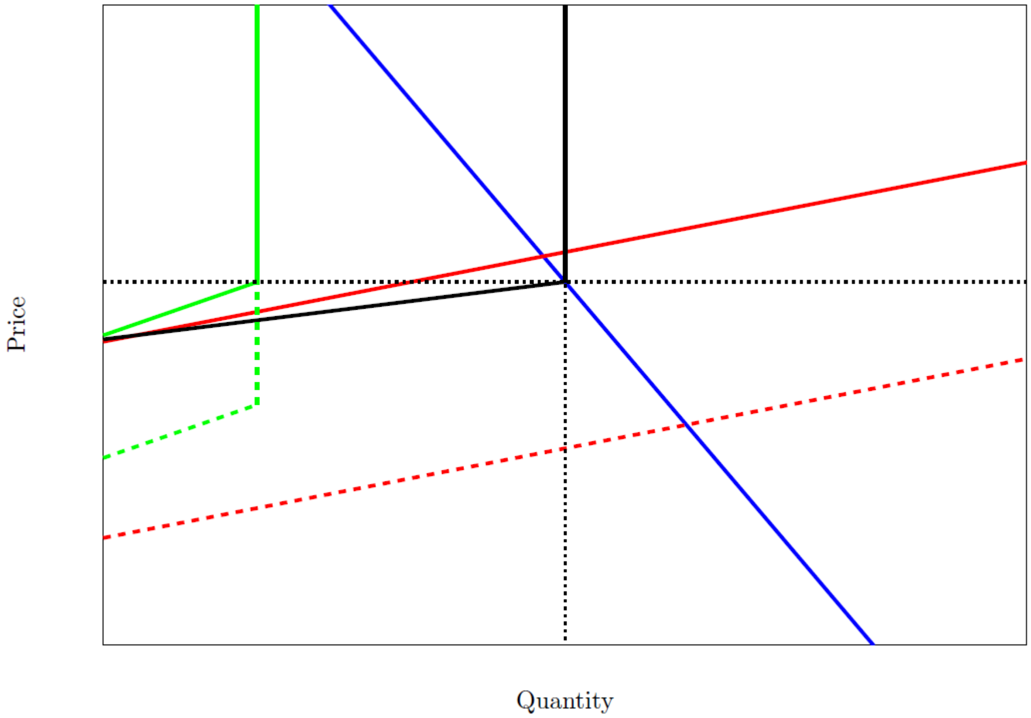


*The red and green lines represent the conventional and renewable private conventional marginal cost curves, respectively. The black line represents the total fuel supply curve which is the horizontal sum of the red and green lines. The blue line represents the final fuel demand curve.

consumption at the level of the constraint. Such a situation would lead to high and volatile LCFS credit prices.

In reality, capacity constraints on the renewable fuel industry will likely not binding as depicted in Figures 5 and 6. For example, whenever the biofuel market is facing the 10% blend wall, further compliance with the LCFS can be achieved by discounting the price higher blend biofuels such as E85 or high blends of biodiesel relative to low blend fuels. This will induce fuel consumers with FFVs to switch fuels, which would relieve the blend wall. In order to discount alternative fuels relative to conventional fuels, however, firms will require high LCFS credit prices. As in the capacity constraint case, LCFS credit prices will rise until the cost of discounting renewable fuels is equal to the price of LCFS credits. Thus, as compliance options become more costly to meet the program, LCFS credit prices will rise to equalize those costs across regulated parties.

Figure 6: LCFS Equilibrium with Capacity Constraints



*The red and green lines represent the conventional and renewable private conventional marginal cost curves, respectively. Solid lines represent marginal cost curves after being adjusted for relevant LCFS credit generation of credits and deficits and adjusting for the capacity constraint. The black line represents the total fuel supply curve which is the horizontal sum of the solid red and green lines. The blue line represents the final fuel demand curve.

2.4 Generation of Credits Outside Traditional Liquid Fuels

An important issue we have yet to address is the effect of credits generated outside the conventional liquid fuel industry on our results. An important component of compliance with the LCFS in years to come will involve credits generated by fuels other than liquid fuels as an increasing volume of credits are generated from fuels such as electricity, hydrogen, and natural gas. Allowing for credits generated outside liquid fuels in our previous model does not change the analysis other than to reduce the amount of biofuels necessary to meet the LCFS. Whenever credits are purchased by the fuel industry from sources such as electric utilities, instead of requiring every unit of final fuel to be composed of 20% biofuel, regulated parties may only be required to blend 10-15% biofuel.

This will hold so long as liquid fuels remain the predominant generator of LCFS credits. If credits generated from outside liquid fuels exceed those needed for the industry to maintain compliance with the LCFS and are cheaper than blending biofuel, the industry will not blend any biofuels and will instead purchase the credits. Given that over 75% of compliance is derived from biofuels, this scenario is unlikely in the near future.

Regardless of which fuels are used to meet the Standard, the key driver of LCFS credit prices will be the price difference between conventional liquid fuels and the marginal renewable fuel used to meet the Standard.

If it is cheaper to comply on the margin using natural gas or hydrogen rather than with E85 or biodiesel, LCFS credit prices will be equal to the difference in costs between natural gasoline and conventional liquid fuels on an energy unit basis. Given that firms can always comply either through increasing the amount of low CI fuels in their production mix or through purchasing LCFS credits from other parties, the tendency of the market will be to equalize the costs. Thus, the intuition from previous sections holds when thinking about compliance costs and risks factors in more complex settings.

2.5 Dynamic Considerations and the Role of Uncertainty

Our discussion uses a static, one-period model of the fuel industry where there is no uncertainty about the market supply or demand curves. In reality, the LCFS standard evolves over time, becoming more stringent each year.[15] In addition, there is significant uncertainty regarding how the Standard will be met in years to come. Under the program, credits do not expire and firms are allowed to generate excess credits in any year and apply them to future year obligations. Firms are not allowed, however, to borrow credits from anticipated future year reductions.

As discussed in Weitzman (2003), static models of economic phenomena are first-order approximations of dynamic and uncertain economic systems. Because firms are allowed to bank credits, LCFS credit prices today are directly related to expected credit prices in the future. Banking in credit markets has been studied in the context of a number of other environmental compliance markets.[16] Previous studies show that in perfectly competitive industries, allowing firms to bank over time can lead to substantial cost savings and efficiency gains (Rubin, 1996).

However, whenever banking is allowed, anticipated cost increases, technological constraints, and policy changes will be reflected in current credit prices. For example, if firms anticipate that compliance costs will be high in coming years, demand for LCFS credits generated in the current compliance period will increase and prices will rise as firms equalize the expected compliance costs across years. The fact that credit prices are tied over time strengthens the argument for instituting a cost containment mechanism. Our static model illustrates situations where LCFS credit prices may become very high and volatile. The anticipation of such high cost scenarios could lead to rising LCFS credit prices well in advance of when the constraints actually bind on the industry.

2.6 Strategic Considerations and Market Power

Our report assumes throughout that no firms have market power in the output, input, or LCFS credit markets. Market power exists if any single firm or group of firms is able to influence prices through their production decisions. Market power may be a concern on many fronts. For example, if there is market power

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[15] The current schedule of the LCFS is published in the Final Rule online at http://www.arb.ca.gov/fuels/lcfs/CleanFinalRegOrder112612.pdf .

[16] Examples include Schennach (2000) and Rubin and Kling (1993). Rubin (1996) derives a number of general results on the effect of banking in pollution permit markets which motivate our discussion.

in the output market, some firms can influence fuel prices through reducing their production.[17] Borenstein et al. (2004) discuss the difficulty in distinguishing between the exercise of market power and the effect of binding capacity constraints in California's gasoline market. To the extent that an LCFS diversifies the fuel mix and reduces the incidents where refiners may face a binding capacity constraint, the LCFS will mitigate market power in the state's fuel markets. Holland et al. (2007) discuss how market power in the output market affects the results in a model similar to our own. The authors find that the presence of market power does not qualitatively change their results. It does, however, affect the equilibrium quantity and prices in the market.

There are other forms of market power which may arise in the fuel market. For example, refiners and blenders may have purchasing power of renewable fuels, driving down prices renewable fuel producers receive for their product. The opposite may also be true if renewable fuel producers are able to raise prices for refiners and blenders by restricting throughput. Last, market power may exist in the LCFS credit market if any party which actively trades in the market attempts to influence prices by restricting the amount of credits available to be purchased. In all cases, a key condition which must hold in order for firms to successfully exercise market power is a lack of additional supply from other sources. In the output market, market power is a concern only when most firms in the market are capacity constrained. Whenever one firm restricts its output and increases market prices, there must be no other firms which can increase their output and reduce prices back to competitive levels.

The same is true if firms wish to exercise market power in the LCFS credit market. First, a firm must control a large enough share of LCFS credits that withholding a portion of their credits from the market would increase prices. Second, the resulting increase in LCFS credit prices must not be met by increased generation of credits from other sources. Unless both conditions hold, market power would not be a concern in the credit market. We recommend further analysis of individual LCFS credit transaction and generation data to determine whether market power may be an issue.

2.7 Interactions with California's Cap and Trade Program

California's fuel industry must comply with other carbon policies in addition to the LCFS. The most important carbon policy which will affect California fuel markets in the near future is the phase-in of all emissions associated with the combustion of fossil fuels under the state's cap and trade program. The state's cap and trade program is composed of two phases. During the first compliance period from 2013-2015, refiners are responsible for all GHG emissions directly associated with their production.[18] Beginning in 2015, in addition to emissions directly associated with production activity, California refiners will also be responsible for CO_2, CH_4, and N_2O emissions which result from the combustion of all fossil fuels produced in and imported into the state. Emissions associated with qualifying biomass-derived fuels are not included in the

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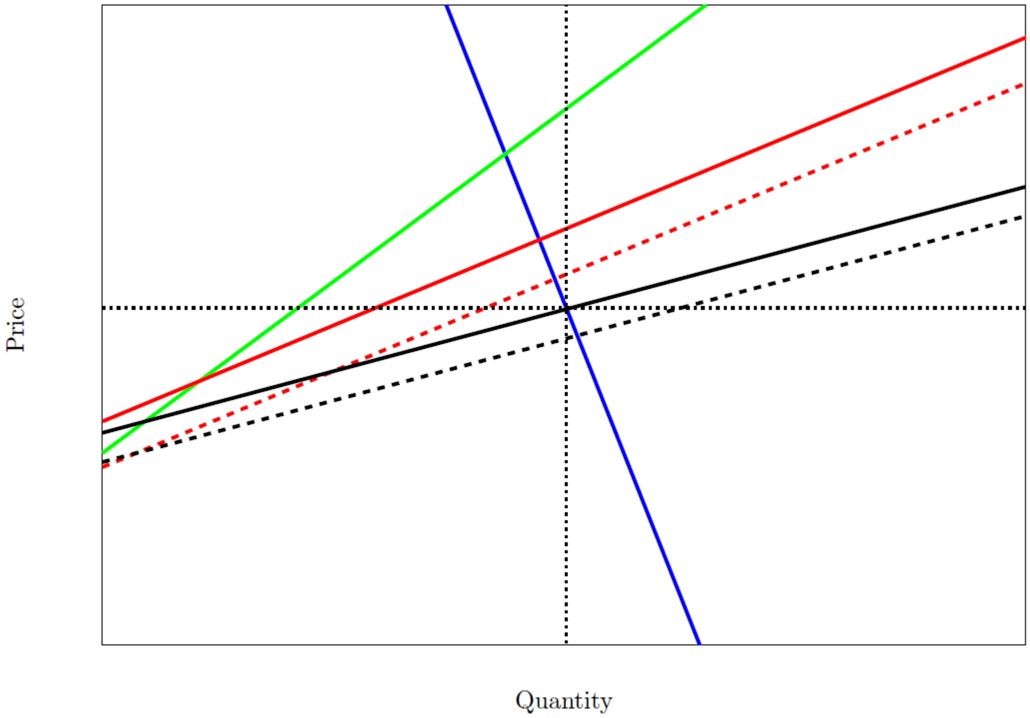
[17] Market power in California's fuel market is the most common concern cited by the media. Concerns over refiner market power typically arises whenever the industry is facing strict capacity constraints such as in high demand periods where there is an unexpected refinery outage. For example, in October 2012 California Senator Barbara Boxer called on the Department of Justice to investigate gasoline price spikes after an outage occurred at a Richmond refinery and prices increased substantially in weeks following the outage.

[18] Emissions covered under the cap in the first compliance period include emissions from stationary combustion, processing, catalyst regeneration and flare and destructive devices.

Figure 7: LCFS Equilibrium with Conventional Fuel Included Under the Cap



*The red and green lines represent the conventional and renewable private conventional marginal cost curves, respectively. Solid lines represent marginal cost curves after being adjusted for relevant LCFS credit generation of credits and deficits and the cap and trade program. Dashed lines represent previous marginal cost curves under an LCFS with no cap and trade market. The black line represents the total fuel supply curve which is the horizontal sum of the solid red and green lines. The blue line represents the final fuel demand curve.

compliance obligation of any refiner.[19] Thus, any portion of fuel produced from fuel ethanol, bio-diesel or other renewable sources will not be included under the cap.

As a result of the cap and trade program, beginning in 2015, for every gallon of conventional fossil fuel produced or imported, refiners will be required to purchase permits to cover the emissions associated with the fuel. So long as individual refiners cannot affect cap and trade permit prices, the cap and trade program can be modeled as a fee on conventional fuels, where the fee is equal to the cap and trade permit price times the emissions of each unit of fuel. The effect of the program is illustrated in Figure 7. In the figure, the solid lines represent the supply curves under a cap and trade program which covers only conventional fuel emissions and the dashed lines represent the supply curves in the absence of a cap and trade policy. The policy shifts the conventional and total fuel supply curves upward, leading to higher fuel prices and decreasing fuel demand.

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[19] Also excluded from having a compliance obligation are emissions associated with geothermal facilities, natural gas, hydrogen fuel cells, emissions from the storage of petroleum and natural gas, emissions from asphalt blowing operations, equipment leaks, storage and loading operations, emissions from low bleed pneumatic devices, emission from high bleed pneumatic devices reported prior to 01/2015, vented emissions from well-site centrifugal and reciprocating compressors with horsepower less than 250 hp; carbon dioxide that is imported or that is exported for purposes other than geological sequestration; and emissions from facilities covered under NAICS code 92811- national security facilities through 2013.

Because all renewable fuel emissions are not included under the cap, the relative price difference between the inputs becomes smaller. As a result, LCFS credit prices will experience downward pressure as cap and trade permit prices increase.

2.8 Incentives to Innovate and Invest in Renewable Fuels

An important feature of the LCFS is the incentive it provides for investments and innovation in low carbon intensive fuels. There are a number of dimensions along which we can consider how the program provides incentives for innovation. A key dimension along which firms may innovate is through investing in technologies which decrease the CI factors of the fuels they produce. As shown in the Technical Appendix, the incentive to decrease the CI factor of each fuel increases as both the LCFS credit price and the amount of fuel used by the industry increases. By decreasing the CI factor, firms are able to generate more credits or fewer deficits. If a large volume of the fuel is sold in the state or LCFS credit prices are high, the payoff to reducing the CI assignment is high.

The superiority of alternative policies in inducing innovation depends crucially on a number of factors. There is a large economics literature studying the effect of alternative policies as well as their effectiveness in inducing innovation. In addition, many large-scale energy models such as the EIA NEMS model assume some form of learning or technological innovation which is induced by policy interventions. The economics literature has found mixed results as to the superiority of the incentives provided by policies such as the LCFS i over more environmental policies such as taxes and cap and trade programs. Gerlagh and van der Zwaan (2006) find intensity standards such as the LCFS may outperform traditional environmental policy whenever there is learning by doing in the market which drives down costs as cumulative production increases. Fischer and Newell (2008), however, show that the results found by Gerlagh and van der Zwaan (2006) depend on the assumed production technologies of the renewable inputs.

Some experts such as Montgomery and Smith (2007) argue traditional environmental policies do not provide a sufficient incentive for research and development (R&D) because the government suffers from a dynamic inconsistency problem.[20] A dynamic inconsistency problem exists whenever regulated parties anticipate that the government will waive all or part of a regulation in the future if costs become too high. In this case, firms will not fully internalize the expected future benefits of investments because they believe the program will not exist in its full form in the future. This will dampened long-run incentives to invest in new technologies. Overall, there is a consensus that an important aspect of policies such as the LCFS is in inducing innovation. There is no consensus, however, as to the superiority of intensity standards over other more direct policies. We recommend further research studying scenarios where the LCFS outperforms traditional policies in incentivizing investments in low CI fuels.

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[20] The argument presented in Montgomery and Smith (2007) is perhaps more compelling when one considers that David Montgomery wrote one of the most cited academic articles proving the efficiency of cap and trade programs whenever permits are allowed to be traded freely among firms (Montgomery, 1972).

3 Cost Containment Mechanisms and Recommendations

The main purpose of this report is to analyze the potential effects of instituting cost containment mechanisms on the performance of the LCFS and relevant market outcomes. In the previous sections we identify key factors which influence compliance costs and may lead to high and volatile LCFS credit prices. As will be shown, options which directly address the underlying issues driving high compliance costs are most successful in containing costs. We first consider a number of provisions proposed by the ARB. Next, we discuss other potential mechanisms, the effect of cost containment mechanisms on incentives to innovate, the potential for implementing an LCFS credit price floor, as well as other important issues which affect LCFS credit markets.

3.1 ARB Proposed Cost Containment Mechanisms

In May 2013, the ARB released a white paper discussing a number of mechanisms meant to contain LCFS compliance costs.[21] The report cites two important goals that any cost containment provision should satisfy: (i) any provision should stimulate further investment in low-CI fuels; and (ii) any provision should provide additional compliance strategy options. Below we discuss each provision and provide specific comments on the efficacy of each mechanism.

3.1.1 Credit window option

Under an LCFS credit window option, if regulated parties are unable to obtain credits on the market at reasonable prices, regulated parties could purchase compliance credits directly from the ARB. The credits would not be associated with the production of any low CI fuels and would serve only to increase liquidity in the market. Funds collected from the window would be distributed to parties which use or produce low-CI fuels to 'incent the development of commercially-viable, low-CI technologies.'

Whenever regulated parties can purchase credits from the credit window, firms have an additional compliance option beyond blending renewable fuel. If firms are unable to purchase credits from the credit market or blend more renewable fuel, they may alternatively comply with the Standard by producing conventional fossil fuels and purchasing credits to account for the resulting deficits from the credit window. So long as the ARB is willing to sell an unlimited number of credits at the window, the credit window price will serve as a hard cap on LCFS credit prices and prices will never exceed the credit window price. Thus, the proposed mechanism would always be successful in containing program costs. In addition, the mechanism has the added advantage that the ARB can update the credit window price each year, allowing the price to rise at the rate of interest to ensure the real price of the cap remains constant.

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[21] The white paper is available at http://www.arb.ca.gov/fuels/lcfs/regamend13/20130522ccp_conceptpaper.pdf .

3.1.2 Reinvestment plan option

Under a reinvestment plan mechanism, regulated parties would have the option to invest funds they would have used to purchase compliance credits in ‘investments that would be specified in the regulation that advance the objectives of the LCFS.’ The option would be triggered whenever credit prices on the private market traded consistently above a given threshold.

Given the ambiguity of the proposed mechanism, it is difficult to determine how the policy would affect the LCFS credit market. If the ARB establishes a specific value of the deficits which must be reinvested in low CI fuels, the policy would have an equivalent effect as the credit window option. If, however, the value of reinvestments is determined by the market clearing LCFS credit price, the provision would do nothing to constrain costs in the short-run. In the long-run, if the mandated investments decrease production costs of low CI fuels or reduce the carbon intensity of fuels, costs will decrease; however, the option would remain vulnerable to short-term price volatility.

3.1.3 Credit multiplier option

Under a low CI credit multiplier option, the ARB would apply a multiplier to fuels which are below a specified carbon-intensity threshold. Under the provision, one mega-joule of fuel below the CI threshold would generate more compliance credits than a mega-joule of fuel above the threshold. The option is meant to ‘send a stronger signal to fuel providers that the lower-CI fuels have a disproportionally higher value within the program’ and ‘ensure additional credits are available in the market.’

While the credit multiplier will put downward pressure on LCFS credit prices, the effect of the multiplier on the volume of low CI fuel sold in the state is generally ambiguous. As shown in the Technical Appendix, Section A.3, the low CI multiplier may increase or decrease the amount of low CI fuels produced. Overall, the mechanism has similar effects as reducing the LCFS constraint on the industry in a given compliance year. Given the ambiguity as to how a low CI credit multiplier would affect the market, we defer studying the potential effects of the mechanism to the numerical model in the next section.

There are several disadvantages to the low CI multiplier option. The low CI multiplier remains susceptible to large price volatility whenever the market faces technological or capacity constraints, and does not guarantee price volatility will be reduced. As discussed in section 2.8, the incentive to invest in low CI technologies is related both to the LCFS price and to the volume of fuel sold. Thus, while incentives may increase if firms increase the use of low CI fuels under the multiplier, the mechanism reduces LCFS credit prices, which reduces incentives to innovate. In addition, as will be shown in our numerical model, the likely effect of the policy is to decrease the use of lower CI fuels and therefore the policy would unambiguously decrease the incentive to invest in innovative technologies for low CI fuels.

3.1.4 Credit clearance option

Under the current regulation, parties are unable to carry deficits from one year to the next if they anticipate generating excess credits in the future at lower costs. Under the credit clearance option, the ARB would allow parties to carry over deficits if they commit to purchase a share of all credits made available for sale during a "credit clearance" period. During a credit clearance period, parties would pledge credits they would like to sell which they were not able to sell during normal compliance periods, and would sell the credits at or below a price cap determined by the ARB.

This option is meant to address concerns of stranded credits in the market. Without more details regarding why certain parties would be unwilling to sell credits on the LCFS credit market or why regulated parties would be unwilling to purchase the credits, it is difficult to discuss the effects of such a provision. In general, the credit clearance mechanism does not address the fundamental drivers of credit prices discussed in our previous section. Namely, the provision would not contain costs should renewable fuels become very expensive relative to conventional fossil fuels or if the renewable fuel industry is faced with a capacity or technological constraint.

3.1.5 Noncompliance penalty

The last option discussed in the ARB white paper is a noncompliance penalty for any deficits generated in a given compliance year. Under the mechanism, for a given deficit each regulated party would have the option to pay a pre-established penalty to cover their remaining compliance obligation. The penalty may be determined in a number of ways still under consideration.

If the payment were a fixed amount per ton CO_2e, the non-compliance penalty will have an equivalent effect as the credit window option. The alternative compliance mechanism in this case would be for firms to produce conventional fossil fuels and pay the noncompliance penalty per ton CO_2e of deficits accrued. Firms would do this whenever the cost of compliance by purchasing LCFS credits becomes greater than the penalty. As with the credit window option, a noncompliance penalty would guarantee credit prices would not rise above the penalty.

3.2 Linking the LCFS to Other Carbon Markets

One option not considered in the ARB White Paper which has been proposed in other settings is to link the LCFS credit market to other carbon markets.[22] Burtraw et al. (2013) provide a thorough discussion of the benefits and issues associated with incrementally linking carbon markets from multiple cap and trade programs. Given the global nature of the damages from greenhouse gas emissions, the source of emission reductions will not affect potential global warming outcomes. Thus, substantial efficiency gains may be realized by linking carbon markets across jurisdictions, especially if firms in certain jurisdictions are able to decrease carbon emissions at lower costs than those in others. Linking cap and trade programs is complicated

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[22] We thank Sonia Yeh for bringing this proposal to our attention.

by institutional and regulatory factors such as the stringency of reporting and verification requirements, compliance timing issues, the scope of coverage, and alternative credit allocation methods.

A potential alternative compliance mechanism is to allow regulated parties to purchase credits from other cap and trade markets which may be converted into LCFS compliance credits at a given 'exchange rate.' For example, the ARB could require three credits from an approved cap and trade program be purchased to count as one LCFS credit. The proposal is complicated by a number of issues. First, administratively it may be difficult to align the LCFS with other cap and trade programs for many of the issues mentioned previously which make aligning cap and trade markets difficult. Second, the proposal would only contain costs if cap and trade prices remain low relative to LCFS credit prices. Cap and trade permit markets are subject to much of the same volatility concerns as LCFS credit prices. As a result there is no guarantee that costs will be contained by linking the LCFS credit market to other carbon markets. In addition, beginning in 2015 the LCFS program will already be linked to California's cap and trade program through the compliance obligation of refiners and blenders for the combustion of fossil fuels. As such, efforts to align California's cap and trade market with other regional markets will automatically benefit the LCFS program.

3.3 Effect of Cost Containment Provisions on Incentives to Innovate

The incentive to innovate in the low CI fuel market is directly tied to both the amount of fuel used in the market and the price of LCFS credits. By placing a cap on LCFS credit prices, the ARB will limit scenarios with very high returns for producers of low CI fuels. For example, if firms investing in low CI fuels originally anticipate that LCFS credits will exceed \$200/ton CO_2e and the ARB institutes a credit window selling unlimited credits at \$150/ton CO_2e, the firms will revise their expectations and may reduce investments in low CI technologies. As a result, whenever cost containment mechanisms are put in place, the incentive to invest in new technologies may decrease (Nemet, 2010; Burtraw et al., 2010).

Several provisions considered by the ARB involve raising funds which can be used to counteract the decrease in investment incentives. Using funds collected through a cost containment mechanism, the ARB has the opportunity to directly increase investments in low CI fuel production, increasing the supply and reducing the cost of low CI fuels. These investments would act not only to expand the low CI fuel market, but also to reduce future compliance costs and lower credit prices.

If the cost containment mechanism is triggered, the likely cause is that low CI fuels are unavailable at volumes required to meet the LCFS at reasonable prices. Two likely scenarios may cause this. First, investment in low CI production facilities may be low due to large, up-front capital costs of production facilities. Second, capacity for production may exist, but firms cannot produce low CI fuels at competitive prices due to high marginal cost differentials between conventional and renewable fuels. The two situations are different in nature and require different policy prescriptions to address them.

If large, up-front capital costs inhibit investments in low CI production facilities, the ARB can use funds raised through the cost containment mechanism to establish grants for new low CI projects.[23] Alternatively, if high marginal production costs plague the industry and production capacity is readily available, the ARB can establish a per unit production subsidy or tax credit for low CI fuels.

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[23] Alternatively, the state could offer tax incentives for investment in infrastructure. Lade (2011) studies investment in E85 fueling infrastructure and finds state grant programs are historically more successful in increasing investments in alternative vehicle infrastructure in the U.S. and have been more successful than tax credits. They lessons may equally apply to investments in new production facilities.

3.4 LCFS Credit Price Floor

An alternative mechanism which may counteract decreases in the incentive to invest in low CI technologies would be to establish a price floor to compliment the price cap in the LCFS credit market. By limiting both extreme high and low prices, the ARB would send a clearer price signal to investors in low CI fuels by reducing price uncertainty in the LCFS credit market.

Establishing a price floor for LCFS credits has a number of special implementation issues relative to cap and trade markets. In cap and trade markets, a regulator can create a price floor by restricting the amount of permits available on the market. This is achieved in California's cap and trade program through a reserve price in each auction. If parties are unwilling to pay the minimum reserve price at each auction, no permits are sold and the amount of permits available on the market is reduced. So long as the ARB auctions a large enough volume of credits, the reserve price will create a price floor in the market.

In contrast, the ARB does not directly control the supply of credits generated in the LCFS market. In order to maintain a price floor in the market, the ARB must directly or indirectly reduce the number of credits when supply of credits is highest and demand for credits is lowest. This can be achieved in a number of ways. First, the ARB can directly purchase and retire credits on the market whenever the LCFS credit prices fall below a given threshold. This would reduce the supply of credits on the market, increasing the price. Alternatively, the ARB can levy a fee on all transactions below the price floor equal to the difference between the transaction price and the price floor. This mechanism would require firms to properly report transaction prices to the ARB.

Given that the first two mechanisms are likely politically infeasible, the ARB can consider other mechanisms. A potential solution is to establish an inverse credit multiplier option whenever prices are trading below a given threshold. Under this option, the ARB can apply an inverse multiplier to all credits generated when LCFS credit prices reach a certain level, making any generated credits worth less.[24] For example, all credits can count for only half their original value when prices trade below a certain level. This would serve to limit additional credits generated on the market and put less downward pressure on credit prices. The mechanism would serve only as a soft floor on credit prices, however, and would not prevent prices from falling lower than the threshold price.

Alternatively, a more direct approach would be to apply a multiplier to all deficits generated whenever LCFS credit prices fall below a certain level. This would restrict the supply of available credits whenever the price threshold is reached and increase credit prices. Last, whenever credit prices reach a price floor the ARB can simply make the LCFS standard for that compliance period more stringent. The last three mechanisms are all indirect means of either restricting further generation of credits or reducing the number of available credits on the market. We recommend further research on their efficacy as a price floor mechanism.

A note should be made regarding the reason LCFS credits would trade for low prices. As discussed in section 2, the key driver of LCFS credit prices is the price difference between renewable and conventional fuels and technological or capacity constraints on the renewable fuel industry. If low CI fuels become cheap and can easily be deployed, compliance costs and LCFS credit prices will be low. Thus, low LCFS credit

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[24] We thank James Bushnell for helpful discussions on these mechanisms.

prices indicate that the industry is able to meet the Standard at a low cost, which is presumably a positive outcome.

Despite this, instituting a price floor may send a clearer price signal to investors in low CI fuels and counteract the adverse effects of a price cap on incentives to invest in low CI fuels (Burtraw et al., 2010). As discussed previously, however, should only a price cap on credit prices be implemented, many of the adverse effects on investment incentives could be counteracted directly through subsidies or grant programs for low CI fuels using funds raised through the credit window or non-compliance penalty.

3.5 Effect of Cost Containment Provisions on Emissions

One concern with instituting a price cap on LCFS credit prices is that the GHG reduction goals of the program will be compromised. As we discussed above and as is corroborated in our subsequent numerical simulations, whenever a hard cap is in place on LCFS credit prices, firms will comply with the Standard by using low CI fuels up to the point where the cost of compliance is equal to the price ceiling. After this point, firms will use the cheapest fuel and purchase credits or pay a noncompliance fee to cover any deficits. Thus, the average industry carbon intensity factor will be greater than the Standard in years when the price ceiling is reached.

Beginning in 2015, however, all emissions from the combustion of all fossil fuels will be covered under the state's cap and trade program. As a result, excess emissions from fossil fuels resulting from firms purchasing compliance credits or paying fees will be covered under the cap. Thus, the greenhouse gas reduction goals of AB 32 will not be compromised by establishing a cost containment provision for the LCFS.

While the overall emission reduction goals of AB 32 would not be compromised by the establishment of a cost containment provision for LCFS compliance credits, the composition of emission reductions would change if the cost containment provision is triggered. For example, if a credit window option is triggered, transportation fuels will have a higher average carbon intensity than the Standard in that year. As a result, the LCFS may contribute less toward the emission reductions goals of AB 32 when cost containment provisions are triggered, and the share of emissions covered by the state's cap and trade program will be greater than originally anticipated. This may shift the share of emission reductions away from transportation fuels and towards other sectors which can reduce emissions at lower costs.

3.6 Strategic Considerations

As discussed in section 2.6, there is concern that some parties may withhold LCFS credits in an attempt to increase credit prices and receive windfall profits. By placing an upper bound on the payoffs from such a strategy, a cost containment mechanism has the additional benefit of restricting the potential exercise of market power. Thus, while cost containment mechanisms do not directly address the concerns of market power in the LCFS credit market, any provision which places a hard cap on credit prices will reduce the payoff to strategic withholding. We recommend a more detailed analysis of the credit market moving forward and more research on provisions and amendments directly aimed at addressing the potential for parties to exercise market power in the LCFS credit market.

4 Numerical model of California's Fuel Market and the LCFS

In order to develop a better understanding of the potential effects of the LCFS as well as the proposed cost containment mechanisms on important market outcomes in California, we developed a simulation model of California's gasoline market, similar to those developed by Holland et al. (2007) and Lemoine (2013).[25] We model California's gasoline market at the market level rather than modeling individual refinery production decisions as is attempted by the Boston Consulting Group (2012). In doing so, we assume the LCFS credit market is well functioning. So long as the market for LCFS credits is robust in that there are no transaction costs to trading credits, there is no market power in the credit market, and there is no uncertainty regarding the availability of credits, the cost of complying with the LCFS will be equal for all regulated parties and we can infer the market clearing credit price directly from our model. The result holds regardless of the differences in individual obligated party costs of meeting the LCFS. Thus, while individual refiners may over or under comply with the LCFS, so long as the credit market is robust, we appeal to the fact that we know the LCFS must hold at the market level to determine the market clearing prices and quantities.

For the purposes of this report we have made multiple simplifying assumptions, appealing to Ockham's Razor rather than attempting to account for all factors which may affect California's fuel market in years to come.[26] Thus, the model does not provide predictions of future market outcomes. Instead, it is used to study the effectiveness of cost containment provisions in a simple setting, which yields important insights into the economic mechanisms underlying each proposal.

Our model has the following key features that are important in driving many of the results:

- **Final fuel demand:** We assume CARBOB gasoline and ethanol are viewed as equivalent to consumers of final fuel after adjusting for the fuels' respective energy contents.
- **Available renewable fuels:** We assume the industry can comply with the LCFS by blending two renewable fuels: conventional ethanol and cellulosic ethanol. Conventional ethanol is assume to be derived from either corn or sugar-cane and is more readily available at lower prices. We assume some cellulosic ethanol is available on the market; however, it is more expensive than conventional ethanol and is less scalable.
- **Availability of credits generated by non-biofuel sources:** Our model allows for a certain amount of LCFS credits to be generated by natural gas and electric vehicles. The inclusion of outside credits is used to illustrate the insensitivity of our main results to the availability of additional credits. We model the availability of non-biofuel credits as being unresponsive to the price of LCFS credits. Thus, we assume for any LCFS credit price, the specified volume of credits from natural gas or electric vehicles will be sold to obligated parties.[27]

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[25] Disclaimer: The results presented in this section are not predictions or forecasts of future economic outcomes. Rather, the results from our model are illustrations of the effects of an LCFS in a simple setting and the effects of various cost containment mechanisms on various market outcomes. Qualitative effects are emphasized over the quantitative results.

[26] Ockham's razor is a principle of simplicity in the sciences based on a singular quote from William of Ockham: "*Pluralitas non est ponenda sine necessitate*," or "Plurality should not be posited without necessity."

[27] For all simulations presented in the current report, we assume no credits are available from non-biofuel sources. The qualitative results are unaffected by assuming additional credits are available for compliance. Results illustrating the effect of credits outside liquid biofuels are available from the authors upon request.

- **Exclusion of the diesel market:** Under the LCFS, refiners face separate compliance obligations for diesel and gasoline. The diesel and gasoline compliance markets are intimately intertwined. The ARB allows for credits generated in either market to count towards compliance in the other. Thus, a refiner can over-comply (generate more credits than needed) in one product market and use the credits to meet compliance in the other product market. As discussed in ICF International (2013), the diesel market has the potential to generate significant credits in coming years. For the current report, we choose to exclude the diesel and biodiesel market from our simulations. By focusing on compliance in one market, our results more clearly illustrate the effects of instituting a cost containment mechanism. We believe adding an interaction with the diesel market, while more realistic, would obfuscate our results. In addition, the risk factors for increased compliance costs as well as the analysis of cost containment mechanisms are unchanged by the inclusion of a diesel market. Future work may build on and extend the current numerical model to include a biodiesel market.

Table 1 summarizes the key parameters and assumptions of our model. We initialize the model so that the quantity of CARBOB, conventional ethanol, cellulosic ethanol, and fuel prices are similar to California's fuel market in 2010. In order to allow for the availability of some cellulosic fuel, we assume as in Lemoine (2013) that initial cellulosic ethanol sold in the state is 200 million gallons in our baseline model.

Each supply and demand curve is defined as having a constant elasticity.[28] The assumption is restrictive in that it implies demand and supply are equally responsive to similar magnitudes changes in price regardless of the level of prices. The assumption, however, has the benefit of allowing us to proxy for the availability of each fuel by assigning higher elasticities of supply. A higher elasticity of supply implies the fuel is more readily available than lower elasticities supply curves. In addition, the assumption allows us to take advantage of an empirical literature which estimates supply and demand curves in fuel markets.

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[28] A constant elasticity supply (demand) function is of the form $Q = Ap^{\epsilon}$, where A is some constant and ϵ is the elasticity of supply (demand). For demand curves, $\epsilon < 0$ and for supply curves $\epsilon > 0$. The elasticity of supply (demand) is defined loosely as the percentage change in supply (demand) from a one percent change in price. Formally, the elasticity of a curve is defined as

$$\frac{\partial Q}{\partial p}\frac{p}{Q} = \epsilon A p^{\epsilon - 1}\frac{p}{Q},$$

which is equal to ϵ in this case. Thus, for any one percent change in price, the volume of fuel supplied (demanded) will respond by ϵ.

Table 1: LCFS Numerical Simulation Parameters*

Variable	Range	Baseline Value	Source
Fuel Demand Elasticity	{-0.05; -0.2}	0.1	Hughes et al. (2012)
CARBOB Supply Elasticity	{0.20; 3}	3	Dahl and Duggan (1996); Coyle et al. (2012); Lemoine (2013)
Conventional Ethanol Supply Elasticity	{0.2; 6}	3	Luchansky and Monks (2009); Lee and Sumner (2010)
Cellulosic Ethanol Supply Elasticity	{0.2; 6}	1,3	N/A
Carbon Intensity CARBOB (gCO_2e/MJ)	–	99.18	ARB LCFS CI Lookup Tables
Carbon Intensity Conventional Ethanol (gCO_2e/MJ)	{73; 99}	80	ARB LCFS CI Lookup Tables
Carbon Intensity Cellulosic Ethanol (gCO_2e/MJ)	{20; 50}	30	Lemoine (2013)
Initial Fuel Consumption (billion gallons)	–	15	Energy Information Agency (2010)
Initial Conventional Ethanol Availability (billion gallons)	–	1.3	DOE Energy Efficiency & Renewable Energy Office
Initial Cellulosic Ethanol Availability (billion gallons)	–	0.2	Lemoine (2013)
Initial Fuel Price ($ /gallon)	–	$3.138	Energy Information Agency (2010)
Availability of Credits from Natural Gasoline (MT CO_2e)	{0; 320,000}	0	LCFS Quarterly Reports
Availability of Credits from Electric Vehicles (MT CO_2e)	{0; 80,000}	0	LCFS Quarterly Reports
Energy Density of Gasoline (MJ/gallon)	–	119.53	ARB LCFS Final Reglation Order
Energy Density of Ethanol (MJ/gallon)	–	81.51	ARB LCFS Final Regulation Order
LCFS Carbon Intensity Constraint	{89.06; 97.96}	89.06	ARB LCFS Final Regulation Order
Cap and Trade Permit Price ($/ton CO_2e)	{0; 100}	0	Bailey et al. (2013)
LCFS Credit Window Permit Price ($/ton CO_2e)	{75; 250}	0	N/A
LCFS Low CI Credit Multiplier	{1; 5}	0	N/A

4.1 Baseline Model Results: The Effect of Varying Elasticities

When no policy or constraints are imposed, all supply and demand curves are calibrated to reproduce the baseline quantities and prices in Table 1. Before analyzing the effects of the various cost containment mechanisms, we first study the effect of the LCFS on the model under alternative assumptions about the availability of low CI fuels. We set the LCFS constraint at 2020 levels to illustrate the effect of the policy when it is set at a very stringent level.

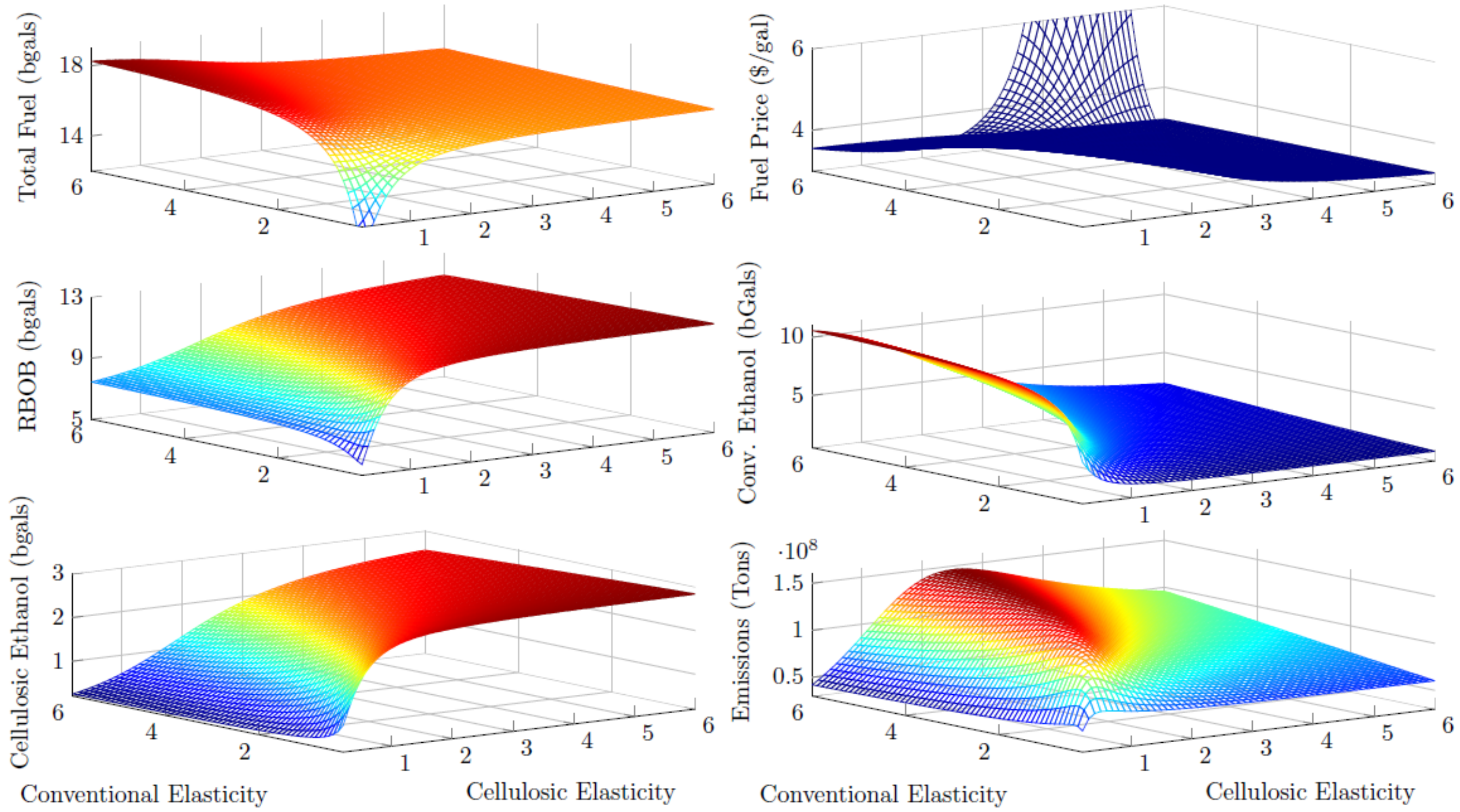
We first study the sensitivity of our results to various assumptions about the availability of the renewable fuels. To do this, we vary the elasticities of supply for both the cellulosic and the conventional ethanol supply curves from 0.2, representing a scenario where both fuels are only available for very high prices, to 6, where both fuels are readily available. The results are meant to illustrate two important features of our own model. First, that our results are very sensitive to alternative assumptions about the availability of renewable fuels in the economy. This motivates our focus on qualitative rather than quantitative outcomes. Second, the costliest scenarios arise when neither fuel is available, and the lowest cost and lowest emissions outcomes depend crucially on the development of low CI fuels, a parameter we know little about.

Figure 8 illustrates our results holding all variables equal and varying the conventional and cellulosic ethanol supply elasticities. Whenever both renewable fuel supply elasticities are low, the only means to maintain compliance with the Standard is to increase final fuel prices and reduce demand to a level where the LCFS is technologically feasible. This is illustrated in the top two graphs. When both renewable fuel elasticities are low, total fuel supply falls dramatically while final fuel prices rise. As either fuel elasticity becomes more available, total fuel increases and prices decrease.

Whenever cellulosic ethanol is not readily available but the elasticity of supply for conventional ethanol increases, the market responds by increasing the use of conventional ethanol and reducing CARBOB as illustrated in the middle figures. The outcomes ignores the blend wall. Were the blend wall a binding constraint, the market would increase conventional ethanol up to the blend wall, after which prices would rise and supply would fall. Thus, the blend wall would have a similar effect as a capacity constraint. As can be seen, whenever the elasticity of cellulosic ethanol is high, the market favors selling low CI fuels at lower blends and using higher volumes of cheaper CARBOB.

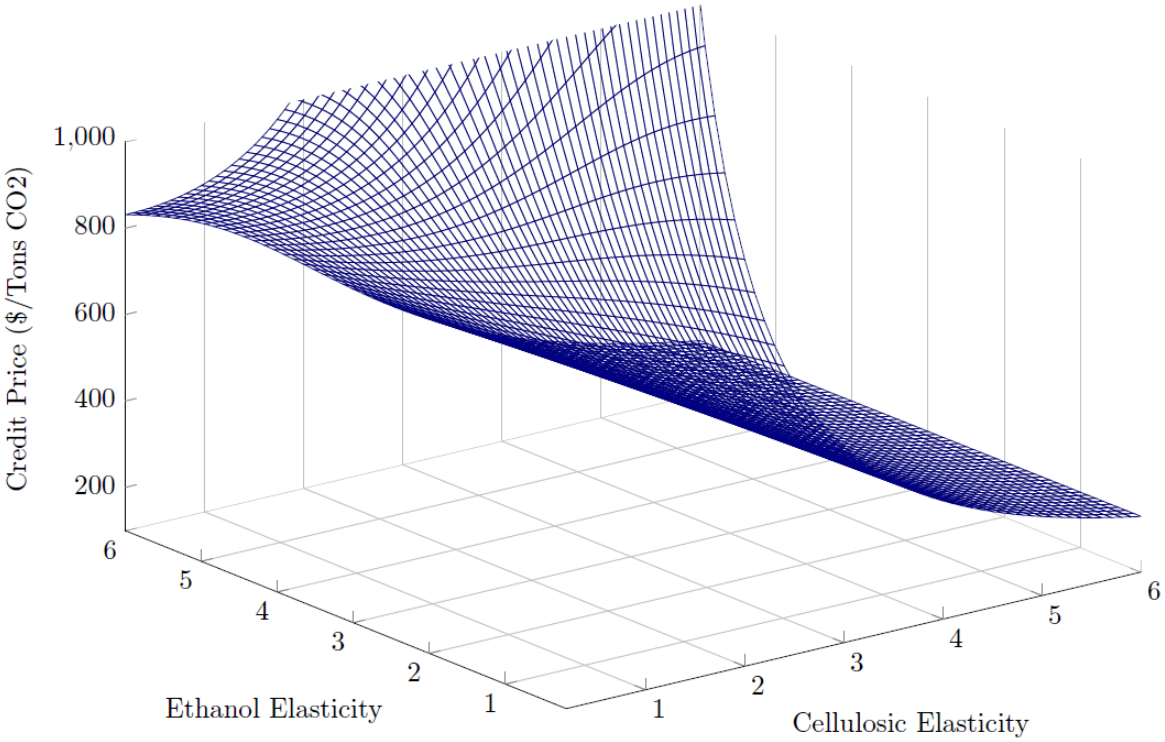
As illustrated in the bottom right graph, the range of elasticities where compliance is met primarily with conventional ethanol can have adverse effects on total emissions. In all simulations, the LCFS constraint holds so that the average carbon intensity of the fuel is equal to the Standard. Under alternative market outcomes, however, there can be substantial differences in the level of emissions in the market. Emissions are highest when the supply elasticity of conventional ethanol is high and the supply elasticity of cellulosic ethanol is low. Whenever low CI fuels are not available, the market shifts toward using higher CI fuels in greater volumes to overcome the deficits from conventional fossil fuels. The shift results in higher fuel consumption and higher emissions than in scenarios where low CI fuels are available. The result illustrates a key criticism of intensity standards by economists, namely that it is difficult to predict total emission savings from an intensity standard.

Figure 8: Market Outcomes and Varying Elasticities Under an LCFS



*The left axis represents the varying conventional ethanol elasticity of supply and the right axis represents the cellulosic ethanol elasticity of supply.Each figure presents various market outcomes for the given elasticities of supply holding all other variables equal. The LCFS standard was set to 2020 levels for gasoline at 89.06 gCO_2/MJ.

Figure 9: LCFS Credit Prices and with Varying Elasticities



*The left axis represents the varying conventional ethanol elasticity of supply and the right axis represents the cellulosic ethanol elasticity of supply.Each figure presents various market outcomes for the given elasticities of supply holding all other variables equal. The LCFS standard was set to 2020 levels for gasoline at 89.06 gCO_2/MJ.

Figure 9 illustrates the effect of varying availability of conventional ethanol and cellulosic ethanol on LCFS credit prices. As expected, when neither fuel is readily available, compliance costs increase substantially. This occurs because LCFS credits must be large in order to compensate firms for the large price differential between low CI fuels and fossil fuels. When cellulosic ethanol is unavailable but conventional ethanol is available, credit prices remain high, falling to just over \$800/ton CO_2e. Prices decrease rapidly as cellulosic ethanol becomes more available and prices become flatter in the region where cellulosic ethanol is most available, averaging around \$200/ton CO_2e.

Figure 9 also illustrates the relationship between high LCFS credit prices and the potential for high volatility in the credit market. The plane of credit prices is steepest along the region where cellulosic ethanol is not very available (where the elasticity is lowest). In this region, small changes in the supply of conventional ethanol, final fuel demand, or other market parameters may lead to large changes in LCFS credit prices. Whenever both cellulosic and conventional ethanol are more readily available, the LCFS credit price plane flatter and changes in market parameters do not lead to large movements in LCFS credit prices. Thus, the presence of capacity constraints may lead to both LCFS credit prices being high and volatile.

Overall, our analysis illustrates that the largest threat to high LCFS credit prices in the near term is low CI fuels being expensive relative to conventional fossil fuels or un-scalable at the volumes required to meet the Standard. In the absence of low CI fuels, the market responds by either reducing total consumption by increasing fuel prices or increasing the use of higher CI alternatives, both of which are costly options and require high LCFS credit prices.

4.2 Analysis of Cost Containment Provisions

Having illustrated the features of our model under an LCFS as well as the potential for large compliance costs, we turn our attention to the effectiveness of the proposed cost containment mechanisms. Using our numerical model, we focus on two general proposals. First, we illustrate the effect of instituting a hard cap on LCFS credit prices through either a credit window option or noncompliance penalty. Second, we illustrate the effect of a low CI credit multiplier.

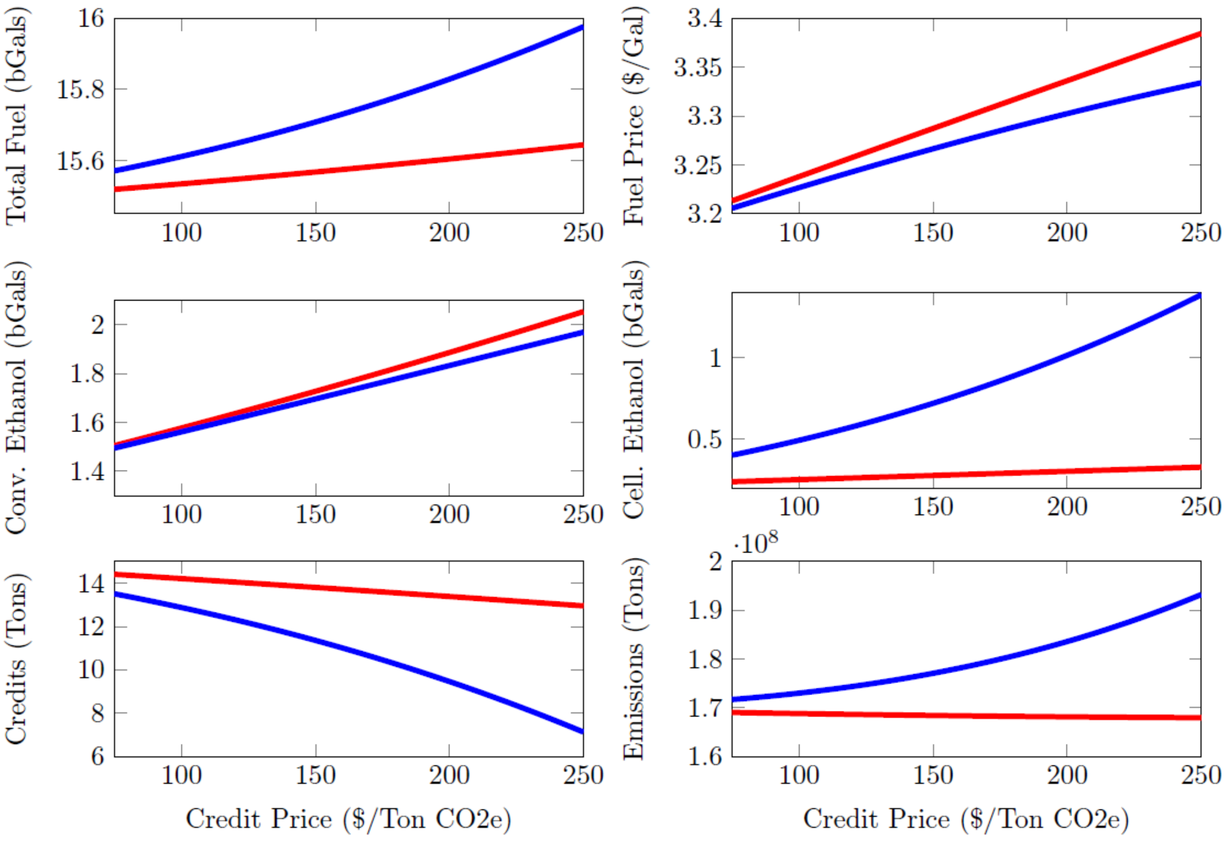
Several proposed cost containment mechanisms act as hard caps on LCFS credit prices and would ensure credit prices do not rise above the limit set by the ARB. The credit window, reinvestment plan, and noncompliance penalty options all provide alternative compliance mechanisms when LCFS credits reach a given price. If the three mechanisms are triggered at the same price, they will have equivalent effects on the market. For example, if the credit window option is triggered at \$150/ton CO_2e and allows parties to purchase unlimited credits, it will have an equivalent effect as a noncompliance penalty which is levied at the same price. The only difference between the two mechanisms is that the credit window option requires firms to purchase compliance credits while the noncompliance penalty assesses a fee on firms. The same outcome would also occur under a reinvestment plan option if the option is triggered at \$150/ton CO_2e and firms are required to reinvest an amount equal to their deficits multiplied by \$150/ton CO_2e to maintain compliance.

To study the qualitative features of these options, we model the credit window option, and refer to credits available from the window as 'emergency credits.' We study the effect of varying emergency credit prices from \$75-\$250/ton CO_2e. In all scenarios we hold all other variables equal to their baseline values with the exception of the emergency credit price and the elasticity of cellulosic ethanol. Given the sensitivity of our previous results to our assumption about the availability of cellulosic ethanol, we consider both high and low elasticity of supply scenarios for cellulosic fuel.

In all simulations, the emergency credit price binds in that the market clearing LCFS credit price equals the emergency credit price and firms always purchase a positive quantity of emergency credits from the credit window. Thus, the market complies with the LCFS by blending alternative fuels up to the point where the cost of compliance using available renewable fuels equals the credit window price. After this point, firms produce only fossil fuels on the margin and purchase credits at the credit window to maintain compliance.

Figure 10 illustrates the effect of varying emergency credit prices on total fuel sold, fuel prices, conventional ethanol, cellulosic ethanol, as well as the amount of credits purchased and emissions. The blue lines represent the scenario with a high elasticity of supply for cellulosic ethanol and the red lines represent the scenario with a low elasticity of supply. Whenever cellulosic fuel supply is more elastic, as the emergency credit price increases firms increase total fuel and blend more of both conventional and cellulosic ethanol to maintain compliance. Whenever the elasticity of supply for cellulosic ethanol is low, however, cellulosic ethanol does not increase as emergency credit prices increase because the fuel remains too expensive relative to conventional ethanol. In this scenario, compliance is achieved mostly through increasing CARBOB

Figure 10: Market Outcomes with Varying Credit Window Prices*



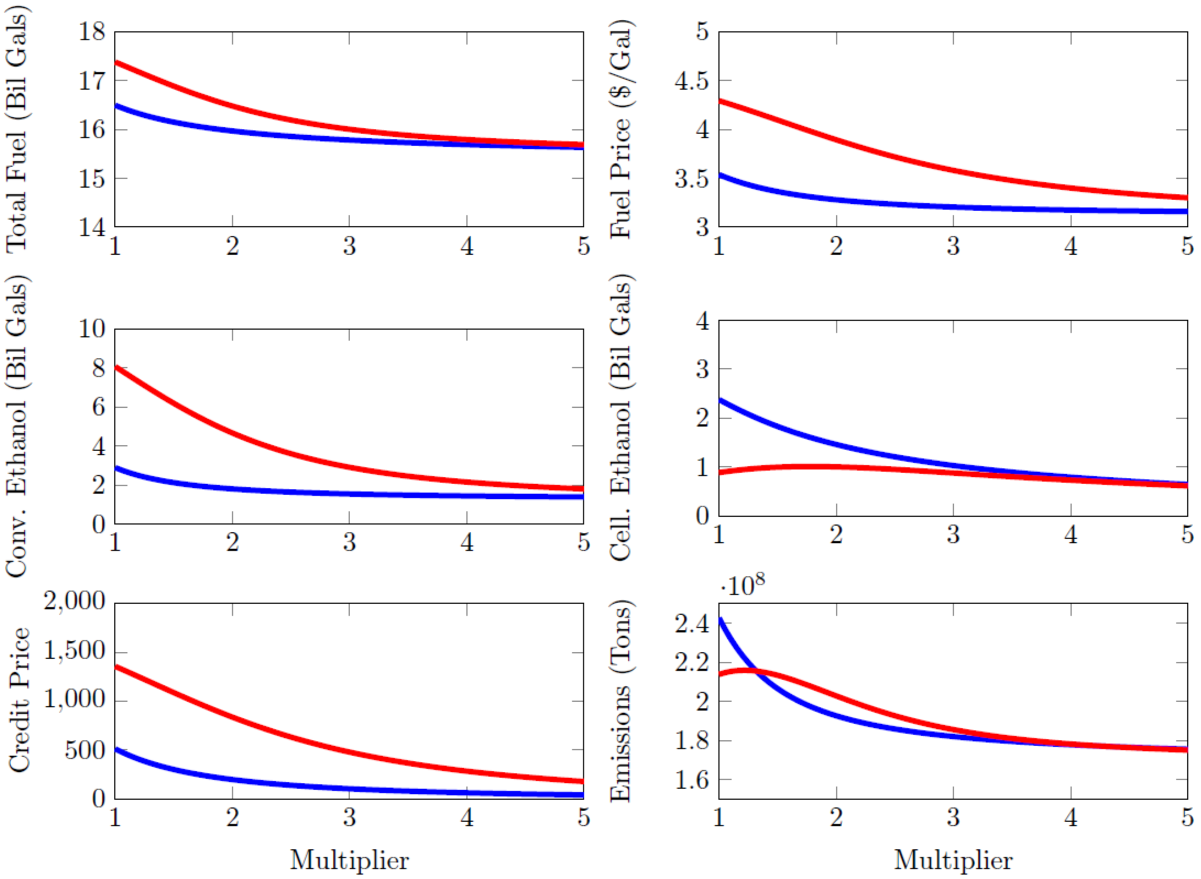
*The red line represents the scenario where cellulosic ethanol is less available (lower elasticity) while the blue line represents the scenario where cellulosic ethanol is more available (higher elasticity).

slightly and increasing conventional ethanol. Overall, final fuel demand in the market is higher and prices are lower whenever the cellulosic ethanol supply elasticity is high.

Whenever the elasticity of supply for cellulosic ethanol is low, firms' demand for credits from the credit window remains fairly constant across the range of prices. When the elasticity of cellulosic ethanol is high, however, the number of credits purchased from the window decreases sharply as credit prices increase. Thus, the elasticity of demand for credits from the window acts as an indicator of whether alternative compliance options are available to firms. If no alternative compliance strategy is available, demand for credits will be fairly constant for a range of prices. If, however, other compliance options are readily available, demand for credits will decrease quickly as prices increase.

The effect of varying emergency credits on emissions depends on the availability of cellulosic ethanol. Whenever the elasticity of supply for cellulosic ethanol is low, total emissions decrease slightly as emergency credit prices increase. This occurs because in this scenario fuel prices increase and demand decreases in response to higher credit window prices. Thus, the level emergency credit prices are set has a direct impact

Figure 11: Market Outcomes with Varying Low CI Multiplier



*The red line represents the scenario where cellulosic ethanol is less available (lower elasticity) while the blue line represents the scenario where cellulosic ethanol is more available (higher elasticity).

on fuel prices and consumption in the state. In general, higher emergency credit prices will result in higher fuel prices and lower fuel consumption. Thus, when setting the emergency credit window price, the ARB should carefully balance incentivizing further investments in low CI fuels through higher credit window prices with increasing fuel prices in the state.

The second cost containment mechanism we explore is a low CI multiplier for cellulosic ethanol. We consider a multiplier on cellulosic ethanol ranging from 1 to 5, holding all other variables equal with the exception of the multiplier and the two cellulosic ethanol supply scenarios. The results from our model are illustrated in Figure 11. As discussed in section 3 and shown in the Technical Appendix, the effect of a low CI multiplier on some market outcomes is generally ambiguous.

Overall, increasing the credit multiplier in our model has similar effects as reducing the Standard on the industry in a given compliance period. As the multiplier increases, both fuel prices and total fuel sold decrease. The amount of conventional ethanol blended decreases as the low CI multiplier increases. Whenever the supply elasticity of cellulosic ethanol is low, firms initially increase the amount of cellulosic ethanol in the market. Overall, however, the volume of cellulosic fuel in the market remains relatively constant as the multiplier increases, and decreases slightly as the multiplier increases from 4 to 5. Whenever the cellulosic ethanol supply elasticity is high, the volume of all fuels decreases as the multiplier increases.

While the results may seem counterintuitive in that a higher multiplier for low CI fuels leads to lower volumes of low CI fuel, it is sensible when economic factors in the market are considered. Low CI fuels are typically the most costly compliance option. So long as the LCFS is costly to firms, any policy which acts to reduce firms' compliance obligation under the program and relax the Standard will result in the market decreasing its use of the most expensive fuel. Thus the incentive to innovate and invest in low CI technology is typically reduced as the multiplier increases because the multiplier reduces LCFS credit prices and will likely decrease the volume of low CI fuels sold.

The model illustrates the difficulty in knowing how a low CI multiplier will affect the fuel market. We illustrate scenarios in which the multiplier reduces the amount of low CI fuels sold on the market and will decrease the incentive to innovate in the market. As shown in the Technical Appendix, the effect of the multiplier depends crucially on the shape of the market demand and supply curves. As a result, predicting actual outcomes is difficult. Given the uncertainty involved in predicting actual outcomes from the option relative to more transparent and certain alternative compliance options such as the credit window option, we do not recommend pursuing a low CI credit multiplier.

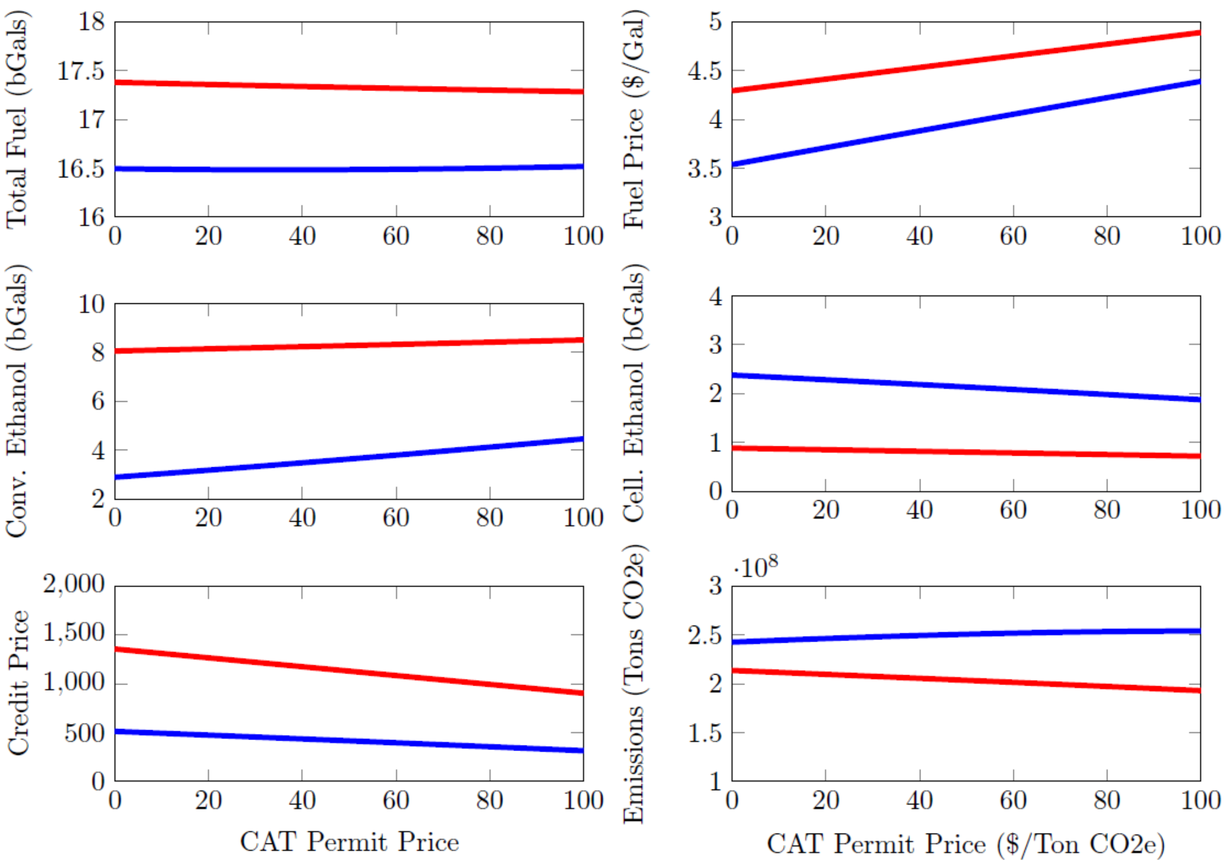
4.3 Interactions of the LCFS with California's Cap and Trade Program

Last, we consider the interactions of California's LCFS with the state's cap and trade program beginning in 2015. From our previous discussion, we expect that cap and trade will increase prices of fossil fuels, increase final fuel prices, reduce consumption, and put downward pressure on LCFS credit prices. We simulate the effect of varying cap and trade permit prices, allowing permit prices to range between \$0-\$100/ton CO_2e. Figure 12 presents the results for the two scenarios from before, holding all other variables equal to their baseline values.

As cap and trade permit prices increase, total fuel demanded in the state remains fairly constant; however, the mix of fuels sold in the state shifts towards using more renewable fuels. Under both elasticity scenarios, CARBOB use decreases and conventional ethanol increases as cap and trade permit prices increase; however, cellulosic ethanol use decreases in both scenarios. This occurs because a carbon tax on CARBOB decreases the relative price difference between CARBOB and conventional ethanol more than it decreases the relative price difference between CARBOB and cellulosic ethanol. As a result, the cap and trade program shifts the market away from lower CI fuels towards cheaper renewable fuels just below the Standard.

Overall, a \$100/ton CO_2e permit price results in around a \$0.50/gallon increase in fuel prices in our model. This is due to the low elasticity of demand assumed in the simulation which results in most of the cost of the cap and trade program being passed directly onto consumers. The total effect on emissions from the fuel sector depends crucially on the nature of fuel switching. When the elasticity of cellulosic ethanol is high, the market increases the use of conventional ethanol and decreases the use of cellulosic ethanol, resulting in slightly higher emissions. In the scenario where cellulosic ethanol is inelastic, emissions decrease as overall fuel reductions lead to lower emissions and the fuel mix does not change as substantially.

Figure 12: Cap and Trade Credit Prices & Market Outcomes*



*The red line represents the scenario where cellulosic ethanol is less available (lower elasticity) while the blue line represents the scenario where cellulosic ethanol is more available (higher elasticity).

The bottom left graph of Figure 12 illustrates the effect of cap and trade permit prices on LCFS credit prices. As expected, in both scenarios we see substantial reductions in LCFS credit prices. For the low supply elasticity scenario, LCFS credit prices are approximately 30% lower when cap and trade allocation prices are $100/ton CO_2e than prices when we do not model the cap and trade program. For the high elasticity scenario, LCFS credits are reduced by around 39%.

Overall our findings suggest that failing to take into consideration the effect of the state's cap and trade program will lead to overestimating LCFS compliance costs. In addition, the presence of a cap and trade program can have important effects on the fuel mix of the state. By differentially affecting fossil fuel prices, the program affects the relative price difference between fossil fuels and low CI fuels which may lead to alternative compliance scenarios than those which would be expected when studying the LCFS in isolation.

5 Future Research

While the main purpose of our report was to study the efficacy of the proposed cost containment mechanisms, we also discusses a number of important topics which deserve to be studied in greater detail. Two research projects we believe deserve in depth analyses are a transactions level study of the LCFS credit market as well as a related study of the potential for firms to exercise market power in the LCFS credit market.

The prior results rely crucially on the assumption that the LCFS credit market is robust in the sense that trading costs are low, there is no uncertainty regarding the availability of credits, and a large enough volume of trades occur so that there is proper price discovery in the market. As of October 2013, the most recent LCFS Reporting Tool data reports that 18-25 transactions a month have occurred in the market from July-September 2013. The low number of transactions may indicate that the market is not operating efficiently. Further study using transaction level data for LCFS credits could yield insight into whether the market is operating efficiently, and could identify opportunities for improving the market for LCFS compliance credits.

A related topic would be to study the potential for firms to exercise market power in the LCFS credit market. As discussed previously, there is potential for the exercise of market power in LCFS credit prices whenever (i) one firm or firms generates a large enough volume of credits such that withholding a portion of their credits would increase LCFS credit prices; and (ii) other firms are unable to generate more credits in response to an increase in the LCFS credit price. We are unable to determine whether these conditions exist given the published aggregate data. Future research using transactions level data may help identify the potential for market power to be exercised as well as recommend policies which may prevent market power.

6 Conclusions and Key Recommendations

While the primary purpose of this report is to illustrate the effect and effectiveness of various cost containment mechanisms under consideration by the California Air Resources Board for the state's Low Carbon Fuel Standard, we hope the report also sheds light on the economic mechanisms underlying intensity standards such as the LCFS. Future research can expand the current models presented in this report, incorporating more complex features of California's fuel market. With regards to the largest threats to substantial compliance cost increases to the program, we have the following key findings:

- **Current low CI fuel costs matter, and technological constraints to deploying low CI fuels can lead to volatile LCFS credit prices:** The largest sources of potential compliance cost increases as the Standard becomes more stringent are high marginal costs of low CI fuels relative to conventional fossil fuels, and technological or capacity constraints to deploying low CI fuels.
- **Anticipated future costs will affect current LCFS credit prices:** Given that firms can bank credits over time, anticipated high future compliance costs will lead to high compliance costs before technological constraints are reached or the highest low CI fuel prices are realized.
- **Expectations matter:** Given the large amount of uncertainty regarding the availability of low CI fuels, high expected compliance costs can increase current compliance costs substantially.

Regarding cost containment mechanisms, we have the following key recommendations:

- **The ARB should institute a cost containment mechanism which places a hard cap on LCFS credit prices:** Potential compliance costs are unknown. Given the potential for high volatility and prices in the LCFS credit market, the ARB should provide an additional compliance option which places a hard cap on permit prices by allowing for unlimited compliance through the option at a fixed cost. We favor establishing either a credit window for emergency compliance credits or a noncompliance penalty, where the trigger price is set to rise over time by the rate of inflation.
- **The ARB can counteract decreases in incentives to invest in low CI fuels through directly investing funds raised through a cost containment mechanism in low CI fuels:** Reinvesting funds raised through a cost containment mechanism can counteract decreases in incentives to invest in low CI fuels and can be used to directly address the cause of high LCFS credit prices. We recommend using the funds for per unit production subsidies for low CI fuels or grant programs for investments in production facilities of low CI fuels.
- **Low CI credit multipliers will reduce compliance costs, but may decrease incentives to invest in low CI fuels and do not guarantee compliance costs will be contained:** By not placing a hard cap on LCFS credit prices, options such as the low CI credit multiplier remain susceptible to large increases in compliance costs. In addition, the policy may decrease the amount of low CI fuel sold in the market and decrease the incentive to invest in those fuels.

- **Instituting a price floor for LCFS credit prices faces unique challenges, but may send a clearer price signal to investors in low CI fuels:** To prevent LCFS credit prices from falling below a certain level, the ARB must either control the supply of LCFS credits or levy fees when credits sell below a given price. The latter relies on accurate reporting of transactions which may be difficult. Further research into potential mechanisms such as an inverse multiplier on credits or a multiplier on deficits is recommended.

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A Technical Appendix

In this appendix, we present the models underlying our results and recommendations in the report "A Report on the Economics of California's Low Carbon Fuel Standard & Cost Containment Mechanisms." We begin with a basic model of a representative firm which produces fuel using a conventional and a renewable input. The representative firm is used to replicate the competitive market equilibrium. So long as all firms' production sets are convex, the solution to the competitive market outcome can be found using the aggregate supply functions for each input. Where necessary, we also aggregate over consumer preferences and define a market utility function for final fuel. Aggregation over consumer preferences is possible so long as preferences as quasilinear with a numeraire good representing all other goods in the economy.[29]

A.1 Baseline model of an LCFS

Assume a perfectly competitive industry must comply with the LCFS. There is no uncertainty in the market and firms seek to maximize profits. So long as the credit trading market is robust such that there are no transaction costs to trading compliance credits, there is no uncertainty regarding the availability of credits, and no firm is able to exercise unilateral market power in the credit market, the optimization problem of the representative firm which prices competitively will yield the competitive market outcome.

Suppose the industry uses two inputs to production, a conventional input, q^c, with associated carbon intensity ϕ^c, and a renewable input, q^r, with associated carbon intensity ϕ^r. Assume both inputs are measured in mega-joules (MJ) and that the carbon intensity factors are measured in grams of carbon dioxide equivalent per mega-joule (gCO$_2$e/MJ). Assume after being adjusted for their respective energy contents that the fuels are perfect substitutes. Both fuels are associated with a market cost curve denoted by $C^i(q^i)$ for $i = c, r$, where $C'(\cdot) > 0$ and $C''(\cdot) \geq 0$.

A low carbon fuel standard places a constraint on the average carbon content of final fuel. Consider a standard σ set by the government.[30] We express the policy as:

$$\frac{\phi^c q^c + \phi^r q^r}{q^c + q^r} \leq \sigma.$$

Assume $\phi^r < \sigma < \phi^c$. If $\sigma < \phi^r$, the policy is infeasible and can not be met with any fuel, while if $\sigma > \phi^c$ the policy is non-binding on the industry and does not require any renewable fuel to meet the policy. The industry's problem can be represented by the following maximization program:

$$\mathcal{L} = \max_{q^c, q^r} p(q^c + q^r) - C^c(q^c) - C^r(q^r) - \lambda \left[(\phi^c - \sigma) q^c + (\phi^r - \sigma) q^r \right],$$

where p is the fuel price and λ is the Lagrange multiplier on the LCFS constraint which is denominated in \$/gCO$_2$e.[31] The optimality conditions under perfect competition are given by the following.

$$\begin{aligned} q^c: &\quad p \leq MC^c(q^c) + \lambda(\phi^c - \sigma) \\ q^r: &\quad p \leq MC^r(q^r) + \lambda(\phi^r - \sigma) \end{aligned}$$

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[29] For more information regarding modeling market outcomes using a representative firm and representative consumer in partial equilibrium analysis, see Mas-Colell et al. (1995), chapters 4, 5.E and 10.B.

[30] The standard is phrased in grams of carbon dioxide equivalent per mega-joule of final fuel sold.

[31] For a background on constrained optimization problems and their use by economists, see Mas-Colell et al. (1995) chapter M.K.

$$\lambda \left[(\phi^c - \sigma)q^c + (\phi^r - \sigma)q^r\right] = 0$$

where $MC^i(\cdot) = \frac{\partial C^i(\cdot)}{\partial q^i}$ is the marginal cost of input i. The inequalities hold with equality whenever the market clearing quantities of both fuels are strictly positive. The third condition states that either the policy holds exactly in equilibrium or $\lambda = 0$. In the absence of a policy, firms will equate the market clearing fuel price to the marginal costs of each fuel. When the policy binds, however, the effective marginal cost of conventional fuels rise while the effective marginal cost of renewable fuels decrease.

Assume an interior solution for each fuel so that the optimality conditions hold with equality. The conditions above yield a number of key insights into the market equilibrium under an LCFS:

1. Whenever a credit trading system is available, λ will be equalized to the price of LCFS credits. Combining the two optimality conditions, it can be shown that λ is equal to the following.

$$\lambda = \begin{cases} \frac{MC^r(q^r) - MC^c(q^c)}{\phi^c - \phi^r}, & \text{if the policy binds} \\ 0, & \text{if the policy does not bind} \end{cases} \tag{1}$$

   Thus, the LCFS credit price is increasing as the difference between the marginal cost of renewable fuel and conventional fuel increase. In addition, the price of LCFS credits decreases as the difference in carbon intensity values between the renewable and conventional fuel increases.

2. Substituting equation (1) into the first order conditions, we have the following expression for fuel prices.

$$p = \frac{\sigma - \phi^r}{\phi^c - \phi^r} MC^c(q^c) + \frac{\phi^c - \sigma}{\phi^c - \phi^r} MC^r(q^r)$$

   The weights are the fraction of each fuel which must be used to meet the LCFS standard σ. For example, suppose $\phi^c = 1.2$, $\phi^r = 0.9$ and $\sigma = 1$. Then we know $p = \frac{1}{3}MC^c(q^c) + \frac{2}{3}MC^r(q^r)$. Thus, the final price of finished motor fuel will be equal to a weighted average of the input prices.

3. Under an LCFS, firms no longer equate prices to marginal costs. For each input i, $(\phi^i - \sigma)$ represents the amount input i's carbon intensity factor is over or under the standard per MJ. Therefore, $\lambda(\phi^i - \sigma)$ represents either additional the cost to firms from having to purchase $(\phi^i - \sigma)$ units of LCFS credits per unit of fuel or the benefit of being able to sell $(\phi^i - \sigma)$ units of LCFS credits on the market.

The Effect of the LCFS on Quantities and Prices

An important consideration is how the level of the standard affects relevant market outcomes. To do this, we use comparative statics of the market equilibrium with respect to σ. In order to conduct our comparative statics, we incorporate the consumer side of the market to represent the demand for final fuel. A representative consumer maximizes the utility of consuming a numeraire good and fuel. Given that the goods are perfect substitutes, let $Q = q^c + q^r$. As shown in Mas-Colell et al. (1995), given our assumption that consumers' utilities are quasilinear we can represent the representative consumer's problem as:

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

where ω is the aggregate wealth of consumers. In an interior solution, consumers will choose their consumption such that $U'(Q) = p$, where $U'(Q)$ is the demand function for fuel. Combining the consumer optimality condition, the firm optimality conditions, and market clearing equations, we have the following three equations which define our endogenous variables q^c, q^r, and λ in terms of the exogenous parameters σ, ϕ^c and ϕ^r:

$$F(q^c, q^r, \lambda | \sigma, \phi^c, \phi^r) = U'_Q - MC^c(q^c) - \lambda(\phi^c - \sigma) = 0$$

$$G(q^c, q^r, \lambda | \sigma, \phi^c, \phi^r) = U'_Q - MC^r(q^r) - \lambda(\phi^r - \sigma) = 0$$

$$H(q^c, q^r, \lambda | \sigma, \phi^c, \phi^r) = (\phi^c - \sigma)q^c + (\phi^r - \sigma)q^r = 0$$

The first two conditions combine the interior optimality conditions for our representative consumer and producer. The last condition states that the LCFS constraint must hold in equilibrium. To conduct comparative statics and determine how the endogenous variables will respond to a slight relaxation or increase in the stringency of the LCFS, we take the total derivative of each equation above with respect to σ. Note that $\frac{dQ}{dq^c} = \frac{dQ}{dq^r} = 1$. We can write the system of equations in matrix form as follows:

$$\underbrace{\begin{bmatrix} (U''_Q - C''_{q^c}) & U''_Q & -(\phi^c - \sigma) \\ U''_Q & (U''_Q - C''_{q^r}) & -(\phi^r - \sigma) \\ (\phi^c - \sigma) & (\phi^r - \sigma) & 0 \end{bmatrix}}_{=H} \begin{bmatrix} dq^c \\ dq^r \\ d\lambda \end{bmatrix} = \underbrace{\begin{bmatrix} -\lambda \\ -\lambda \\ Q \end{bmatrix}}_{=D} d\sigma.$$

We want to solve for $\frac{dx}{d\sigma}$ for $x \in \{q^c, q^r, \lambda\}$. To do so, we apply Cramer's rule which states:

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

where $H(\cdot)$ is the matrix above and $H^i(\cdot)$ is the matrix H with the ith column replaced with D. Let $A = C^{c''}(q^c) - U''(Q) > 0$ and $B = C^{r''}(q^r) - U''(Q) > 0$. The comparative statics are given by the following.

$$\begin{aligned} \frac{dq^c}{d\sigma} &= \left[B(\phi^c - \sigma)Q - U''(Q)(\sigma - \phi^r)Q + (\sigma - \phi^r)(\phi^c - \phi^r)\lambda\right](\det(H))^{-1} \geq 0 \\ \frac{dq^r}{d\sigma} &= \left[-A(\sigma - \phi^r)Q - U''(Q)(\sigma - \phi^c)Q + (\phi^c - \phi^r)(\phi^c - \sigma)\lambda\right](\det(H))^{-1} \\ \frac{d\lambda}{d\sigma} &= \left[-AC^{r''}(q^r)Q + U''(Q)C^{c''}(q^c)Q - \lambda\left(C^{c''}(q^c)(\sigma - \phi^r) - C^r(q^r)(\phi^c - \sigma)\right)\right](\det(H))^{-1} \end{aligned}$$

Note that $\det(H) > 0$ as expected given concavity of the objective function. To confirm this, note that $\det(H) = \left(C^c(q^c) - U''(Q)\right)(\sigma - \phi^r)^2 + \left(C^r(q^r) - U''(Q)\right)(\sigma - \phi^c)^2 - 2U''(Q)(\phi^c - \sigma)(\sigma - \phi^r) \geq 0$. Thus, the signs of the effects on each variable are determined by sign $\left(\det(H^i)\right)$.

Note that increasing σ relaxes the policy constraint, so the sign of the effect of increasing the stringency of the LCFS is $-\text{sign}\left(\frac{dx}{d\sigma}\right)$. The sign of the first expression is positive and therefore increasing the stringency of the program decreases conventional fuels.

The signs of $\frac{dq^r}{d\sigma}$ and $\frac{d\lambda}{d\sigma}$ are ambiguous without further restrictions. Suppose demand is linear such that $U''(Q) = 0$. In this case we have the following expressions.

$$\frac{dq^r}{d\sigma} = (\phi^c - \phi^r)(\phi^c - \sigma)\lambda - C^{c''}(q^c)(\sigma - \phi^r)Q$$
$$\frac{d\lambda}{d\sigma} = \lambda C^{r''}(q^r)(\phi^c - \sigma) - C^{c''}(q^c)C^{r''}(q^r)Q - \lambda(\sigma - \phi^r)C^{c''}(q^c)$$

The first term is negative if $C^{c''}(q^c) \geq \frac{(\phi^c - \phi^r)(\phi^c - \sigma)}{(\sigma - \phi^r)} \frac{\lambda}{Q}$. The second term is negative if $C^{c''}(q^c)C^{r''}(q^r)Q + \lambda(\sigma - \phi^r)C^{c''}(q^c) > \lambda C^{r''}(q^r)(\phi^c - \sigma)$. Thus, even with fairly restrictive assumptions in our simple model the effect of an LCFS on the amount of renewable input use, compliance costs, and prices is ambiguous.

A.2 Extensions to the Baseline Model

The previous results are derived using a relatively simple model of a representative firm facing an LCFS in order to study market level outcomes when an LCFS is enacted. In this section, we explore the robustness of the previous results to the inclusion of additional complexities in the model.

Firm Heterogeneity and Tradable Credits

Under the LCFS, many firms are covered as regulated entities. By modeling a representative firm at the market level, we do not capture the heterogeneity in compliance strategies in the industry. By allowing firms to trade credits, the policy allows firms which can more easily incorporate renewable fuels into their production process to over-comply with the standard, generate credits, and sell them to other obligated parties. Alternatively, firms also have the ability to blend less than the Standard and purchase credits from other obligated parties to cover their obligation.

Here, we illustrate how the inclusion of a credit trading market affects the firms in the industry. Suppose there are $i = 1, \cdots, N$ obligated parties in the market. Firms can comply with the standard either by blending the renewable fuel into their final product or by purchasing LCFS credits at price p^c which is denominated in $\$/\text{CO}_2\text{e}$. Let LCFS credits be denoted by c_i. Assume each firm is small enough so that they cannot influence the final output price or the LCFS credit price. The firm's maximization program is given by the following:

$$\mathcal{L}_i = \max_{q_i^c, q_i^r, c_i} p(q_i^c + q_i^r) - C_i^c(q_i^c) - C_i^r(q_i^r) - p^c c_i - \lambda_i \left[(\phi^c - \sigma)q_i^c - (\phi^r - \sigma)q_i^r - c_i\right].$$

Note that the firms have heterogeneous costs in this model. The optimality conditions for q_i^c and q_i^r are given by the following:

$$\begin{array}{lcl} q_i^c: & p \leq MC_i^c(q_i^c) + \lambda_i(\phi^c - \sigma) & i = 1, \cdots N \\ q_i^r: & p \leq MC_i^r(q_i^c) + \lambda_i(\phi^r - \sigma) & i = 1, \cdots N \\ c_i: & \lambda_i \leq p^c & i = 1, \cdots N \end{array}$$

$$\lambda_i \left[(\phi^c - \sigma)q_i^c + (\phi^r - \sigma)q_i^r - c_i\right] = 0 \quad i = 1, \cdots, N\ .$$

As before, all conditions will hold with equality so long as q_i^c, q_i^r and c_i are positive. As we can see, so long as firms purchase credits on the LCFS credit market all regulated parties will equate their individual shadow value of complying with the LCFS constraint to the credit price. The result holds despite the fact that firms have heterogeneous costs to meeting the policy. In fact, the gains from instituting a tradable compliance credit system increase as the heterogeneity of costs increases.[32]

Compliance in Gasoline and Diesel Markets

We model the LCFS as affecting a single output from a representative firm. In California, however, the LCFS establishes separate standards for diesel and gasoline, and compliance with the LCFS is determined through overall compliance with both standards. As a result, firms may over-comply with one fuel and

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[32] See Tietenberg (2006) for an overview of the economics of emission trading systems.

under-comply with the other. So long as the credits and deficits from each fuel balance, firms will remain in compliance.

Here, we consider the sensitivity of our results to explicitly modeling compliance with both gasoline and diesel standards. Letting g and d subscripts denote gasoline and diesel variables. As before, we consider the problem of a representative firm which prices competitively in order to derive the market clearing conditions defining the competitive market outcomes. We model the policy constraint for both policies as:

$$(\phi^c_g - \sigma_g)q^c_g + (\phi^r_g - \sigma_g)q^r_g + (\phi^c_d - \sigma_d)q^c_d + (\phi^r_d - \sigma_d)q^r_d \leq 0.$$

The maximization program in this case is given by the following:

$$\begin{aligned}\mathcal{L} = \max_{q^c_g, q^r_g, q^c_d, q^r_d} & \, p_g(q^c_g + q^r_g) + p_d(q^c_d + q^r_d) - C^c_g(q^c) - C^r_g(q^r) - C^c_d(q^c_d) - C^r_d(q^r_d) \\ & - \lambda \left[(\phi^c_g - \sigma_g)q^c_g + (\phi^r_g - \sigma_g)q^r_g + (\phi^c_d - \sigma_d)q^c_d + (\phi^r_d - \sigma_d)q^r_d \right].\end{aligned}$$

The optimality conditions are given by the following:

$$\begin{aligned} q^c_i : p_i \leq MC^c_i(q^{c*}_i) + \lambda(\phi^c_i - \sigma_i), \quad i = g, d \\ q^r_i : p_i \leq MC^r_i(q^{r*}_i) + \lambda(\phi^r_i - \sigma_i), \quad i = g, d \end{aligned}$$

$$\lambda \left[(\phi^c_g - \sigma_g)q^c_g + (\phi^r_g - \sigma_g)q^r_g + (\phi^c_d - \sigma_d)q^c_d + (\phi^r_d - \sigma_d)q^r_d \right] = 0.$$

All optimality conditions hold with equality so long as the market clearing quantities are positive. As before, we can derive the following expression for λ for an interior solution:

$$\lambda = \begin{cases} \frac{MC^r_g(q^r_g) - MC^c_g(q^c_g)}{\phi^c_g - \phi^r_g} = \frac{MC^r_d(q^r_d) - MC^c_d(q^c_d)}{\phi^c_d - \phi^r_d} & \text{if the policy binds} \\ 0 & \text{if the policy does not bind} \end{cases}.$$

Whenever we consider a binding LCFS in the case of multiple markets, quantities and prices will adjust to the point where the weighted difference between the marginal costs of renewable and conventional inputs in each market is equalized across markets. Thus, the qualitative features of our baseline model are unaffected by the inclusion of a second market, however, market clearing quantities and prices will adjust so long as costs to meeting the LCFS are different across the diesel and gasoline market.

The Availability of Many Renewable Inputs

In our baseline model, we assume there is only one renewable input which may be used to comply with the policy. In reality, firms have met and will continue to comply with the Standard using many renewable fuels all with different respective costs and carbon intensities. Here, we incorporate the availability of multiple renewable inputs into our analysis. In particular, suppose there are K available inputs which firms can use to meet compliance. The representative firm's maximization program is given by the following:

$$\mathcal{L} = \max_{q^c, \{q^r_i\}^K_{i=1}} p \cdot \left(q^c + \sum_{i=1}^{K} q^r_i \right) - C^c(q^c) - \sum_{i=1}^{K} C^r_i(q^r_i) - \lambda \left[(\phi^c - \sigma)q^c + \sum_{i=1}^{K} (\phi^r_i - \sigma)q^r_i \right]$$

The optimality conditions for the program are given by the following:

$$\begin{aligned} q^c: &\quad p \le MC^c(q^c) + \lambda(\phi^c - \sigma) \\ q_i^r: &\quad p \le MC_i^r(q_i^r) + \lambda(\phi_i^r - \sigma), \quad i = 1, \cdots, K \end{aligned}$$

$$\lambda \left[(\phi^c - \sigma) q^c + \sum_{i=1}^{K} (\phi_i^r - \sigma) q_i^r \right] = 0$$

Whenever there are multiple renewable inputs, we have two important considerations when deriving the market equilibrium outcomes. First, we must determine which fuels are supplied on the market. Second, we must derive conditions which define the market clearing quantities and prices.

To answer the first, assume the conventional input is cheapest and will always be used in equilibrium. Suppose renewable inputs are ranked from cheapest to most expensive and suppose the first k inputs are used and inputs $k+1$ thorugh K are not used in equilibrium. From the optimality conditions, we know the following must hold.

$$\begin{aligned} p &= MC_i^r(q_i^r) + \lambda(\phi_i^r - \sigma), \qquad i = 1, \cdots, k \\ p &\le MC_i^r(0) + \lambda(\phi_i^r - \sigma), \quad i = k+1, \cdots, K \end{aligned}$$

Thus, whenever the initial marginal cost of a fuel net of the value of any credits the fuel generates under the LCFS is greater than the market clearing price, the fuel will not be used. As can be seen, for a give price p, a fuel is more likely to be blended whenever the LCFS credit price is greater, its CI rating is smaller, and the intercept of its marginal cost curve is lower.

As before, we can derive an analytical solution describing the LCFS credit price for those fuels which are sold on the market as follows.

$$\lambda = \frac{MC_1^r(q_1^r) - MC^c(q^c)}{\phi^c - \phi_1^r} = \cdots = \frac{MC_k^r(q_k^r) - MC^c(q^c)}{\phi^c - \phi^k}$$

Thus, the equilibrium LCFS credit price will clear where the weighted difference between the marginal costs of each renewable fuel and the conventional fuel are equal. Thus the results from our baseline model extend easily to the multiple input case.

Technological and Capacity Constraints

Last, consider the effect of a capacity or technological constraint on our model. For simplicity, consider a case where the renewable input cannot be blended above a certain level. The restriction on the renewable input corresponds to an additional constraint on the model which we write as $q^r \le \bar{Q}^r$. Let Ψ be the Lagrange multiplier associated with the renewable capacity constraint. The maximization program of the representative firm in this case is given by:

$$\mathcal{L} = \max_{q^c, q^r} p(q^c + q^r) - C^c(q^c) - C^r(q^r) - \lambda \left[(\phi^c - \sigma) q^c + (\phi^r - \sigma) q^r \right] - \Psi \left[q^r - \bar{Q}^r \right].$$

The optimality conditions are given by the following:

$$\begin{aligned} q^c: &\quad p \le MC^c(q^c) + \lambda(\phi^c - \sigma) \\ q^r: &\quad p \le MC^r(q^r) + \lambda(\phi^r - \sigma) + \Psi \end{aligned}$$

$$\lambda\left[(\phi^c-\sigma)q^c+(\phi^r-\sigma)q^r\right]=0$$

$$\Psi[q^r-\bar{Q}^r]=0.$$

The last condition states that either $\Psi=0$ or the capacity constraint binds such that $q^r=\bar{Q}^r$. Consider the case where the capacity constraint binds. In this situation, we can solve for the LCFS credit price as follows:

$$\lambda=\frac{MC^r(\bar{Q}^r)-MC^c(q^c)+\Psi}{\phi^c-\phi^r}.$$

In addition, we have the following market clearing conditions:

$$p=MC^c(q^c)+\lambda(\phi^c-\sigma)=MC^r(\bar{Q}^r)+\lambda(\phi^c-\sigma)+\Psi$$

$$(\phi^c-\sigma)q^c+(\phi^r-\sigma)\bar{Q}^r=0.$$

Thus, whenever the renewable fuel capacity constraint binds on the industry, LCFS credit prices will increase. In addition, the market clearing price will increase by Ψ due to the capacity constraint, reducing q^c to the point where the LCFS constraint is just satisfied at the renewable capacity constraint. Overall, a binding capacity constraint acts to increase fuel prices, increase LCFS credit prices, and decrease the quantity of fuel sold on the market.

A.3 Cost Containment Analysis

In this section we model alternative mechanisms aimed at containing LCFS credit prices. We discuss both the options considered by the ARB as well as other potential cost containment mechanisms.

Credit Window Option

Suppose the ARB allows obligated parties to purchase compliance credits, denoted c, at a price p^c. Consider our baseline model of a representative firm. The maximization program is given by the following:

$$\mathcal{L} = \max_{q^c, q^r, c} p(q^c + q^r) - C^c(q^c) - C^r(q^r) - p^c c - \lambda \left[(\phi^c - \sigma)q^c + (\phi^r - \sigma)q^r - c \right].$$

The optimality conditions are given by the following.

$$\begin{aligned} q^c: &\quad p \leq MC^c(q^c) + \lambda(\phi^c - \sigma) \\ q^r: &\quad p \leq MC^r(q^r) + \lambda(\phi^r - \sigma) \\ c: &\qquad\qquad \lambda \leq p^c \end{aligned}$$

$$\lambda \left[(\phi^c - \sigma)q^c + (\phi^r - \sigma)q^r \right] = 0.$$

All conditions hold with equality in an interior solution. From the conditions, we can derive the following equation describing LCFS credit prices:

$$\lambda = \begin{cases} 0 & \text{if the policy does not bind} \\ \frac{MC^r(q^r) - MC^c(q^c)}{\phi^c - \phi^r} & \text{if the policy binds and } c = 0 \\ p^c & \text{if the policy binds and } c > 0. \end{cases}$$

The condition states that whenever the market can comply with the LCFS at a cost lower than the credit window price, the LCFS credit price will be the same as in our prior analysis. If, however, compliance costs reach p^c, firms will purchase emergency credits to maintain compliance and LCFS credit prices will equal p^c.

Reinvestment Plan Option

Under the reinvestment plan option, whenever credits trade above a price threshold, firms will have the option to invest money which would have been used to purchase emergency credits into low CI fuel investment options. Qualifying investments would be specified by the ARB. Given the ambiguity of how the ARB would determine the amount of money which would be required to be invested, it is difficult to determine how the policy would affect the LCFS credit market. If firms are required to invest the amount of money per CO_2e ton over compliance times the price threshold in renewable energy investment, the policy would be equivalent to the credit window option, and our model would yield the same results as in the credit window option above.

If, however, compliance were required to be equal to the market LCFS price times the amount of per CO_2e ton over compliance times the market LCFS credit price, the provision would do nothing to contain costs in the short-term. In the long-run, if the investments drive down costs of renewable fuels or reduce the carbon intensity of the fuel, costs will decrease. This option would therefore remain susceptible to short-term price volatility.

Credit Multiplier Option

Under the credit multiplier option, the ARB would apply a multiplier to fuels that are below a specified CI threshold. While the credit multiplier will put downward pressure on LCFS credit prices, the effect of the multiplier on other variables is not as straight forward as other proposed mechanisms. In addition, the multiplier option remains susceptible to price volatility in the face of technology constraints and does not guarantee prices will not rise above a given level.

To analyze the mechanism with our current model, consider the two input case and suppose the ARB applies multiplier δ to the renewable input. In this case, the LCFS constraint is given by $\frac{\phi^c q^c + \phi^r \delta q^r}{q^c + \delta q^r} = \sigma$. We can analyze the effect of the credit multiplier using the same technique as in section A.1. The three conditions which implicitly define q^c, q^r and λ in terms of exogenous parameters σ, δ, ϕ^c and ϕ^r are given by the following:

$$\begin{aligned}
F(q^c, q^r, \lambda | \sigma, \delta, \phi^c, \phi^r) &= U'_Q - MC^c(q^c) - \lambda(\phi^c - \sigma) = 0 \\
G(q^c, q^r, \lambda | \sigma, \delta, \phi^c, \phi^r) &= U'_Q - MC^r(q^r) - \lambda\delta(\phi^r - \sigma) = 0 \\
H(q^c, q^r, \lambda | \sigma, \delta, \phi^c, \phi^r) &= (\phi^c - \sigma)q^c + (\phi^r - \sigma)\delta q^r = 0.
\end{aligned}$$

As before, to solve for the effect of a small change in δ on our market equilibrium quantities and LCFS credit prices we take the total derivative of each condition above with respect to δ. In matrix form, the condition is given by the following:

$$\underbrace{\begin{bmatrix} (U''_Q - C''_{q^c}) & U''_Q & -(\phi^c - \sigma) \\ U''_Q & (U''_Q - C''_{q^r}) & -\delta(\phi^r - \sigma) \\ (\phi^c - \sigma) & (\phi^r - \sigma)\delta & 0 \end{bmatrix}}_{=H} \begin{bmatrix} dq^c \\ dq^r \\ d\lambda \end{bmatrix} = \underbrace{\begin{bmatrix} 0 \\ (\phi^r - \sigma)\lambda \\ (\sigma - \phi^r)q^r \end{bmatrix}}_{=D} d\delta.$$

Applying Cramer's rule and solving, we have the following solutions for the effect of a small change in the credit multiplier on the outcomes of interest:

$$\frac{dq^c}{d\delta} = \frac{(C''_{q^r} - U''_Q)(\phi^c - \sigma)(\phi^r - \sigma)q^r + [U''_Q q^r - (\phi^c - \sigma)\lambda](\phi^r - \sigma)^2\delta}{(U''_Q - C''_{q^c})(\phi^r - \sigma)^2\delta^2 + (U''_Q - C''_{q^r})(\phi^c - \sigma)^2 - 2U''_Q(\phi^c - \sigma)(\phi^r - \sigma)\delta}$$

$$\frac{dq^r}{d\delta} = \frac{U''_Q(\phi^r - \sigma)q^r[(\phi^c - \sigma) - (\phi^r - \sigma)\delta] + C''_{q^c}(\phi^r - \sigma)^2 q^r\delta + (\phi^r - \sigma)\lambda(\phi^c - \sigma)^2}{(U''_Q - C''_{q^c})(\phi^r - \sigma)^2\delta^2 + (U''_Q - C''_{q^r})(\phi^c - \sigma)^2 - 2U''_Q(\phi^c - \sigma)(\phi^r - \sigma)\delta}$$

$$\frac{d\lambda}{d\delta} = \frac{(U''_Q - C''_{q^c})C''_{q^r}q^r(\phi^r - \sigma) + (C''_{q^r}q^r + (\phi^c - \sigma)\lambda)U''_Q(\phi^r - \sigma) + (C''_{q^c} - U''_Q)(\phi^r - \sigma)^2\lambda\delta}{(U''_Q - C''_{q^c})(\phi^r - \sigma)^2\delta^2 + (U''_Q - C''_{q^r})(\phi^c - \sigma)^2 - 2U''_Q(\phi^c - \sigma)(\phi^r - \sigma)\delta}.$$

The interactions between the credit multiplier and our outcomes of interest are quite complex. As before, consider the case of linear demands such that $U''_Q = 0$ and consider evaluating the conditions around $\delta = 1$. The modified equations are given by the following:

$$\left.\frac{dq^c}{d\delta}\right|_{\delta=1} = \frac{(\phi^c - \sigma)(\sigma - \phi^r)C''_{q^r}q^r + (\phi^c - \sigma)(\phi^r - \sigma)^2\lambda}{C''_{q^c}(\phi^r - \sigma)^2 + C''_{q^r}(\phi^c - \sigma)^2}$$

$$\left.\frac{dq^r}{d\delta}\right|_{\delta=1} = \frac{C''_{q^c}(\phi^r - \sigma)^2 q^r - \lambda(\phi^c - \sigma)^2(\sigma - \phi^r)}{-[C''_{q^c}(\phi^r - \sigma)^2 + C''_{q^r}(\phi^c - \sigma)^2]}$$

$$\left.\frac{d\lambda}{d\delta}\right|_{\delta=1} = \frac{(\phi^r - \sigma)^2\lambda C''_{q^c} + (\sigma - \phi^r)C''_{q^c}C''_{q^r}q^r}{-[C''_{q^c}(\phi^r - \sigma)^2 + C''_{q^r}(\phi^c - \sigma)^2]}.$$

The first equation states that slightly increasing δ will increase the amount of the conventional input around $\delta = 1$. Thus, a low CI multiplier in will unambiguously increase the conventional input. The renewable input will increase as the low CI multiplier increases only if $\frac{(\phi^c-\sigma)^2(\sigma-\phi^r)}{(\phi^r-\sigma)^2} > \frac{C''_{q^c}q^r}{\lambda}$. The effect of a low CI multiplier on the renewable input is generally ambiguous without imposing further assumptions. The third equation states that as the low CI multiplier increases, LCFS credit prices will decrease.

Overall, the low CI multiplier acts in a very similar way to relaxing the LCFS constraint as discussed in section A.1. The multiplier would be successful in putting downward pressure on LCFS credit prices; however, the multiplier may decrease the amount of the renewable input on the market.

Credit Clearance Option

Under a credit clearance option, the ARB would only allow regulated parties to carry over deficits to subsequent years (or borrow credits from future year credits which are anticipated) if they commit to purchase a *pro rata* share of all credits made available for sale during an established "credit clearance" period.

The option is meant to address concern of stranded credits on the LCFS credit market. Without more details regarding why parties may withhold credits or why regulated parties would be unwilling to purchase the credits, it is difficult to model the effects of such a provision. The provision certainly would not address a fundamental driver of credit prices, namely scenarios when renewable fuels are very expensive relative to liquid fossil fuels or the industry faces a technology constraint.

Non-compliance Penalty

When faced with a non-compliance penalty, a regulated party with a net deficit at the end of each year's compliance would be required to pay a penalty per ton of CO_2e over-compliance. If the payment were a fixed amount per ton CO_2e, we can model the non-compliance penalty just as we did the credit window option, where c is interpreted as the choice of the deficit in a given year and p^c is the non-compliance penalty. Therefore the non-compliance penalty has an equivalent effect as the credit window option.

Establishing an LCFS Credit Price Floor

Proponents of cost containment mechanisms in cap and trade programs often advocate for a price floors to compliment the price cap. Whenever there is uncertainty regarding the value of LCFS credit prices, a price floor may be used to counteract a decrease in the expected value of permits which results from establishing a price cap on credit prices. To study how the ARB may enforce a price floor, consider again our equation for the market clearing LCFS credit price:

$$\lambda = \begin{cases} \frac{MC^r(q^r) - MC^c(q^c)}{\phi^c - \phi^r} & \text{if the policy binds} \\ 0 & \text{if the policy does not bind.} \end{cases}$$

LCFS credit prices can be low for a number of reasons. First, the policy may not bind in a given period so that prices are zero. In this case, increasing the LCFS standard is the most direct way to increase credit prices. In addition, any policy which increases the difference in marginal costs of the two fuels would also act to increase credit prices.

A potential policy would be to establish an inverse a multiplier which decreases the value of credits generated by low CI fuels. Our analysis would be equivalent to the analysis in the credit multiplier option with $\delta < 1$. In addition, the ARB could consider applying a multiplier to the deficits generated by conventional fuels. We recommend further analysis of these options. As shown in our analysis of the low CI credit multiplier option, the effect of the multiplier on market outcomes is not always clear and the mechanism could lead to adverse market outcomes.

A.4 Incentives to Innovate

An important feature of the LCFS is the incentive the program provides for innovation in new technologies. By instituting cost containment provision, the ARB will affect the industry's incentive to innovate. In this section, we study how the LCFS and cost containment provisions affect firms' incentive to reduce the carbon intensity of each fuel and explore how the incentive changes under different policies. In addition, we consider how various policies affect the mix of fuel sold in the state.

Incentives to Decrease Carbon Intensity Factors

A key dimension along which firms may innovate is through investing in technologies which decrease the carbon intensity factors of all fuels ϕ^i. Consider the two input case.[33] To solve for the incentive of firms in reducing ϕ^i for all fuels we appeal to the Envelope Theorem as in Holland et al. (2007), and take the derivative of the optimized Lagrangian from the maximization program in section B.1 with respect to the carbon intensity factor. The optimized Lagrangian is given by the following:

$$\mathcal{L} = p(q^{c*} + q^{r*}) - C^c(q^{c*}) - C^r(q^{r*}) + \lambda^* \left[(\phi^c - \sigma)q^{c*} + (\phi^r - \sigma)q^{r*}\right].$$

Stars denote the optimized values of each variable. Applying the envelope theorem, the incentive to reduce the carbon factor of each fuel is given by the following.

$$-\tfrac{\partial \mathcal{L}}{\partial \phi^i} = \lambda q^{i*} \quad i = c, r.$$

As we can see, the incentive to innovate is a function of both the LCFS credit price and the amount of fuel used in equilibrium. As either the LCFS credit price increases or the amount of fuel used by the industry increases, the incentive to invest in a technology which reduces ϕ^i increases as well. By capping the LCFS credit price, the ARB limits the incentive if expectations were that the LCFS credit price would be above the cap before the cap were instituted.

Consider now the effect of California's cap and trade law on incentives to innovate. Through a similar exercise as above, we can show the incentive to innovate is given by the following in the two input case:

$$-\frac{\partial \mathcal{L}}{\partial \phi^c} = (\lambda + \tau)q^{c*}$$

$$-\frac{\partial \mathcal{L}}{\partial \phi^r} = \lambda q^{r*}.$$

where τ is the permit price for cap and trade permits. As can be seen, beginning in 2015, the incentive to reduce the carbon intensity factor of conventional fossil fuels will increase while the incentive to reduce renewable fuel carbon factors may decrease as cap and trade permit prices increase.

Effect of Cost Containment on California's Fuel Mix

Another effect of a cap on LCFS credit prices is its potential to change the fuel mix of the industry. For this case, consider the model of multiple renewable inputs from Section A.2. Suppose there is a cap $\bar{p}$ on

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[33] The analysis extends easily to the multiple renewable input case.

LCFS credit prices. Consider input j and suppose the Lagrange multiplier for the non-negativity constraint is given by δ_j. The first order condition for the input is given by the following:

$$p = MC_j^r(q_j^r) + \bar{p}(\phi_j^r - \sigma) - \delta_j.$$

Suppose the industry does not use the input so $\delta_j > 0$. In this case, the following two conditions must hold:

$$\phi_j^r > \frac{p - MC_j^r(q_j^r = 0) + \delta_j}{\bar{p}} + \sigma$$

$$MC_j^r(q_j^r = 0) > p - \bar{p}(\phi_j^r - \sigma) + \delta_j.$$

Therefore, firms will not blend whenever the following two conditions hold:

$$\phi_j^r \geq \frac{p - MC_j^r}{\bar{p}} + \sigma$$

$$MC_j^r(q_j^r = 0) \geq p - \bar{p}(\phi_j^r - \sigma).$$

Thus, whenever the increased marginal costs associated with a fuel are not offset by the sale of LCFS credits generated by blending the fuel, the firm will not blend the fuel. Instituting a cap on LCFS credit prices may therefore change the mix of fuels sold on the market.

A.5 Interactions of the LCFS with California's Cap and Trade Law

Under California's cap and trade law, refineries are responsible for the emissions associated with their production during the first compliance period from 2013-2014. Beginning in the second compliance period in 2015, refiners' compliance will also include emissions associated with gasoline, natural gas, distillate fuel and liquefied petroleum gasoline combustion. Importantly, refiners will not be responsible for emissions associated with combustion from fuel derived from renewable sources.

Baseline LCFS and CAT model

We model the cap and trade program as a gasoline tax. So long as there is no uncertainty as to the cost of meeting the program and transaction costs to trading permits are minimal, it is a well known result that a properly chosen cap and trade program is equivalent to a gasoline tax (Tietenberg, 2006; Stavins, 1995). Suppose τ is the tax on gasoline emissions, where total emissions are given by $\phi^g q^g$ and consider the case where the cap and trade program is binding such that $\tau > 0$. The maximization program in this case is given by the followingL

$$\mathcal{L} = \max_{q^c, q^r} p(q^c + q^r) - \tau \phi^c q^c - C^c(q^c) - C^r(q^r) - \lambda \left[(\phi^c - \sigma) q^c + (\phi^r - \sigma) q^r \right].$$

The optimality conditions are given by the following:

$$\begin{aligned} q^c: &\quad p \leq MC^c(q^{c*}) + \delta(\phi^c - \sigma) + \tau\phi^c \\ q^r: &\quad p \leq MC^r(q^{r*}) + \delta(\phi^r - \sigma) \\ &\lambda \left[(\phi^c - \sigma) q^c + (\phi^r - \sigma) q^r \right] = 0. \end{aligned}$$

Using the optimality conditions for an interior solution, we can derive the following equation for the LCFS credit price:

$$\lambda = \frac{MC^r(q^{r*}) - MC^c(q^{c*}) - \tau\phi^c}{\phi^c - \phi^r}.$$

As can be seen, a binding cap and trade law will decrease the LCFS credit price. This occurs because cap and trade program acts reduces the difference between the marginal cost of the renewable and conventional fuel. Given that renewable fuel emissions are not covered under the cap, the cap and trade program makes renewable fuel inputs more attractive to refiners relative to conventional fuel, reducing the cost of the LCFS and hence LCFS credit prices.

Baseline LCFS, CAT, Cost Containment and Emissions

Suppose the ARB allow for firms to comply with the LCFS through an open credit window, or equivalently through paying a non-compliance penalty. As shown in section A.3, whenever firms purchase credits from the credit window, the LCFS credit price will have a hard cap. Compliance beyond the cap will involve firms blending the cheapest fuels on the margin and purchasing credits to maintain compliance. So long as the cost of renewable fuels remains higher than conventional liquid fuels, the most likely compliance scenario will involve firms using only conventional liquid fossil fuels.

Because all emissions associated with fossil fuels are covered under the state's cap and trade program, in addition to purchasing LCFS credits, firms must also purchase CAT permits to cover their compliance obligation. As a result, post 2015 all additional emissions that result from firms not complying with the LCFS will be covered under the state's cap and trade program. The only threat to emission levels exceeding the requirements under AB 32 would be blending of renewable fuels not covered under the cap beyond the LCFS price cap, which is unlikely.