WELFARE EFFECTS OF BIOFUEL POLICIES IN THE PRESENCE OF ENVIRONMENTAL EXTERNALITIES AND PRE-EXISTING DISTORTIONS

BY

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DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Agricultural and Consumer Economics
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2010

Urbana, Illinois

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Abstract

Policy intervention in the biofuel market has led to a significant increase in biofuel production and use in the past several years. However, the welfare effect of biofuel policies, specifically the ethanol tax credit for corn ethanol, ethanol import tariff and renewable fuel standard (RFS) mandate has not been adequately examined. Moreover, the environmental impact of these policies, and their impact on fuel taxation has not been sufficiently addressed in the literature. This dissertation examines the market and welfare effects of biofuel policies in the US, specifically those relating to corn and sugarcane ethanol, with the aim of determining the welfare implications of existing policies, and designing second-best optimal policies. In measuring welfare effects, changes in social surplus, as well as environmental externalities are taken into account. In addition, the interaction of fuel and biofuel policies with the broader fiscal system is also considered.

This dissertation consists of three papers. In the first paper, a stylized model of the US miles and fuel market, including ethanol trade is developed to quantify the market and welfare effects of biofuel policies in the US. In order to examine the effect of the ethanol tax credit and import tariff, several market scenarios are simulated. The market outcome with the two policies in place are compared to a non-intervention scenario, and an optimal baseline where Pigouvian taxes are levied on fuel and miles. Results show that the effect of the tax credit on social surplus is clearly negative, while the impact of the tariff depends on the ability of the US to influence ethanol prices in the world market. Numerical simulations show that the existing ethanol tax credit and import tariff increase miles externalities and GHG emissions and decrease social welfare by \$5.9 B relative to non-intervention and by \$235 B relative to the optimal scenario.

In the second paper, detailed production data on ethanol production costs in the US and Brazil are used together with a numerical model of US biofuel trade with Brazil to quantify the welfare effect of the US RFS mandate for traditional and advanced biofuel (excluding cellulosic and biomass biodiesel) under various scenarios on the currency exchange rate between the US dollar and Brazilian *reais*. Numerical results show that in 2015, the cost of the mandate is lower when the US currency is appreciated relative to the Brazilian currency, and when the excess supply elasticity of ethanol from Brazil is more elastic. Relative to a baseline without a mandate but with an ethanol subsidy and import tariff in place, GHG emissions decrease and the welfare effect of the mandate ranges from -\$23 to +\$5 Billion dollars as the exchange rate varies from US\$1 = R\$1.81 to US\$1 = R\$3.11.

The third paper analyzes the impact of biofuel policies and biofuel use on the second-best optimal carbon tax for fuels in the presence of a labor tax and a biofuel subsidy. Findings show that when biofuel is part of the fuel mix, the carbon tax has a commodity price effect which arises from tax-induced changes in land rent. The commodity price effect could exacerbate or attenuate the tax interaction effect caused by higher fuel prices, depending on the elasticity of substitution between gasoline and biofuel, the price elasticity of miles demand, and the relative emissions intensity of gasoline and biofuel. Numerical results show that the commodity price effect affects the value of the second-best optimal carbon tax, and that the effect is greater if the elasticity of substitution between gasoline and ethanol is higher, miles demand is more price inelastic, and the emissions intensity of biofuel is lower relative to gasoline. In addition, the existence of a fixed biofuel subsidy lead to a greater divergence between the value of the second-best optimal carbon tax with or without biofuels. A carbon tax policy decreases GHG emissions and increases welfare, in contrast to a biofuel subsidy, which also decreases GHG emissions but at a net welfare loss.

Acknowledgements

I would like to thank my adviser, Professor Madhu Khanna for her guidance and support during the preparation and writing of this dissertation. I also thank my commitee members: Robert Thompson, Don Fullerton and Amy Ando for their helpful advice and suggestions. I'm grateful to my friends in TCBC for prayers and encouragement and my friends at the UIUC campus, especially Xiang, Shravan, Jun, Moni, Liza, Xiaoguang, Raffy and Mery for their companionship and support.

I'm very grateful to my husband Neal, my parents Rodel and Haydee, my brothers Gideon and Jonathan, and my cousin Grace for the love and encouragement that they have given me throughout the years. Most importantly, I thank the Lord for the life He has given me, and the goodness and faithfulness that He has shown.

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Chapter 1: Introduction

The introduction of a new technology and policies that accompany its widespread adoption creates many questions that could be addressed by economic analysis. What are the market impacts of this new technology? What are the non-market impacts? Who gains and who loses? What is the optimal set of policies that should be implemented to make sure that social welfare is maximized? Should this new technology even be adopted? The use of plant material to produce fuel is an old technology dating back to the early 1900s, but it was not until the later part of this decade that biofuel use and its concomitant policies started to have significant impact on two important sectors in the US economy, namely energy and agriculture. The rapid growth in biofuel demand is mainly driven by the renewable fuel standard (RFS) mandate, although the ethanol blender subsidy and import tariff also help support the domestic biofuel industry. The push to increase the share of biofuel in total fuel demand is rationalized by the desire to decrease GHG emissions from the transportation sector, improve energy security, and support the agricultural sector. However, the policies used to stimulate demand and support production cause deadweight losses in the economy, and it is not certain whether the perceived benefits from the use of biofuel justify these policy interventions. Less than 5 years ago, biofuel accounted for less than 3% of total fuel use in the US. Today the share of biofuel is over 8% and by 2030, biofuel could account for as much as 30% of total blended fuel. As the share of biofuel in total fuel use increases, the impact of biofuel policies could be even greater. Thus, it is important to provide a clear picture of what the effects of these policies are, and provide policy alternatives that could also achieve the stated goals of biofuel policy.

The broad objective of this dissertation is to examine market impacts of biofuel policies in the US, with the aim of determining the welfare implications of existing policies, and designing optimal policies. The contribution of this work relative to the existing literature is that it examines the welfare impact of biofuel policy using a broader criteria which goes beyond market impacts to include environmental externalities such as GHG emissions and miles externalities, and interaction with the broader fiscal system.

Existing literature on biofuel policy has focused on its welfare impacts, in terms of social surplus without considering environmental externalities. However, given that one of the objectives of biofuel policy is to reduce GHG emissions in the transportation sector, it is also important to determine the impact of biofuel policies on greenhouse gas (GHG) emissions and miles externalities in general. Elobeid and Tokgoz (2008) and de Gorter and Just (2007) examine the market and welfare effects of an ethanol subsidy and an import tariff on fuel prices and quantities and find that these two policies reduce social surplus. A few studies have looked at the welfare effect of biofuel policies while incorporating the cost of environmental externalities. Gallagher et al. (2003a) and Ando, Khanna, and Taheripour (2010) examine the welfare effect on the US RFS standard, considering social surplus as well as GHG and miles externalities. They find that the RFS mandate decreases GHG emissions, but at a net social welfare loss. Both Gallagher et al. (2003a) and Ando, Khanna, and Taheripour (2010) use a closed economy framework to examine the market and welfare impact of the US RFS. In contrast, I use a open economy framework that considers US biofuel trade with Brazil to analyze the impacts of the corn ethanol tax credit and import tariff, and RFS mandate on traditional and advanced (sugarcane) biofuel. Since sugarcane ethanol has lower GHG emissions than corn ethanol, the importation of ethanol from Brazil could affect the level of GHG emissions from fuel use. Moreover, since the production costs are different in the two countries, the level of imports and the cost at which these imports can be obtained is important in determining the welfare impact of US biofuel policies.

In addition to considering welfare effects in terms of social surplus and environmental externalities, this dissertation also examines the impact of biofuel use and policies that promote greater biofuel production on optimal fuel taxes. Biofuel constitutes only a fraction of total fuel use in the US. Thus, biofuel policy has to be examined in the context of broader fuel and fiscal policy. Several studies, notably Parry and Small (2005a) and West and Williams (2007) focus on determining the second-best optimal tax rate for gasoline. The analysis on optimal fuel taxes is extended to consider the implications of the presence of biofuel and biofuel policies on the welfare effect of fuel taxes, and the second-best optimal carbon tax rate. In addition, I also examine the potential of a biofuel subsidy to reduce emissions, and determine the welfare cost at which these reductions can be achieved.

This work relies on stylized models of the economy to obtain analytical solutions that build intuition on the effect of biofuel policies on the demand for miles and fuels. Analytical solutions are also used to inform the numerical simulation models used in obtaining numerical results on the market impact of biofuel policies. Another contribution of this work is that it identifies key parameters that drive numerical results, namely, the elasticity of substitution between gasoline and biofuel, the price elasticity of miles demand, and the price elasticity of gasoline demand.

This dissertation is divided into three essays, each addressing a particular set of research questions. The rest of this chapter gives a brief introduction to the next three chapters.

Chapter 2 of this dissertation examines the environmental and trade policy instruments that maximizes social welfare, in terms of social surplus and GHG and miles externalities. In this paper, a stylized model of fuel markets in an open economy is used to derive the optimal mix of trade and environmental policy instruments for biofuel and gasoline that maximizes social surplus and internalizes externalities from miles and GHG emissions. This optimal scenario is then used as a benchmark to compare existing and alternative biofuel policies including the import tariff and the tax credit for corn ethanol. Using an optimal scenario as the benchmark, rather than non-intervention provides a more accurate measure of the potential for welfare improvement, relative to the status quo policies.

In Chapter 3, the policy analysis shifts to the RFS mandate. Because the mandate implicitly requires some importation of ethanol from Brazil, especially in the short run, the availability of ethanol from Brazil and the cost at which it can be purchased becomes an important consideration. Thus, in Chapter 3, attention is given to understanding the ethanol production process in the US and Brazil, and identifying the factors that affect the cost competitiveness of both types of ethanol. The implications of the cost of obtaining biofuel from Brazil on the welfare cost of the mandate is then analyzed. The contribution of Chapter 3 is two-fold: first, the effect of the cost of importing ethanol on the welfare effect of the mandate is examined. Second, the study provides detailed estimates of the costs of ethanol production in the two countries which are lacking in the previous literature.

Chapters 2 and 3 provide policy analyses in a partial equilibrium framework, which is suitable for analyzing policies in markets that are small and have little impact on the rest of the economy. Chapter 4 expands the scope of the analysis on the effects of biofuel use and biofuel policies to consider their interaction with the broader fiscal tax system. In particular, this chapter examines the impact of the presence of biofuel in the fuel mix on the second-best carbon tax rate for fuels. Since biofuel production is land intensive, a carbon tax on fuels could affect land rent, which in turn could affect commodity prices. Changes in commodity prices could add to the labor market impacts of a carbon tax, and affect the rate of the second-best fuel tax. I use a stylized general equilibrium model to examine whether a carbon based tax for fuels could be used to lower an existing labor tax, and whether this revenue-neutral tax swap can yield welfare gains while also internalizing externalities from fuel use. By linking policies in the fuel market to agricultural markets, this chapter explores how the presence of biofuel could affect the likelihood of obtaining welfare gains through the imposition of a revenue-neutral carbon tax for fuels.

Chapter 2: Welfare Effects of Biofuel Policies in the Presence of Environmental Externalities

Ethanol has been gaining attention as a renewable fuel due to concerns about energy security, climate change and high oil prices. Energy policy in the US has supported production of domestic ethanol through several policies including mandates on the use of renewable fuel, a subsidy [1] for blending ethanol with gasoline and a tariff on ethanol imports, which are principally from Brazil. While these policies encourage domestic production of ethanol and displacement of gasoline, the economic costs of these policies and the extent to which they reduce greenhouse gas (GHG) emissions is yet to be examined. Ethanol in the US is primarily produced from corn while in Brazil it is produced from sugarcane. Corn ethanol reduces GHG emissions relative to gasoline (Farrell et al. 2006a; Wang, Wu, and Huo 2007) but it is more carbon intensive to produce than sugarcane ethanol in Brazil (Macedo, Seabra, and Silva 2008b). An import tariff on sugarcane ethanol could be justified if it improves the terms of trade for the US by lowering the world price of ethanol but would need to be balanced with the smaller carbon footprint of sugarcane ethanol relative to corn ethanol and gasoline.

The purpose of this paper is to examine the social welfare maximizing environmental and trade policy instruments, and their implications for the gasoline and biofuel mix in the US, while incorporating the environmental externalities associated with each of these fuel types and the potential market power of the US in the world ethanol market. The welfare and GHG effects of alternative and existing

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[1] This refers to the ethanol blender tax credit.

biofuel policies is then compared to this benchmark. I extend the closed economy framework developed in Khanna, Ando, and Taheripour (2008) to analyze the welfare effect of biofuel policy in an open economy which has market power in ethanol trade. This framework is based on the premise that the demand for gasoline and biofuel is derived from the demand for vehicle miles traveled (VMT). Moreover, while VMT provides utility to consumers, it also generates at least two types of negative externalities, congestion on the roads and GHG emissions. I incorporate the differential GHG mitigation potential of the two types of ethanol (from sugarcane and corn) relative to gasoline based on life-cycle analysis of alternative fuels.

Several recent papers have examined the welfare effects of existing domestic biofuel policies in the US. Gallagher et al. (2003b) analyze the implications of a national ban on the use of Methyl Tertiary Butyl Ether (MTBE) as a fuel additive and the imposition of a Renewable Fuel Standard of 5 billion gallons of ethanol on fuel prices, consumption and welfare [2]. They show that the high cost of the blended fuel relative to baseline levels reduces total fuel consumption, emissions of air pollutants and social welfare (without including environmental benefits). Gardner (2007) examines the effect of an ethanol subsidy which raises demand for corn on corn prices and corn growers' surplus, assuming a fixed demand for ethanol. He compares its welfare effects to those of a deficiency payment policy that directly subsidizes corn. He estimates that the environmental benefits of ethanol would need to be valued at least at \$0.23 per gallon to offset the deadweight losses of the ethanol subsidy. de Gorter and Just (2008) extend Gardner's analysis by linking the demand for ethanol to the price

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[2] "Fuel" refers to gasoline and ethanol, while "Fuel price" refers to the price of blended fuel consisting of gasoline and ethanol.

of gasoline, assuming that gasoline and ethanol are perfect substitutes and analyze the welfare effects of an ethanol tax credit in the presence of a farm subsidy. They find that the deadweight losses associated with the ethanol tax credit more than offset the welfare gains associated with the reduced need for price contingent farm subsidies. In contrast, Rajagopal et al. (2008) find that the ethanol subsidy led to an overall welfare gain for the US mainly due to benefits to consumers because of decreased fuel prices.

These papers disregard the potential for ethanol imports or treat them as exogenously given. In contrast, de Gorter and Just (2007) examine the effects of an ethanol mandate and an import tariff on fuel prices and quantities. Elobeid and Tokgoz (2008) analyze the effects of trade liberalization and removal of the ethanol tax credit for fuel prices and quantities and for producer surplus in the ethanol and corn markets in US and Brazil. These papers show that trade liberalization will increase imports of ethanol from Brazil and improve social welfare.

Existing papers examining the welfare impacts of biofuel policies have typically ignored their environmental impacts. A few exceptions include Parry and Small (2005b) who estimate the optimal gasoline tax for the US using a general equilibrium framework that considers the externality cost of gasoline consumption due to GHG emissions, pollution, congestion and accidents and a Ramsey tax that balances the government budget. They find that the optimal gasoline tax for the US is \$1.01 per gallon which is more than double the existing tax of \$0.38. Vedenov and Wetzstein (2008) use a similar framework to find the optimal subsidy for ethanol while incorporating environmental and fuel security externalities, and effects on government spending. They find that it is optimal to subsidize ethanol at a rate of $0.22 per gallon, provided that the subsidy is accompanied by an increase in the gasoline tax. Khanna, Ando, and Taheripour (2008) also examine the welfare effects of an ethanol subsidy, and find that the current ethanol subsidy leads to significant welfare losses with negligible reductions in GHG emissions. These papers have focused on a closed economy and do not consider the potential to import biofuels that are more carbon friendly than domestically available fuel sources.

This paper differs from much of the existing literature analyzing the welfare impacts of ethanol policy in several important aspects. Current studies have assumed that ethanol and gasoline are either perfect substitutes (de Gorter and Just 2007) or strong complements (Vedenov and Wetzstein 2008; Elobeid and Tokgoz 2008). With a small share of flex fuel vehicles in the total vehicle fleet, the assumption of perfect substitutability is questionable. Moreover, while current blends of ethanol and gasoline are constrained to have either 0%, or 10%, or 85% ethanol for an individual vehicle, there is flexibility in the share of ethanol in the aggregate fuel blend consumed, implying that the assumption of perfect complementarity is restrictive. The share of ethanol in aggregate fuel use in 2008 was about 7% (Department of Energy 2009; RFA 2009b). I therefore assume that ethanol and gasoline are imperfect substitutes in the production of miles and specify a constant elasticity of substitution production function for miles. This function allows for flexibility in the degree of substitutability between gasoline and ethanol and in their shares in the resulting fuel blend used in vehicles. The sensitivity of results to varying degrees of substitutability between ethanol and gasoline is also examined in this paper.

Secondly, a demand for miles is explicitly defined to incorporate the externalities associated with vehicle miles traveled and determine the optimal taxes on miles and fuel. I use this as a benchmark to measure welfare effects of deviating from this optimal state. In previous work (de Gorter and Just 2007; Elobeid and Tokgoz 2008), the subsidy and tariff scenario is compared to non-intervention, which is sub-optimal in the presence of externalities.

Thirdly, I consider the effect of the assumed trading relationship between the US and Brazil on the welfare effect of a tariff. The US is the largest buyer of Brazilian exports. In 2005, over 50% of ethanol exports from Brazil were destined for the US. This figure decreased to 30% in 2006, but is still significant given that the share of the next largest buyer from Brazil is only 11% (FNP 2008). The trade data above suggests that the US could exert considerable influence on the world market price for ethanol. Lee and Sumner (2010) estimate the elasticity of the excess supply of ethanol from Brazil facing the US and show that it ranges between 2.5-3 which is consistent with the assumption of US market power in the world ethanol market. I examine the impact of this assumption on the welfare impacts of the import tariff.

Finally, I differentiate ethanol from Brazil and the US based on their environmental impacts and examine the interaction between the carbon intensity of alternative fuels and optimal tariff rate.

Existing studies differ substantially in their assumption about the own price elasticity of gasoline. Some of the studies cited previously assume that gasoline supply is perfectly elastic (de Gorter and Just 2007) or has a very high price elasticity of 10 (Gallagher et al. 2003b). In contrast, Austin and Dinan (2005) assume a value of 2 and Rajagopal et al. (2008) assume a value of 0.25. The appropriate value will depend on whether one is considering a short run or a long run effect. Given the range of values in the literature, I explore the sensitivity of policy outcomes to different assumptions about the supply elasticity of gasoline and the elasticity of substitution between ethanol and gasoline. The analysis in this paper focuses on the effects of two existing policies, namely the ethanol tax credit and the import tariff using data and calibrated parameters for 2008. The ethanol mandate of nine billion gallons in 2008 was not binding and consistent with the observed ethanol production levels, numerical results show production levels above the mandated level. The analysis here also focuses only on analyzing welfare effects in the fuel market. While I incorporate an upward sloping supply curve of corn which influences the marginal costs of corn ethanol production, I do not examine the welfare effects in the food market.

The paper proceeds as follows: The theoretical framework is presented in section 2.1. Section 2.2 discusses data and parameters used to calibrate the numerical model. Section 2.3 presents results of the numerical simulation. Section 2.4 discusses the analysis performed to test the sensitivity of results to parameter assumptions, and section 2.5 concludes.

2.1 Theoretical Framework

In this section, optimal taxes for gasoline, corn ethanol and miles, and the optimal tariff for sugarcane ethanol are derived [3]. Optimal taxes refer to taxes that internalize externalities associated with miles consumption. I discuss the determinants of trade

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[3] These "optimal" taxes are necessarily second-best because other distortions exist in the economy.

policy and the effect of deviations from optimal taxation on welfare and miles and fuel consumption. I assume that consumers obtain utility from the consumption of miles and a private good. Miles(m) are produced using gasoline(g), corn ethanol(c) and sugarcane ethanol(s). Ethanol and gasoline are imperfect substitutes while corn ethanol and sugarcane ethanol are perfect substitutes in the production of miles. The consumption of miles causes two types of externalities, air pollution, accidents and congestion that are directly related to miles and GHG emissions that are related to the type of fuel consumed. The cost of direct miles externalities and GHG emissions are given by ζ and ϕ respectively. Aggregate emissions are given by $E(g, c, s)$. The cost functions for gasoline and corn are $C^g(g)$ and $C^c(c, P^F)$ respectively. The cost of corn ethanol is a function of the quantity of ethanol produced and the price of corn feedstock (P^F). The world price of sugarcane ethanol is given by P^s. In the maximization problem below, the US is assumed to be a large country in ethanol trade and so that it can influence the world price. In fact, it can set the world price by imposing some tariff on imported ethanol. Thus, P^s is endogenous and the level of imports, s (equal to the excess supply) is an upward sloping functions of P^s. This assumption does not limit the analysis here to consider price taking behavior. If the world ethanol price were given, the level of imports will no longer be a function of P^s. In this case, the marginal utility from imported ethanol is simply equated to its price and externality cost.

The social planner chooses g, c and P^s to maximize:

$$\begin{aligned}\max_{g,c,P^s} u(m(g,c,s(P^s))) - \zeta m(g,c,s(P^s)) - \phi E(g,c,s(P^s)) \\ -C^g(g) - C^c(c,P^F) - P^s s(P^s)\end{aligned} \tag{1}$$

The FOCs are:

$$(u_m - \zeta)m_g - \phi E_g - C^g_g = 0 \tag{2}$$

$$(u_m - \zeta)m_c - \phi E_c - C^c_c = 0 \tag{3}$$

$$(u_m - \zeta)m_s \frac{\partial s}{\partial P^s} - \phi E_s \frac{\partial s}{\partial P^s} - s(P^s) - P^s \frac{\partial s}{\partial P^s} = 0 \tag{4}$$

in which subscripts denote partial derivatives. The utility from miles consumption net of the per mile externality cost is $u_m - \zeta$. The marginal product of each fuel i in miles production is denoted by m_i $(i = g, c, s)$ while E_i is the marginal emissions (emissions intensity) from fuel i.

The FOCs imply that it is optimal to equate marginal utility of each fuel type to its marginal cost of production plus the externality cost of emissions. In a market economy, consumers will not consider the externality cost of miles and fuel use in making consumption decisions. To induce optimal choice, conditions (2) and (3) show that a tax of $\tau^O_g = \phi E_g$ and $\tau^O_c = \phi E_c$ should be levied on gasoline and corn ethanol respectively. Moreover, there should be a miles tax of $\tau^O_m = \zeta$ per mile. Since $E_g > E_c$ the per-gallon tax on gasoline is greater than the tax on corn ethanol.

To determine the tax and tariff on imported ethanol, rewrite (4) as:

$$(u_m - \zeta)m_s - \phi E_s - \frac{s(P^s)}{\frac{\partial s}{\partial P^s}} = P^s \tag{5}$$

$$(u_m - \zeta)m_s = P^s + \phi E_s + \frac{s(P^s)}{\frac{\partial s}{\partial P^s}} \tag{6}$$

The lefthand side of equation (6) is the marginal utility from sugarcane ethanol which must be equated to the world price of ethanol plus the marginal externality cost. Since the first term on the righthand side is the world price (P^s), the optimal tax-cum-tariff for sugarcane ethanol (τ_s^O) is $\phi E_s + \frac{s(P^s)}{\frac{\partial s}{\partial P^s}}$.

Dividing τ_s^O by P^s gives the percent tax-cum-tariff

$$\frac{\tau_s^O}{P^s} = \frac{\phi E_s}{P^s} + \frac{1}{\eta^{ES}} \tag{7}$$

where $\eta^{ES} = \frac{\partial s}{\partial P^s}\frac{P^s}{s(P^s)}$ denotes the price elasticity of the excess supply function of sugarcane ethanol. Equation (7) shows that the percent tax-cum-tariff on sugarcane ethanol should be equal to its GHG externality cost divided by its price, plus the inverse of the price elasticity of the excess supply function. The latter term is the familiar optimal tariff for large trading countries (see Dixit 1985). As the exporting country's supply curve becomes more inelastic, the optimal tariff increases. This is reasonable because a steeper excess supply curve leads to a larger decrease in the price of imported ethanol with the imposition of a tariff. Equation (7) also shows that the tax-cum-tariff is postively related to ϕ and E_s. The larger the marginal social cost of GHG emissions, and the more GHG intensive sugarcane ethanol is, the higher the magnitude of the tax is.

To see the relationship of the tax-cum-tariff on sugarcane ethanol with the tax on corn ethanol, define T as the ratio of τ_c^O and τ_s^O.

$$T = \frac{\frac{\phi E_c}{P^s}}{\frac{1}{\eta^{ES}} + \frac{\phi E_s}{P^s}} \tag{8}$$

The optimality conditions imply that if $\eta^{ES} \cong \infty$, then

$$\begin{aligned} T \geq 1 \quad if \quad E_c \geq E_s \\ T < 1 \qquad\quad E_c < E_s \end{aligned} \tag{9}$$

Since corn ethanol is more emissions intensive than sugarcane ethanol, the tax on corn ethanol should be greater than the tax-cum-tariff on sugarcane ethanol. However, if η^{ES} is small, then the tax-cum-tariff on sugarcane ethanol could exceed the tax on corn ethanol even if $E_c > E_s$. To make this more precise, re-write $E_s = E_c - (E_c - E_s)$. If $\tau_c^O = \phi E_c$, T becomes:

$$T = \frac{\frac{\tau_c^O}{P^s}}{\frac{1}{\eta^{ES}} + \frac{\tau_c^O - \phi(E_c - E_s)}{P^s}} \tag{10}$$

implying that the difference between the optimal tax on corn ethanol and the optimal tax-cum-tariff on sugarcane ethanol depends on the relative sizes of η^{ES} and the difference between the disutility caused by corn and sugarcane ethanol. If $\frac{1}{\eta^{ES}} > \frac{\phi(E_c - E_s)}{P^s}$, the tax-cum-tariff on sugarcane ethanol will be greater than the tax on corn ethanol and vice versa.

2.1.1 Non-Optimal Policies

I now consider departures from the optimal condition, specifically a tax on fuel, non-intervention (no tax, subsidy or tariff), an ethanol subsidy, an ethanol tariff, and an ethanol subsidy and tariff.

Fuel Tax

In comparison to inputs like gasoline and ethanol, miles are difficult to tax since it is very costly to monitor individual miles consumption. From (2) to (4), if $\tau_m = 0$ instead of ζ, the marginal cost of each fuel will be equated to a value that is higher than its marginal utility. This will increase use of g, c, and s and will lead to a higher consumption of miles. Welfare will decrease relative to the optimal since the level of consumption of all three fuel types and miles will be higher than what is optimal. The increased consumption of fuel, as well as higher miles consumption will lead to higher GHG emissions and miles externalities compared to the optimal.

Non-Intervention

The non-intervention scenario is the case with $\tau_m^O = \tau_g^O = \tau_c^O = \tau_s^O = 0$. From (2) to (4), g,c,s and m will be higher than in the previous case with a fuel tax only since removing the tax on miles as well as inputs will lead to a larger gap between the marginal cost and marginal utility for fuel and miles. Since miles and fuel use are expected to be higher than with a fuel tax alone, GHG and miles extenalities are expected to be higher as well. A non-intervention policy is, therefore, likely to lead to lower welfare than either the fuel tax or the optimal policy because it fails to take into account the external cost of miles and fuel consumption. Furthermore, it fails to exploit potential gains from better terms of trade in ethanol.

Subsidy on Ethanol

Suppose that there is no tax on miles or fuel. Instead the government provides a subsidy of σ per gallon of ethanol whether it is domestically produced or imported. With a subsidy on ethanol, consumers will consume corn ethanol until its marginal utility is equal to $C_c^c - \sigma$ instead of $C_c^c + \tau_c^0$. Similarly, sugarcane ethanol will be consumed until its marginal utility is equated to $P^s - \kappa$, where κ is some number smaller than σ. The subsidy shifts consumption from gasoline to ethanol of both types, although relative to the optimal level, the share of corn ethanol will be greater than sugarcane ethanol.

I illustrate the deadweight loss associated with policy intervention, starting with the effect of a subsidy which is shown in Figure 1. To keep the discussion tractable, the non-intervention is used as the baseline, although it should be clear from previous discussion that non-intervention yields lower welfare than the optimal. Welfare loss from externalities, as well as welfare changes in the gasoline and miles markets are excluded in the graphical analysis. A subsidy benefits consumers through decreased prices and benefits ethanol producers by decreasing the marginal cost of ethanol production. However, this is at the expense of government outlays. In Figure 1, the domestic ethanol market is on the left panel and ethanol trade with Brazil (representing all foreign production) is on the right panel. I assume that world excess demand for ethanol is the excess demand of the US. The excess demand curve is expected to be fairly flat because the share of imported ethanol in domestic consumption is small (Lee and Sumner 2010). In the non intervention scenario, ethanol price in the domestic and world market is P_W^0. Domestic supply is S^0, demand is D^0 and imports are $M^0 = D^0 - S^0$. Suppose the government provides a subsidy of σ per gallon of ethanol consumed. This shifts the domestic demand curve of ethanol by σ to D_E^σ, which increases the domestic producer price to P_σ^S and decreases the consumer price to $P_\sigma^D = P_\sigma^S - \sigma$. As a result, domestic production and demand increases to S_σ and D_σ respectively. The excess demand curve also shifts to $ED_{(\sigma)}^{US}$ which increases the price received by importers to P_σ^S and increases imports to M_σ. The vertical shift of the excess demand curve is less than σ because the increase in the producer price of ethanol induces an increase in domestic production. Because the subsidy increases the producer price in both the domestic and world markets, domestic and foreign producers both benefit from the subsidy. The welfare effect of a subsidy is clearly negative. Consumers gain area $(e + f + g + h + i)$ and producers gain area a. However, the government incurs a cost of area $(a + b + c + d + e + f + g + h + i + j)$ to subsidize all ethanol consumption leading to a net welfare loss of $(b + c + d + j)$. Area b is the deadweight loss due to the distortion caused by the increase in domestic production at a marginal cost that is higher than the world price P_W^0. Area $(c + d)$ is the deadweight loss due to the indirect subsidization of imported ethanol and area j is the loss in social welfare due to the subsidization of consumption at quantities where the marginal utility is less than the world price. The subsidy decreases the price difference between ethanol and gasoline, which induces substitution of ethanol for gasoline. Since ethanol is less GHG intensive than gasoline, this substitution of ethanol for gasoline could reduce carbon emissions. However the subsidy also lowers fuel prices which could lead to higher miles consumption, thereby increasing air pollution, congestion and accidents and also GHG emissions through higher fuel consumption. Thus, the net effect on externalities is unclear since disutility from increased consumption of miles may or may not offset benefits from reduced carbon emissions (as in Khanna, Ando, and Taheripour (2008), Vedenov and Wetzstein (2008)).

Tariff

A tariff by itself taxes sugarcane ethanol without taxing miles and other fuel inputs. Such a policy clearly results in higher g and c, higher miles and thus greater externality costs. This policy would lead to lower welfare than the socially optimal policy. Equations (4) to (7) show that if other fuels are taxed optimally, the optimal tax-cum-tariff depends on the supply elasticity of the exporting country as well as the externality cost of sugarcane ethanol. If externalities are ignored (i.e. $\tau_g^O = \tau_c^O = \tau_m^O = 0$) and the excess supply elasticity is perfectly elastic (the US is a price taker) the optimal tariff is zero. However, if the US faces an upward sloping supply curve and can influence the world price, (7) reduces to $\tau_s^O = \frac{P^s}{\eta^{ES}}$.

If a country has market power and the tariff rate is not set at the optimal level, then the welfare effects relative to non-intervention become ambiguous even in the absence of externalities as shown in Figure 2 and discussed below. The tariff drives a wedge between the excess supply curve of Brazil (ES^B) and the excess demand curve of the US (ED^{US}). Since the US is assumed to be the only buyer in the ethanol market it faces an upward sloping excess supply curve from Brazil. The tariff lowers the world price of ethanol to P'_W and raises domestic price of ethanol in the US to P_t. Domestic supply increases to S_t but imports (M_t) and overall (D_t) demand decrease. The welfare effect of this tariff is ambiguous since the tariff lowers the world price of ethanol. The improvement in terms of trade for the US creates welfare gains that offset some of the loss in welfare caused by the tariff induced increase in domestic price and loss in domestic consumer surplus. Consumers lose area $(a+b+c+d)$ due to the price increase while producers gain area a. The government gets tax revenues equal to $(c+e)$ which means that net welfare is positive if $e-b-d>0$ and negative otherwise.

The tariff biases consumption against imported sugarcane ethanol in favor of domestic corn ethanol and gasoline which are both more carbon intensive. Furthermore, the tariff increases overall ethanol price which leads to more gasoline consumption. These two effects increase GHG emissions relative to the optimal level as well as relative to other policy alternatives. Since a tariff could increase overall fuel price it could also lead to less miles consumption and, therefore, less externalities associated with miles. Thus, the net external impact of a tariff is ambigous since it is not clear whether benefits from reduced direct miles exernalities will offset disutility from increased GHG emissions.

To summarize, a tariff can be welfare improving relative to non-intervention if the US has market power and there are no externalities. However, in the presence of externalities, a tariff will not necessarily be welfare improving relative to non-intervention even if there is market power. The tariff will result in better terms of trade and lower miles but possibly higher emissions than under non-intervention because it causes a substitution away from the less carbon intensive sugarcane ethanol to the more carbon intensive corn ethanol and gasoline. Thus, the effect of a tariff on environmental quality and welfare is ambiguous.

Subsidy and Tariff

Current US policy gives a subsidy in the form of a tax credit for blending ethanol with gasoline regardless of whether the ethanol is produced domestically or imported and imposes a tariff to more than offset the subsidy and prevent foreign producers from benefitting from the subsidy. This policy creates incentives for a much larger increase in corn ethanol production and in the welfare of domestic ethanol producers than the other policy alternatives considered above.

In the absence of externalities, the subsidy and tariff policy creates deadweight losses relative to non-intervention if the US is a price taker. However, if the US has market power, it is not clear whether subsidy and tariff or non-intervention yields greater welfare. In Figure 3, with both a tariff and a subsidy in place a wedge equal to the tariff exists between ES^B and $ED^{US}_{(\sigma)}$. This means that domestic and foreign producers receive a price of $P^S_{\sigma,t}$ which is higher than the initial world price, P^0_W. However, since Brazilian producers have to pay the tariff, they end up receiving only $P^{'}_w$. Consumers pay $P^S_{\sigma,t} - \sigma$ or $P^D_{\sigma,t}$. Depending on the magnitude of the tariff and subsidy the resulting demand price in the US could be higher or lower than the non intervention price. As shown, $P^D_{\sigma,t}$ is lower than P^0_W. Compared to the non intervention scenario, the increase in producer price leads to an increase in domestic ethanol production ($S_{\sigma,t}$) while the decrease in consumer price increases ethanol demand ($D_{\sigma,t}$). Because of the tariff, imports are reduced to $M_{\sigma,t}$. As in the case where only a tariff is in place, the welfare effect of a tariff and a subsidy is ambiguous. Consumers gain $(g+h+i+j+k)$ and producers gain $(a+b)$ from the price change while the government spends $(a+b+c+d+e+f+g+h+i+j+k+l)$ on subsidies and gets a tariff revenue of $(e+f+j+k+l+m+n)$. The net social surplus is positive if $(j+k+l+m+n)-(d+c)>0$ and negative otherwise.

In the case where the non intervention price is lower than the domestic price with subsidy and tariff, this ambiguity in welfare effect remains, although as a result of the subsidy and tariff, consumers will lose from the price increase and producers of domestic ethanol will have greater gains in producer surplus.

The subsidy and tariff policy induces a substition towards corn ethanol away from gasoline and sugarcane ethanol. The net impact on GHG emissions is, therefore, ambiguous because gasoline is more carbon intensive whereas sugarcane ethanol is less carbon intensive than corn ethanol. The effect on miles and miles externalities is also ambiguous since ethanol (and hence fuel) price could either increase or decrease. The subsidy would decrease ethanol prices but the presence of a tariff would mitigate the drop in prices. Thus, the net external cost of the subsidy and tariff policy is ambigous relative to the non-intervention case. Since the subsidy and tariff policy differs considerably from the optimal policy based on the FOCs, the resulting miles and fuel consumption levels are unlikely to replicate those that are socially optimal. As a result, a subsidy and a tariff will decrease welfare and increase environmental externalities relative to the optimal level.

Without considering externalities, the subsidy and tariff policy is likely to be welfare superior to a subsidy-only policy if the US has market power (as shown on Figure 3) since the presence of a tariff could provide terms and trade benefits. If the US is a price taker in the world market, this policy is welfare inferior to a subidy-only policy because the tariff creates additional deadweight losses. However, regardless of whether the US is a price taker or has market power, it is still uncertain whether a subsidy with a tariff is preferred to other policies if externality effects are considered.

I now develop a numerical simulation model to operationalize the framework developed above and quantify the effects of an optimal policy; a tax on fuel; non intervention; a tariff on imported ethanol; a subsidy by itself and a subsidy with a tariff on miles and fuel markets.

2.2 Data and Parameters

I parameterize the numerical model by assuming a homogenous of degree one, constant elasticiy of substitution production function for miles. The elasticity of substitution between ethanol and gasoline in the miles production function has not been estimated by any study and values used in the literature vary from 0 to infinity with the GTAP model assuming a value of 4 (Hertel, Tyner, and Birur 2009). I assume that the elasticity of subsitution is 2 and examine sensitivity of results to this assumption. The scale and share parameters are determined by calibrating the model to 2008 market data.

The miles supply function and the demands for domestic ethanol and refined gasoline are derived within the model. Imported ethanol demand is defined as the excess demand in the domestic market. The supply curves for gasoline, corn ethanol and sugarcane ethanol are assumed to have constant elasticity forms and are parameterized based on estimates available in the recent literature in this area and market data. The corn ethanol supply curve is assumed to be a function of its own price and the price of corn. The price of corn is determined endogenously in the model based on its supply and demand curves which also have a constant elasticity form. I assume that corn supply elasticity is 0.25 based on Lee and Helmberger (1985) and corn demand elasticity is -0.17 (USDA 2009b).

For the ethanol supply elasticity, Gallagher (2003) reported a value of 1.5. Gasoline supply elasticity is assumed to be 0.25 based on the Department of Energy's estimates of gasoline demand and refining capacity (Department of Energy 2009). For the supply elasticity of imported ethanol, I use 2.7 as reported by Lee and Sumner (2010). The demand elasticity for miles is -0.40 (Parry and Small, 2005; Vedenov and Wetzstein,2007).

I use 2008 market data to calibrate the model (see Table 2.1). The price of corn is \$3.65 per bushel which is the weighted average farm price reported by the USDA (2009b). Ethanol and gasoline prices are \$2.47 and \$2.57 per gallon (Omaha wholesale free-on-board average rack price, (NEB 2009)). A markup of \$0.30 per gallon and taxes of \$0.38 per gallon are added to get the retail prices of ethanol and gasoline. In 2008, 13.7 B bushels of corn were produced, 27% (3.7 B bushels) of which went into the production of 9 B gallons of ethanol (RFA 2009b; USDA 2009b). RFA also reports that total ethanol imports for the same year are 0.6 B gallons which brings total demand to 9.6 B gallons. According to the Department of

Energy (2009), total gasoline input to motor fuel production was 125 B gallons. The US Federal Highway Authority (2009) also reported that miles driven in 2006 was 2974 B miles.

To parameterize the environmental disutility functions, I set the marginal damage of a metric ton of carbon emission to be $25 while the marginal disutility of miles due to congestion, accidents and reduced air quality is $0.08 per mile, based on Parry and Small (2005). Emissions intensity of gasoline from "well to wheel" is 3.2 kg C per gallon. For corn ethanol, the emissions intensity is 1.2 kg C/gallon while for sugarcane ethanol, the value is 0.60 kg C/gallon. Values for emissions intensities of corn and sugarcane ethanol are based on the results of Chapter 3, section 3 of this dissertation, and are consistent with the existing literature. The emissions intensities above imply that for an equal energy content, the use of corn ethanol emits about 43% less carbon than gasoline while sugarcane ethanol emits 72% less. I conduct sensitivity analysis using a range of estimates for the various parameters.

2.3 Numerical Results

Table 2.2 summarizes the results of the numerical simulation. Consumer prices, quantities and environmental and welfare effects for the various scenarios analyzed are reported. In the welfare section, rows two to four decompose welfare changes into the change in gross benefit from miles consumption; change in corn ethanol, gasoline, and sugarcane ethanol costs; change in government revenue and change in externality cost. The last two rows show the magnitude of the change in producer surplus for gasoline and ethanol producers.

2.3.1 Optimal Tax and Trade Policy

I find that it is optimal to tax miles consumption and to impose a differential tax scheme for gasoline, corn ethanol and sugarcane ethanol. Miles should be taxed at a rate of \$0.08 per mile. The optimal tax for gasoline is \$0.08 per gallon while for corn ethanol the optimal tax is \$0.03 per gallon. The optimal tax for sugarcane ethanol is \$0.015 per gallon. These tax rates reflect the marginal externality cost of miles and fuel. Under the assumption that the US has market power in ethanol trade and that Brazil's excess supply elasticity is 2.7, a tariff of \$0.78 per gallon should be imposed on sugarcane ethanol to maximize terms of trade improvement. The optimal tax-cum-tariff (τ_s^O) on sugarcane is, therefore, \$0.765 per gallon. Figures 4 and 5 show how τ_s^O changes as η^{ES} and the externality cost of GHG emissions change. As η^{ES} increases (becomes more elastic), τ_s^O decreases in its level. In fact, if $\eta^{ES} = \infty$ which means that the US faces a perfectly elastic excess supply curve, the optimal tax-cum-tariff is just the externality tax. On the other hand, as the externality cost of GHG emissions increase the optimal tax-cum-tariff increases as well. In this scenario, miles consumption is 2693 billion while gasoline and ethanol consumption are 115.1 and 6.5 billion gallons respectively.

2.3.2 Fuel Tax

Suppose miles cannot be taxed and only a fuel tax is imposed to reduce greenhouse gas emissions. A tax on fuel only internalizes GHG emission externalities but not miles externalities, which is a larger portion of the total externality cost (>90%).

Removing the tax on miles decreases its cost to consumers and increases consumption by 9.5% relative to the optimal level. This gives welfare gains to consumers. However, demand for fuel inputs also increases which in turn increases input prices by 25% for ethanol and 37% for gasoline. Furthermore, externality cost from miles and fuel increases due to higher miles demand and increased input use. Thus, welfare decreases by $217 B. The decrease in welfare is due to forgone income from taxation of miles ($206 B), increased externality costs and the deadweight loss associated with sub-optimal input choice in which the marginal cost of each fuel input is higher than its marginal utility.

2.3.3 Non Intervention

Miles demand is higher by 10% and demand for fuel inputs increase as well due to the absence of taxes, compared to the optimal level. Because ethanol supply is assumed to be more elastic than gasoline supply, the increase in ethanol demand (35%) is greater than the increase in gasoline (9%). Government revenues decline by $217 B due to forgone income from miles (96%) and also fuel (4%) taxation. Welfare further decreases by $229 B which is lower than the fuel tax case because losses in forgone revenue as well as externality costs are greater. Moreover, the gap between marginal cost and marginal utility for fuels further increases, leading to larger deadweight losses.

2.3.4 Ethanol Subsidy

In this scenario, I assume that a subsidy of \$0.45 per gallon is given to corn and sugarcane ethanol. This increases the price received by producers by almost 37%. Miles consumption shows the highest increase at 2977 B miles (10.5% higher than the optimal) due to a lower ethanol price compared to other non-optimal policy alternatives. This causes gasoline and ethanol demand to increase by 8.5% and 51% respectively. Domestic production and imports also increase by 49% and 411% respectively. The large increase in imports is due to the absence of the tariff which is imposed in the optimal scenario.

This policy causes the largest demand for ethanol at 9.8 B gallons (51% higher than the optimal) and the lowest demand for gasoline at 125 B gallons. However, because ethanol has a small share in the total fuel composition, the increase in fuel use due to higher miles consumption offsets the GHG mitigation due to increased use of ethanol. Both emissions and miles externalities increase by 8-10% relative to the optimal. This policy actually yields the greatest externality cost and largest decrease in welfare (\$235.1) relative to the optimal. The reason is that relative to other non-optimal policy alternatives, this case has the highest level of GHG and miles externalities and the largest loss in government revenues. Aside from not internalizing GHG and miles externalities, additional deadweight losses are incurred by the provision of the subsidy.

2.3.5 Tariff

The effect of the current tariff on imported ethanol of \$0.54 per gallon plus 2.5% *ad valorem* is simulated in this scenario. Because miles and fuel are not taxed this scenario, consumption of both are higher than the optimal. Consumption of miles increases by 10% relative to the optimal while ethanol and gasoline demand increase by 31% and 9% respectively. However, because of the higher price of ethanol, the increase in miles and fuel consumption is lower compared to other non-optimal policy scenarios, with the exception of the case where there is a fuel tax. The price of ethanol does not increase very much in the domestic market compared to non-intervention because the elasticity of the excess demand for ethanol is very elastic, as suggested by Lee and Sumner (2010). However, the decline in the world price of ethanol could be steep depending on the elasticity of the excess supply curve.

Welfare decreases by \$228 B under this scenario due to forgone income from taxes, externality costs and deadweight losses due to sub-optimal input choice. Because the US has market power in ethanol trade, there is an improvement in the terms of trade due to the tariff, which makes the tariff policy welfare improving by \$400 M relative to non intervention. There are some limitations to the analysis of the impacts of the ethanol import tariff. First, I assume that all ethanol imported in 2008 is subject to the tariff. There are two reason for why a lower percentage of total imports may be subject to the tariff. Some imports come from countries party to the Carribean Basin Initiative (CBI) and these imports are exempt from the tariff at the current level. However, in 2007 only 4% of imports are from CBI. In addition, the duty-drawback provision, which was repealed in October 2008, but was in place in prior to that allows products to come in duty-free when a like product is exported by the same importing entity. Jet fuel was considered a “like product” and was used to offset import duty on ethanol. When the duty draw-back provision and imports from CBI countries are considered, the effect of the tariff on imported ethanol quantity is likely to be less than the case when all imports are subject to the tariff.

The tariff increases the price of ethanol relative to gasoline which shifts fuel consumption away from ethanol in favor of gasoline. Thus, GHG emissions are increased through the substitution of gasoline for ethanol and also through the overall increase in fuel use. Increased miles consumption also increases miles externalities. However, since the tariff increases the price of ethanol, some of the increase in miles consumption due to the absence of taxes is partially offset by the increased ethanol price due to the tariff. As a result, externality effects from miles and fuel consumption is somewhat mitigated. This policy has the second lowest externality costs, next to the fuel tax case.

2.3.6 Subsidy and Tariff

In this scenario I simulate the effects of a \$0.45 per gallon subsidy on ethanol and a \$0.54 per gallon plus 2.5% *ad valorem* tariff on imported ethanol. This policy is roughly equivalent to a domestic corn ethanol subsidy since the tariff prevents foreign producers from benefiting from the subsidy. Numerical results confirm the expectation that domestic corn ethanol production (9 B gallons) as well as ethanol fuel share are highest under this scenario. This policy is the second most welfare decreasing policy next to the subsidy. Welfare decreases by \$234 B relative to the optimal which is slightly lower than the welfare decrease of a subsidy only policy. A subsidy with a tariff is welfare superior to the case where there is only a subsidy since the tariff increases welfare by improving terms of trade. Miles consumption increases by 10% which increases ethanol and gasoline demand by 47% and 9% respectively. This increases GHG emissions and miles externalities. The increase in emissions (8% relative to the optimal) is slightly less compared to the tariff scenario, because the shift towards gasoline brought about by higher ethanol prices is mitigated by the presence of the subsidy.

2.4 Sensitivity Analysis

Sensitivity analysis is performed to determine how parameter assumptions affect numerical results. I also compare the results of the numerical simulation to those of related papers that look into market effects of biofuel policy. Table 3 shows the percentage change from the optimal scenario to the subsidy and tariff scenario, given baseline and alternative parameter values.

I find that the elasticity of excess supply (η^{ES}) of imported ethanol has a significant impact on the level of imports. If the US is close to being a price taker (i.e. $\eta^{ES} = 30$), imports increase by 3800%. The substitution parameter (θ) in the CES production function and the gasoline supply elasticity (ϵ_g) have significant impacts on the share of ethanol and gasoline in the miles production function. Several papers have assumed that ethanol and gasoline are either strong complements or perfect substitutes. I consider these cases by setting $\theta = 0.1$ for very low substitutability and $\theta = 10$ for a high degree of substitutability (given the fleet of vehicles in the US it is unlikely the ethanol and gasoline can be perfect substitutes in the near future). I find that ethanol demand increases by 69% in the subsidy and tariff scenario relative to the optimal when the elasticity of substitution is high but only by 19% when the elasticity of substitution is low. Imports of ethanol increase by over 273% when $\theta = 10$ and 68% when $\theta = 0.1$ relative to the socially optimal. The greater increase in demand for ethanol when the elasticity of substitution is high stimulates an increase in ethanol price. In contrast, ethanol price decreases relative to the optimal scenario when $\theta = 0.1$ due to the limited opportunity for expansion of ethanol demand.

The gasoline supply elasticity (ϵ_g) determines how the quantity of gasoline responds to shifts in the gasoline demand curve. When I assume an elastic gasoline supply ($\epsilon_g = 10$), gasoline demand increases by 19% compared to 9% in the baseline result. Despite the increase in gasoline demand with $\epsilon_g = 10$, the gasoline price under the subsidy and tariff scenario turns out the be slightly lower than the optimal because the price decrease from the removal of the optimal tax is greater than the price increase from the increase in demand in the subsidy and tariff case. This is unlike the baseline case ($\epsilon_g = 0.25$) in which the gasoline price in the subsidy and tariff scenario is 34% higher than the optimal. With an elastic supply curve of gasoline, the gasoline price in the subsidy and tariff scenario does not increase, unlike the baseline result. Consequently, the share of ethanol decreases. In Table 3, ethanol demand increases by only 21% compared to 47% in the baseline result. Gasoline becomes less of a constraining factor in miles production (since gasoline price does not increase as much). Therefore, there is greater miles consumption and greater increase in miles benefit with a move to the subsidy and tariff scenario than in the baseline scenario. The resulting deadweight loss is now $7 B smaller than in the baseline.

Miles demand elasticity (η_m) have been estimated at values as low as -0.2 and as high as -1.0 (Dahl and Sterner 1991). Running the model with values of $\eta^M = -0.2$ and $\eta^M = -0.8$ show that miles demand elasticities have some impact on welfare measures. With an elastic miles demand curve, the subsidy and tariff scenario results in a much larger quantity of miles, fuel consumption and emissions relative to the socially optimal than with an inelastic miles demand curve.

Despite the differences in the magnitude of the response in the ethanol market to different parameter assumptions, the welfare loss from the optimal to the subsidy and tariff scenario is fairly stable with the variation being in the range of -3% to 0% of the baseline welfare loss of 235 B.

Other studies (de Gorter and Just 2007; Elobeid and Tokgoz 2008) on the market implications of ethanol policy have used the subsidy and tariff scenario as the baseline and have analyzed the effect of removing either the subsidy or the tariff, or both. When the non intervention scenario is compared with the subsidy and tariff scenario, results are fairly consistent in terms of the direction of the price and quantity responses although the magnitude of the impacts differ. Table 4 shows selected results of this paper, compared with de Gorter and Just and Elobeid and Tokgoz.

Some differences are notable when the subsidy is removed along with the tariff. de Gorter and Just estimate that removing the subsidy and tariff will decrease ethanol demand by 90%, whereas I estimate that the effect is more modest – removing the subsidy and the tariff will decrease ethanol demand by only 8%. Elobeid and Tokgoz have an even lower value at -2%. The difference in magnitudes could be due to the assumptions regarding elasticity of substitution and supply elasticity of gasoline. de Gorter and Just assume that gasoline and ethanol are perfect substitutes. Compared to the subsidy and tariff scenario, ethanol is relatively more expensive in non intervention. If ethanol can costlessly replace gasoline (as in de Gorter and Just), then removing the subsidy and tariff will cause a significant decrease in ethanol demand. In contrast, if I assume a dominant complementary relationship between ethanol and gasoline as in Elobeid and Tokgoz, the quantity of ethanol demand is tightly linked to gasoline demand, and the substitution of gasoline for ethanol is severely constrained. Since I assume that gasoline and ethanol are imperfect substitutes, the results obtained here lie in between that of the above two papers.

The removal of the subsidy and the tariff leads to a reduction in the demand for ethanol in the US which increases (decreases) the demand for gasoline when they are perfect substitutes (complements) as in de Gorter and Just (Elboeid and Tokgoz). Gasoline consumption increases by 4% in de Gorter and Just but decreases by 0.06% in Elobeid and Tokgoz. Using the assumption of imperfect substitutability I find that gasoline demand increases by 0.2%. When this assumption is modified to consider the case where the elasticity of substitution is 0.1, I find a decline in gasoline is close to 0% (Table 4, column 4) while if the elasticity of substitution is increased to 10, I find an increase in gasoline consumption of 1% (Table 4, column 5), which is consistent in direction with the findings of de Gorter and Just and Elobeid and Tokgoz. Differences in the assumption about the elasticity of substitution among these papers might also explain the large difference in the amount of ethanol imports stimulated by the removal of the subsidy and tariff. Elobeid and Tokgoz estimated that removing the subsidy and the tariff will increase imports by 137%. The estimate here is significantly lower at 33%, while de Gorter and Just estimate the change in imports to be 7%. With a complementary relationship between gasoline and ethanol, the demand for ethanol falls by less than in the case where the two are perfect substitutes. As a result, imports have a greater potential to increase in the former case than in the latter. Results in Table 4 columns 4 and 5 confirm this direction of change in the volume of imports as the elasticity of substitution changes.

2.5 Conclusions

Environmental and energy security concerns motivate current biofuel policy of encouraging domestic production and limiting imports. It is important to evaluate prevailing biofuel policy, which includes a subsidy and a tariff, not only in terms of its impact on social surplus but also on environmental quality. This study develops a framework for measuring welfare impacts of a subsidy and a tariff, taking into account external effects of miles and fuel consumption. I find that a combined subsidy and tariff policy results in substantial deadweight losses and increases GHG emissions and miles externalities. On the other hand, a policy that taxes both miles and fuel according to their respective marginal external damage would increase social surplus and improve environmental quality.

In the model presented here the demand for ethanol and gasoline are determined by the demand for miles. Explicitly defining demand for miles allows for the derivation the optimal tax for miles that would internalize direct miles externalities like traffic accidents, congestion and air pollution. Furthermore, a miles production function with a CES functional form allows for varying degrees of substitutability between ethanol and gasoline. Ethanol and gasoline are assumed to be imperfect substitutes, with a low elasticity of substitution, although sensitivity of results to other values of the elasticity of substitution is tested.

The model also considers the effect of the trading relationship between US and Brazil on the optimal policy intervention in the world ethanol market. I derive the optimal tax-cum-tariff on sugarcane ethanol and show that it depends on the GHG externality cost and (negatively) on the excess supply elasticity of ethanol from Brazil.

Results support the use of a lower tax rate on ethanol relative to gasoline, but not an ethanol subsidy. Although a subsidy increases the use of ethanol which emits less GHG than gasoline, the benefits in terms of GHG reduction is uncertain because the subsidy induces more driving through the unintended subsidization of fuel, which in turn increases miles consumption.

I show that the welfare effect of the current policy which includes a subsidy and a tariff depends on the level of increase in the consumption of miles and the induced substitution of domestic corn ethanol for gasoline and imported ethanol. If the US has market power in ethanol trade, some of the deadweight loss could be offset by welfare gains from terms of trade improvement. As compared to non-intervention, the subsidy and tariff lead to only a 0.3% increase in miles demand but this leads to a 9% increase in ethanol demand, an 25% decrease in ethanol imports, and a 0.2%

decrease in gasoline consumption. Despite the 9% increase in ethanol consumption, GHG emissions are similar to those under non-intervention because of the relatively low potential for corn ethanol to reduce GHG emissions and the offsetting effects of miles increase and replacement of imports by domestic ethanol. On the other hand, relative to the optimal, the combined effect of the subsidy and the tariff increases miles by 10%. This increases ethanol demand by 47%, ethanol production by 51% and gasoline consumption by 9%. As a result, GHG emissions increase by 8%. While other studies have shown that the effect of the tariff and subsidy on social welfare is negative relative to a non intervention scenario, this study shows that ignoring externality costs significantly underestimates the welfare effect of a subsidy and tariff. Compared to non-intervenion, the welfare loss due to both policies are $5.9 B. However, compared to an optimal policy that internalizes external effects of miles and fuel consumption, the welfare loss is $234 B which constitutes forgone revenues in miles and fuel taxation, increased disutility from miles and fuel externalities, and deadweight losses in the economy.

In this analysis, only direct GHG emissions of biofuel and gasoline are considered. The broader impact of biofuel policy on agricultural markets also has important implications for GHG emissions. Increased biofuel production due to the subsidy increases the price of corn and diverts corn use from feed and imports into biofuel production. This puts pressure on grain supply and may cause land conversion to agriculture in other countries to fill the gap in world demand. The conversion of land from forests to crop land causes a significant release of GHGs. The tariff on imported ethanol may also have a substantial effect on production patterns in Brazil. Without the tariff there could be a higher level of ethanol production and this also affects land use and GHG emissions. Thus, the impact of policies that increase biofuel production either domestically or abroad is likely to be greater when broader market and indirect effects are considered.

The sensitivity analysis presented here shows that the magnitude of price and quantity impacts on the ethanol market are dependent on the assumed relationship between ethanol and gasoline, and on elasticities that define supply and demand functions. Given a change in ethanol policy, a high elasticity of substitution induces a greater response in ethanol demand, while a low elasticity of substitution constrains the response in the ethanol market. Despite this, the net welfare cost of the subsidy and tariff policy relative to the optimal in all sensitivity scenarios is within -3% to 0% of the baseline value of $234 B. Further research into appropriate parameter assumptions are needed to increase the accuracy of policy analysis. Simulations show that the framework used here is flexible in accommodating various assumptions on the relationship between ethanol and gasoline, as well as other parameter values.

2.6 Figures and Tables

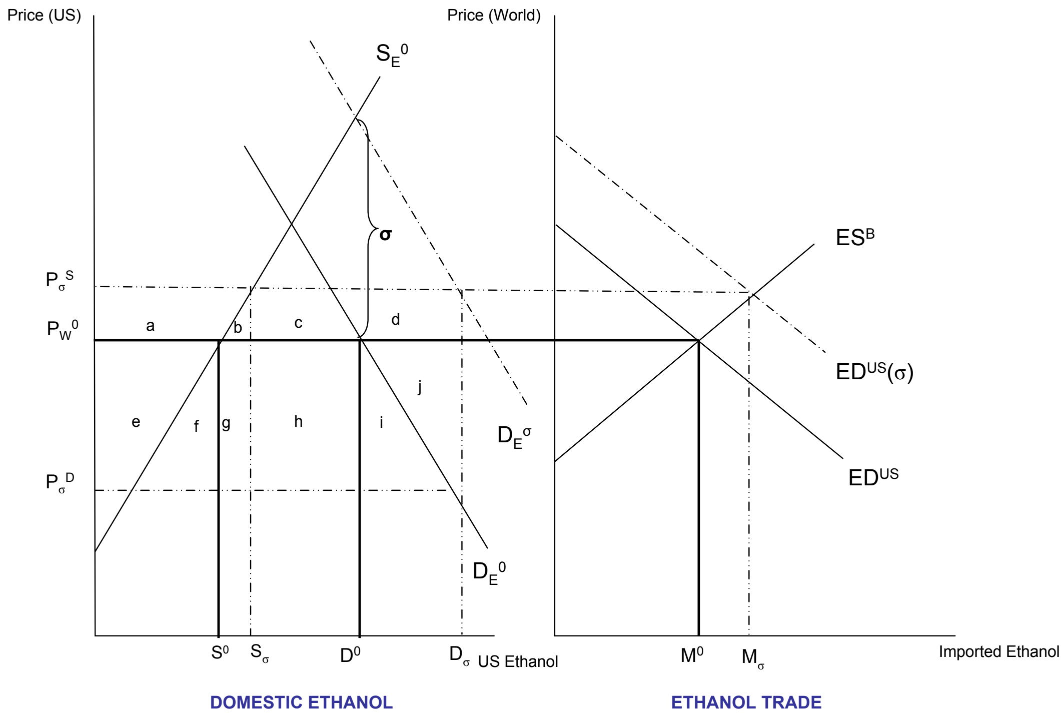

Figure 2.1: Welfare Effect of a Subsidy

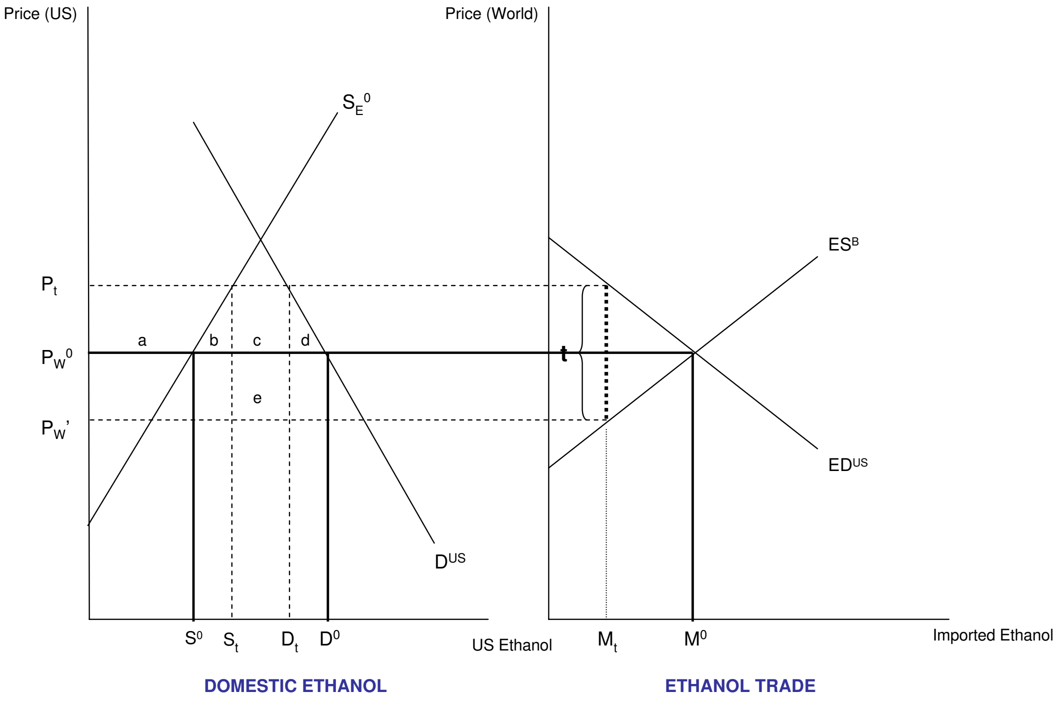

Figure 2.2: Welfare Effect of a Tariff

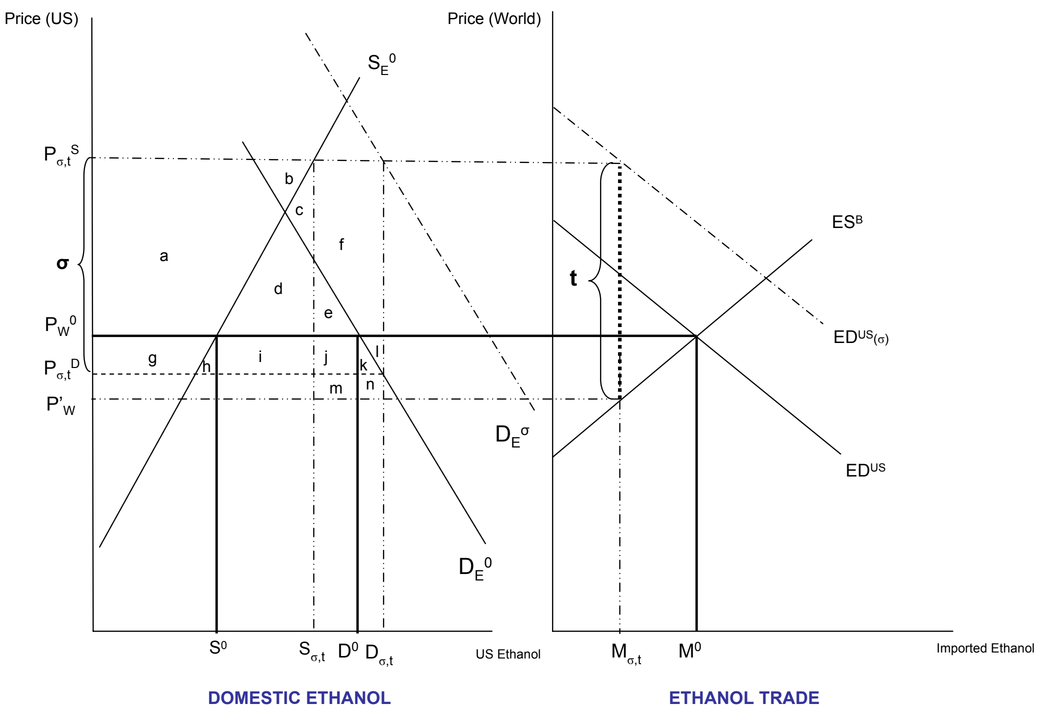

Figure 2.3: Welfare Effect of a Subsidy and a Tariff

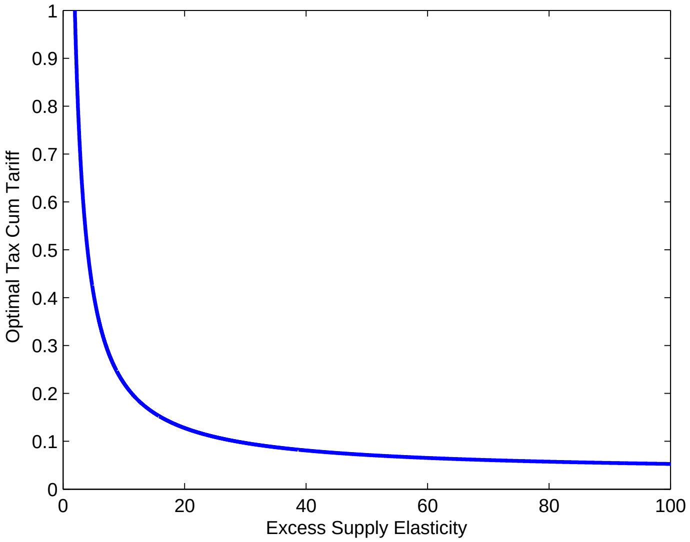

Figure 2.4: Optimal Tax-Cum-Tariff as a Function of the Excess Supply Elasticity of Sugarcane Ethanol

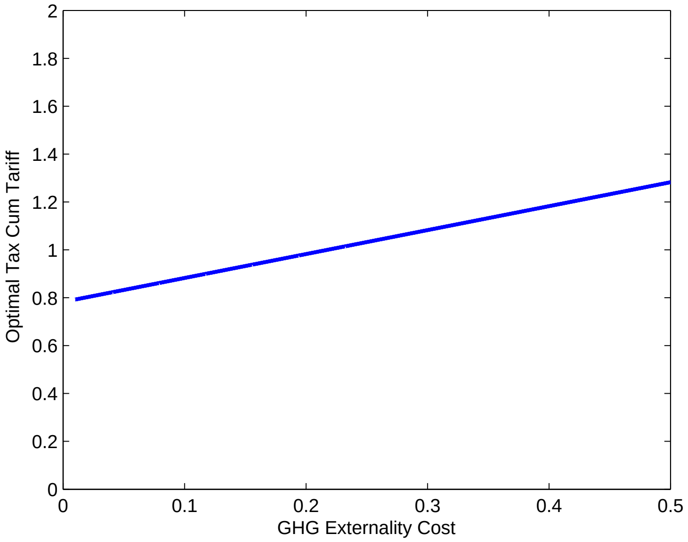

Figure 2.5: Optimal Tax-Cum-Tariff as a Function of GHG Externality Cost

Table 2.1: Baseline Data and Parameters

	Unit	**Value**
Price of corn	US$	3.8
Price of ethanol (retail)	US$	3.15
Price of gasoline (retail)	US$	3.25
Qty corn produced	B bushels	13.7
Qty corn for ethanol	B bushels	3.7
Qty ethanol produced	B gallons	9.6
Qty ethanol imports	B gallons	0.6
Qty miles driven	B miles	2974
Price elasticities		
Corn supply		0.25
Ethanol supply		1.5
Gasoline supply		0.25
Ethanol import supply		2.7
Corn demand		−0.17
Miles demand		−0.40
GHG Intensities		
Gasoline	kg C/gallon	3.2
Corn ethanol	kg C/gallon	1.2
Sugarcane ethanol	kg C/gallon	0.60
Marginal Distutility of Miles	US$/mile	0.08
Marginal Disutility of Carbon	US$/ton C	25.0

Table 2.2: Market and Welfare Outcomes for Alternative Policies

	Optimal	Fuel Tax	Non Intervention	Subsidy Only	Tariff Only	Subsidy & Tariff
CONSUMER PRICES						
Corn Price	3.28	3.65	3.62	3.78	3.64	3.8
$/bushel		*11.28*	*10.37*	*15.24*	*10.98*	*15.85*
Ethanol Producer Price	2.31	2.89	2.84	3.17	2.89	3.21
$/gallon		*25.11*	*22.94*	*37.23*	*25.11*	*38.96*
Ethanol Consumer Price	2.34	2.92	2.84	2.66	2.89	2.7
$/gallon		*24.79*	*21.37*	*13.68*	*23.5*	*15.38*
Gasoline Price	2.42	3.31	3.27	3.24	3.28	3.25
$/gallon		*36.78*	*35.12*	*33.88*	*35.54*	*34.3*
QUANTITIES						
Corn Supply	13.2	13.56	13.53	13.68	13.56	13.7
B bushels		*2.73*	*2.5*	*3.64*	*2.73*	*3.79*
Ethanol Supply	6.33	8.16	8.01	8.87	8.14	9.01
B gallons		*29.52*	*27.14*	*48.89*	*29.21*	*51.11*
Ethanol Demand	6.52	8.5	8.78	9.84	8.56	9.58
B gallons		*30.37*	*34.66*	*50.92*	*31.29*	*46.93*
Ethanol Imports	0.19	0.34	0.76	0.97	0.42	0.57
B gallons		*78.95*	*300.*	*410.53*	*121.05*	*200.*
Gasoline Demand	115.15	124.8	125.21	124.94	125.26	125.01
B gallons		*8.38*	*8.74*	*8.5*	*8.78*	*8.56*
Miles Consumption	2693.43	2948.5	2962.98	2977.17	2960.05	2973.71
B miles		*9.47*	*10.01*	*10.53*	*9.9*	*10.41*
GHG Emissions	0.38	0.41	0.41	0.41	0.41	0.41
B mt C		*7.89*	*7.89*	*7.89*	*7.89*	*7.89*
WELFARE (Level change relative to Optimal, B$)						
Net Welfare		-217.06	-228.61	-235.09	-228.24	-234.54
Gross Miles Benefit		42.43	44.56	46.63	44.13	46.13
Input Costs (Fuels)		-32.61	-34.64	-37.07	-34.27	-36.72
Government Revenue		-206.41	-216.92	-221.94	-216.69	-221.5
Externality Cost		-20.47	-21.62	-22.72	-21.4	-22.46
Producer Surplus						
Ethanol Producers		3.57	3.26	5.72	3.55	319.22
Gasoline Producers		106.75	112.05	108.59	112.77	109.43

Note: Numbers in italics are percentage changes relative to the Optimal.

Table 2.3: Sensitivity Analysis

	Baseline Result	$\eta^{ES} = 30$	$\theta = 0.1$	$\theta = 10$	$\epsilon_g = 10$	$\eta_m = -0.2$	$\eta_m = -0.8$
CONSUMER PRICES (Percent change from Optimal to Subsidy and Tariff)							
Corn	16	16	5	22	7	16	21
Ethanol	15	15	-6	27	-2	15	27
Gasoline	34	34	39	33	-1	34	53
QUANTITIES (Percent change from Optimal to Subsidy and Tariff)							
Corn	4	4	1	5	2	4	5
Ethanol							
Domestic Supply	51	50	19	69	25	51	69
Imports	200	3800	68	273	97	200	280
Total Demand	47	48	14	65	21	47	65
Gasoline	9	9	10	8	19	9	12
Miles	10	10	10	11	19	10	15
GHG Emissions	8	8	11	8	17	8	14
WELFARE (Level change from Optimal to Subsidy and Tariff, B$)							
Net Welfare	-235	-234	-234	-235	-228	-235	-230
Miles Benefit	46	46	44	47	85	46	61
Input Cost	37	37	34	38	69	37	47
Government Revenue	-222	-221	-223	-221	-206	-222	-213
Externality Cost	22	22	22	23	38	22	31

Table 2.4: Comparison of Selected Results: Non-Intervention Relative to Subsidy and Tariff

	de Gorter and Just	Elobeid and Tokgoz	This paper		
			Baseline	Low Substitution	High Substitution
	$\epsilon_g = \infty$	$\epsilon_g = \infty$	$\epsilon_g = 0.25$	$\epsilon_g = 10$	$\epsilon_g = 10$
	$\theta = \infty$	$\theta \to 0$	$\theta = 2$	$\theta = 0.1$	$\theta = 10$
	(1)	(2)	(3)	(4)	(5)
CONSUMER PRICES (Percent change from Subsidy and Tariff to Non Intervention)					
Corn Price	-28		-5	-2	-7
Ethanol Price	-20	-18	-12	-6	-15
Gasoline Price	1	0	0		
QUANTITIES (Percent change from Subsidy and Tariff to Non Intervention)					
Corn Supply	-13		-1	-1	-2
Ethanol					
Domestic Supply		-10	-11	-5	-15
Imports	7	137	33	58	23
Total Demand	-90	-2	-8	-1	-13
Gasoline Demand	4	-0.06	0.2	0	1

Note: Numbers are percentage changes.

Chapter 3: Competitiveness of Brazilian Sugarcane Ethanol Compared to US Corn Ethanol and Its Implications for the Cost of Meeting US Biofuel Mandates

The demand for biofuel in the US has experienced dramatic growth in the last several years, due primarily to biofuel consumption mandates. In 2007, the Energy Independence and Security Act (EISA) which mandates 36 Billion gallons of biofuel consumption by 2022 was signed into law. EISA sets annual renewable fuel standard (RFS) mandates beginning in 2008 for biofuel consumption. The use of corn ethanol has been capped at 15 Billion gallons due to concerns about the effect of starch based ethanol on food prices and their relatively higher GHG emissions compared to other biofuels. "Advanced biofuels," defined as those that decrease GHG emissions by more than 50% compared to gasoline make up the rest of the mandate, and within that category, 16 Billion gallons has to come from cellulosic biofuels and 1 Billion from biodisel. The non-cellulosic and non-biodiesel portion of the mandate account for 4 B gallons and this portion of the mandate could be supplied by sugarcane imports from Brazil, which has been categorized as an "advanced biofuel" by the EPA (EPA 2010). In fact, in the near-term before the production of cellulosic ethanol becomes technologically and economically viable, ethanol imports from Brazil are likely to be the source of advanced biofuels.

The mandate by itself will cause a welfare loss if it increases the cost of obtaining ethanol (either by domestic production of importation) so that the marginal cost is higher than the marginal benefit. The marginal cost and benefit at the level of the mandate will depend on supply and demand side factors. However, Serra et al. (2010) notes that with a binding mandate, the market price of ethanol is mainly driven by supply side considerations. Thus, if the RFS mandate is binding, the cost of producing and importing ethanol would the key factors in determining the welfare effect of the mandate. The relative cost of corn ethanol and sugarcane ethanol will determine the mix of ethanol consumed in the economy, and will also have implications for GHG emissions since sugarcane ethanol has a lower GHG intensity, compared to corn ethanol. Because the advanced biofuel requirement of the mandate is likely to necessitate imports from Brazil, the cost of obtaining sugarcane ethanol from Brazil would be a significant factor in determining the welfare cost of the mandate. If sugarcane ethanol could be obtained at a low cost, the welfare effect of a binding mandate would be small and could even be positive, relative to a scenario without the mandate. On the other hand, if sugarcane ethanol is very costly, then the welfare effect of the mandate could be negative, especially if the existing tariff is kept in place.

A majority of US ethanol imports come from Brazil and it is widely believed that sugarcane ethanol from Brazil is less costly than US corn ethanol (Hettinga et al. 2009; Elobeid and Tokgoz 2008; Von Lampe 2006). However, little documentation exists on what the relative production costs are, and what cost components are included in the calculation. In addition, since sugarcane ethanol is a traded commodity, the exchange rate plays a huge role in determining the price that the US pays for sugarcane ethanol. As shown in Figure 3.1, the exchange rate between the US dollar (US$) and Brazilian reias (R$) has shown significant variability in the last several years. Hettinga et al. (2009) compared US production cost of ethanol with that of sugarcane ethanol production in Brazil using the results reported by Van den Wall Bake et al. (2009) and reported that total production cost of sugarcane ethanol in Brazil is 39% lower than corn ethanol in the US, in 2005. They used an exchange rate of US\$1 = R\$3.6, which is higher than the highest annual average exchange rate in the past decade. If the exchange rate used is closer to current levels, the gap between the production cost of corn and sugarcane ethanol would be smaller.

This chapter has two main objectives, the first is to estimate the welfare effect of the US RFS mandate, given variability in the exchange rates, and thus, the cost of importing ethanol from Brazil. The second is to present detailed estimates of the production cost of ethanol in the US and Brazil. In addition I also calculate GHG emissions from both types ethanol, that are consistent with the inputs used in the cost calculation.

Several studies have examined market and welfare impacts of the US RFS mandate. An early study by Gallagher et al. (2003a) analyzes the implications of a national ban on the use of MTBE as a fuel additive and the imposition of a Renewable Fuel Standard of 5 billion gallons of ethanol on fuel prices, consumption and welfare. Gallagher et al. (2003a) show that ethanol price increases while gasoline price decreases, leading to an overall fuel price increase and a decrease in fuel consumption. Social welfare decreases although the level of air pollutants also decrease. Ando, Khanna, and Taheripour (2010) examine the environmental and welfare impact of the EISA RFS mandate in 2015 using a framework where fuel demand is derived from the demand for miles. Unlike Gallagher et al. (2003a), they found that the mandate decreases the overall price of fuel and hence, the price of miles. The mandate decreases GHG emissions by 0.5% to 5% but does so at a net welfare loss to society. Ando, Khanna, and Taheripour (2010) also found that the market impacts of the mandate are sensitive to the assumed own-price elasticity of gasoline, while Tyner and Taheripour (2008) argue that the price of oil significantly affects the cost of the mandate to consumers.

None of the aforementioned studies have considered the impact of the cost of importing ethanol on the market and welfare effects of the mandate. Given that the current mandate is likely to require significant imports from Brazil to meet the "advanced biofuel" requirement, the cost at which the US can import ethanol could affect the welfare cost of the mandate. Thus, it is important to gain a deeper understanding of the factors affecting the cost competitiveness of domestically produced and imported biofuel relative to each other, and the factors that could affect the cost of importing ethanol.

In this chapter, I examine the components of the production costs of corn and sugarcane ethanol using detailed information about the production process of corn in the Midwestern US and sugarcane in São Paulo state in Brazil. I also use information about the production process of each type of ethanol to obtain life-cycle GHG emissions for both types of ethanol using a consistent methodology. The production cost estimates are then used to calibrate a numerical model representing the US miles and fuels market, including biofuel trade with Brazil. The numerical model is used to examine the effect of changing exchange rates on the cost of meeting the US biofuel mandate in 2015. The implication of the resulting biofuel mix on GHG emissions is also discussed.

Results show that the relative costs of corn ethanol and sugarcane ethanol are highly sensitive to the prevailing exchange rate. The market price of feedstocks is also an important factor but to a lesser extent than the exchange rate. Direct GHG emissions of sugarcane ethanol at the US port are 53% lower than corn ethanol and 74% lower than gasoline.

At an exchange rate of US\$1 = R\$2.15 and with the excess supply of ethanol from Brazil being elastic, the welfare cost of the mandate in 2015 relative to a baseline without the mandate is \$14 Billion dollars. If the exchange rate increases by 40% the welfare effect of the mandate is positive at \$4.6 Billion dollars, due to the availability of cheaper imports from Brazil. On the other hand a decrease in the exchange rate of 16% increases the welfare loss by 64%.

The chapter proceeds are follows: Section 3.1 gives a brief overview of ethanol production in the US and Brazil. In section 3.2, I present the analytical framework. Section 3.3 presents data sources and the methodology used to calculate the cost of production of corn and sugarcane ethanol, as well estimates of GHG emissions. Section 3.4 presents results of the numerical simulation. Section 3.5 discusses policy implications and concludes.

3.1 Background: Ethanol Production in the US and Brazil

The US and Brazil are the two largest ethanol producers with production levels of 9 Billion (B) gallons and 6.5 B gallons, respectively, in 2009. Both countries have been producing ethanol since the 1970s (Figure 3.2) with the US surpassing Brazil in production levels since 2006. The share of corn going into ethanol production has increased from 5% in 2000 to 30% in 2008 (USDA 2009a; RFA 2009a). The increase in corn ethanol production was first driven by the MTBE ban in 2005 which led to increased demand for ethanol as a fuel oxygenate. However, the bigger push came from the RFS which initially mandated 7.5 B gallons by 2012 and later increased that to a maximum of 15 B gallons of corn ethanol annually by 2015, and 36 B gallons of corn and other "advanced biofuel" by 2022. Biofuel production in the US has also been supported through a volumetric tax credit of $0.51 per gallon which was reduced to $0.45 per gallon in 2007, and a tariff on imports of $0.54 per gallon plus an ad valorem tariff of 2.5%.

Brazil has been producing ethanol on a large scale since it instituted the PROALCOOL program in 1975 in response to the first oil crisis, a currency crisis, and fluctuating sugar prices (Moreira and Goldemberg 1999). With PROALCOOL, the government provided numerous incentives to build ethanol mills, improve infrastructure for ethanol distribution, and increase the availability of ethanol-only vehicles. In 1999 ethanol and sugar markets were liberalized. Though there is less government intervention in the biofuel market in Brazil, ethanol production is supported to some extent by a blend mandate of 20-25% and an import tariff of 20%. Ethanol receives no subsidy although the fuel tax on ethanol is also at least 30% lower than the tax on gasoline. Domestic ethanol consumption in Brazil is expected to grow due to growth in demand for fuel as well as the increasing share of flex-fuel vehicles (FFVs) in the vehicle fleet. In 2008, 87.2% of new vehicle sales were FFVs (F.O. Lichts 2009). However, ethanol producers are also actively pursuing market growth outside their borders. The US is currently the largest buyer of Brazilian exports, followed by the Netherlands and Japan. Brazil exported 17% of its production from March 2008 to April 2009. In 2007, it was projected that exports will grow to 36 B gallons by 2017 or almost one-third of Brazil's production (InfoFNP 2008). However, internal demand pressures in Brazil, exchange rates and US biofuel policies will influence the extent to which these projections are realized.

3.2 Conceptual Framework

The model used in this chapter is similar to that used in the second chapter, although some important differences exist. Consumers derive utility from miles, which are produced using gasoline and ethanol. Consumers also derive disutility from environmental externalities, which in this chapter is assumed to be GHG emissions. Gasoline and ethanol are imperfect substitues, while ethanol from the US and Brazil are perfect substitutes in the production of miles. Unlike the model in chapter two, a binding biofuel mandate exists so that the level of biofuel consumption is fixed. The mandate has two categories, a "traditional biofuel" category that can be met by either corn ethanol and sugarcane ethanol, and an "advanced biofuel" category that can only be met by sugarcane ethanol (cellulosic and biomass biodiesel are excluded). Thus, depending on the relative prices of the two types of ethanol, the traditional biofuel mandate will be fulfilled using a combination of corn and sugarcane ethanol. However, because the advanced biofuel can only be met by sugarcane ethanol, the US would have to import at least the mandated amount of sugarcane ethanol, even if it is more expensive than corn ethanol. A binding biofuel mandate would induce a higher ethanol demand than what is supported by a free market. This would raise the marginal cost of producing biofuel and cause deadweight losses by creating a gap between the marginal cost and marginal benefit of biofuel. However, a biofuel mandate could also increase welfare by reducing GHG emissions as consumers are forced to consume biofuel which is less GHG intensive than gasoline.

The cost of producing and importing ethanol to meet the mandate, given different costs of sugarcane ethanol is illustrated by Figure 3.3 below. The left panel shows the US corn ethanol market while the right panel shows sugarcane ethanol trade with Brazil. I assume that unless sugarcane ethanol is less costly than corn ethanol, domestic production of corn ethanol will supply 15 B gallons of the mandate. Because the advanced biofuel mandate can only be met by sugarcane ethanol, demand for sugarcane ethanol is perfectly inelastic at the mandated quantity of advanced biofuel (Q^A). However, at quantities exceeding Q^A, and in the region where sugarcane ethanol is less costly than corn ethanol, the US excess demand curve is elastic, with the elasticity depending on the price elasticities of ethanol supply and demand in the US domestic market.

Consider the two cases presented above. In the first case, sugarcane ethanol is more costly to import than corn ethanol. In the second case, the reverse is true. In the first case, Brazil's excess supply curve intersects the US excess demand curve at a point where the excess demand is inelastic. The US pays the market price of sugarcane ethanol (P_S^0) which is higher than the price of corn, but will import only the amount needed to meet the advanced biofuel mandate. Corn ethanol consumption will be at the maximum allowed quantity (Q^M). Based on Figure 3.3, the total cost of producing and importing biofuel is (a+b+c) for corn ethanol and (d+e+f+g) for sugarcane ethanol. In this scenario, a tariff on imported ethanol will further increase the price of meeting the advanced biofuel mandate, and due to the inelastic US demand for imports, the full burden of the tariff will fall on US consumers.

Depreciation of the Brazilian currency, or appreciation of the US currency would cause imported ethanol to be less costly, and would shift the excess supply curve of Brazil to the right, as shown in the figure by the dashed excess supply curve. In this case the US will import the mandated "advanced biofuel" quantity, but in addition to that will displace corn ethanol with additional sugarcane ethanol imports. In Figure 3.3, imports will be at Q_S^T and the world and domestic price of ethanol will equalize at P_S^1. The cost of meeting the US biofuel mandate is (b) for corn ethanol and (f+g+h) for sugarcane ethanol. Comparing the two cases, the cost of production of corn ethanol is reduced by (a + c) while the cost of importing sugarcane ethanol is reduced by (d + e) and increased by (h) when the cost of sugarcane ethanol is lower than corn ethanol. Area h=c because imports in excess of Q^A are used to displace domestic corn ethanol so the net reduction in the cost of the total mandate is area (a + d + e).

The illustration above shows how changes in the cost of imported ethanol could affect the cost in the ethanol market of meeting the US RFS mandate. The welfare effects of the US RFS mandate, given different costs of obtaining ethanol from Brazil are quantified using the model described above.

The market and welfare effect of the US RFS mandate, with and without the existing ethanol subsidy and mandate, is quantified relative to a baseline without the biofuel mandate, but with other existing policies like the blender subsidy and tariff. The measurement of social welfare is similar to that used in Chapter 2. Welfare is defined as the sum of social surplus in the miles and fuel markets and the cost of GHG externalities. The simulation year is 2015 when the level of RFS mandate for biofuel is substantially larger than the present level. In this study, the main focus of the welfare analysis is the effect of the mandate, given different costs of importing sugarcane ethanol from Brazil. Thus I abstract from optimal taxes and tariff in this chapter. Given the time horizon for the simulation, I assume a larger excess supply elasticity for sugarcane ethanol (η^{ES}) of 10. This assumption would imply that the tariff that maximizes US social welfare considering "terms of trade" effect is very low so that the US can be considered as a price taker. Other assumptions are given in Table 3.5.

In order to calibrate the supply functions for domestic and corn ethanol, detailed cost data are compiled to obtain comparative cost estimates of both types of ethanol. GHG emissions associated with each production process are also calculated. The methods and data sources used to obtain cost and GHG emissions are discussed in the next section. Since detailed data on the production cost of sugarcane ethanol is available for 2007, I use 2007 market data, together with price elasticity estimated from the literature for the initial calibration of the numerical model, and re-calibrate the model to reflect the 2015 market situation. In re-calibrating the model to 2015, I assume that miles consumption increases 1% for each year, so that from 2007 to 2015, miles demand increases by 8%, resulting in a level of consumption of 3272 B miles in 2015. Using 2015 miles consumption, quantities demanded and prices for gasoline and ethanol are obtained using the model. In 2015, the mandate calls for a maximum of 15 B gallons corn ethanol and 1.5 B gallons of advanced biofuel, which is assumed to be sugarcane ethanol from Brazil. Thus, total demand is fixed at 16.5 B gallons.

3.3 Cost of Production

3.3.1 Sugarcane Ethanol

Sugar/ethanol mills in Brazil typically obtain 70% of their sugarcane from owned or leased farm land and the remaining 30% from independent producers. The cost of growing feedstock produced by mills differs from that of independent sugarcane producers because of economies of scale and the use of more advanced technology. The costs of producing sugarcane ethanol using sugarcane grown by independent producers and by mills themselves are calculated using a variety of data sources. Detailed data on the costs of growing sugarcane by independent producers are obtained from Brazil's annual agricultural yearbook published by FNP (InfoFNP 2008). Costs of refinery production are obtained from mills in São Paulo. The cost of production for sugarcane ethanol consists of the cost of feedstock production (including operating expenses and the cost of land) as well as cost of conversion of sugarcane to ethanol at the refinery. To compare the cost of imported sugarcane ethanol to domestically produced corn ethanol, the cost of transporting ethanol from refineries in Brazil to US ports is also included in the total cost.

Feedstock cost

Sugarcane is grown on a six-year cycle, where one planting year is followed by an initial harvest after 12-18 months and four succeeding harvests. Ratoon cultivation follows each harvest except for the last harvest which is followed by field reform in preparation for the next cycle. We average the annual costs for six years to obtain the cost of sugarcane production for independent sugarcane growers. Averaging costs over the 6-year cycle is considered reasonable since at any point in time a farmer is assumed to have one-sixth of the field in a different stage of the cycle. Table 3.1 shows the cost components for a typical six year cycle for an independent sugarcane producer. The average yield for an independent sugarcane ethanol producer is 75 Mt per hectare. This is lower than that observed on land owned by the mills in São Paulo which averaged 81 Mt per ha in 2007 (CONAB 2008). As shown in Table 3.1, the cost of production per hectare is highest during the first planting year and diminishes with each harvest as yield also diminishes. Based on market data, fertilizer application rate per hectare in the establishment year is 600 kg of a formula consisting of 5% nitrogen (N), 25% phosphorous (P), and 25% potassium (K). In the succeeding ratoon years, 500 kg with 20% N, 5% P and 20% K is used. These application rates are comparable those used by Macedo, Seabra, and Silva (2008a) [4]. The price per metric ton (Mt) of the NPK mix is R$940 per Mt and R$1040 per Mt for 5-25-25 and 20-5-20 formulas respectively (in 2007 prices). Price and quantities for other chemicals are obtained from FNP (InfoFNP 2008). Chemicals

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[4] We assume N, P, and K application rates of 30, 150, and 150 kg per hectare respectively in the planting year and 100, 20, and 100 kg per hectare in ratoon years. Macedo, Seabra, and Silva (2008a) assume N, P, and K application rates of 48, 125, and 117 kg per hectare respectively in the planting year and 88, 25, and 114 kg per hectare in ratoon years.

included are pesticides, insecticides, nematicides, and maturador, or ripener, which ripens sugarcane before harvest. Herbicide, insecticide, and nematicide are applied during planting in the first year. Herbicide is also applied at a lower, fixed quantity per year for each of the five ratoon years. The ripener is applied during each of the five harvest years. Machinery used for sugarcane production includes terracing in the first year, ratoon elimination, ratoon thinning for maximum yields, harrowing and fertilizing, chemical application, distribution of filter cake and vinasse (residues from the refining process used as fertilizer), and harvesting. Cost estimates are obtained from FNP (InfoFNP 2008). The expense allocated to machinery and manual labor depends on the level of mechanization. I assume that 33% of harvest operations is mechanized, which is representative for the state of São Paulo in 2007 (CONAB 2008) [5]. The cost of feedstock transport from farm to refinery is R$6.7 per Mt of feedstock based on an average distance of 22 km from the field to the mill.

Table 3.2 summarizes the average cost for each component (over the six years). The first column shows the cost in R$, while the next three columns show the cost in US$ using the minimum and maximum annual exchange rates observed from 1999-2009, as well as the central exchange rate of US$1=R$2.15. The first column shows that the total operating cost for sugarcane production is R$2,892 per hectare. The per gallon cost is obtained by dividing the per hectare cost with the ethanol yield per hectare of 1614 gallons. The ethanol yield per hectare is based on an ethanol yield of 21.5 gallons of anhydrous per Mt of sugarcane, which is the 2007 yield average

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[5] 130 mills that operate in So Paulo have signed the "Green Protocol" that aims to eradicate cane burning by 2018 (Macedo et al, 2008). The change in harvesting practice affects cane costs slightly but is more of a social and health concern as manual harvesting, which necessitates burning, poses health and physical risks to laborers (Novaes 2007).

for So Paulo, and an average sugarcane yield of 75 Mt per hectare (CONAB 2008; InfoFNP 2008). The operating costs of feedstock production are, thus, calculated to be R$1.78 per gallon of ethanol.

The imputed cost of land and management (C_L^{BR}) is defined as the residual returns after covering operating cost. It is calculated as the difference between the revenue per hectare and the cost of production. In Brazil, sugarcane is priced according to its ATR (Aucar Total Recupervel or Total Recoverable Sugar). The price of ATR (P^{ATR}) is determined both by sugarcane producers and buyers, with the goal of equitable distribution of the profits among producers and buyers. It is based on the cost of production of sugarcane as well as the prices of ethanol and sugar, which are the primary uses of sugarcane (UNICA 2009). The following formula is used:

$$P^{ATR} = \frac{1}{Q^{ATR}}(P^E Q^E \times \frac{C^S}{C^E} + P^{SU} Q^{SU} \times \frac{C^S}{C^{SU}}) \tag{11}$$

where the first term in parenthesis is revenue from ethanol production ($P^E Q^E$) multiplied by the share of sugarcane production cost in total production cost of ethanol ($\frac{C^S}{C^E}$) and the second term is revenue from sugar production ($P^{SU} Q^{SU}$) multiplied by the share of sugarcane production cost in total cost of sugarcane production ($\frac{C^S}{C^{SU}}$). The sum of the two terms is divided by the total available ATR (Q^{ATR}). Thus, a portion of revenues from both ethanol and sugar production is allocated to sugarcane producers, according to the share of sugarcane production cost in total cost of producing ethanol and sugar. I use the reported price of ATR, P^{ATR} which had an average value of R$0.29 per kg for 2006-2008, the average yield of sugarcane per hectare (Q_s), and an ATR value in São Paulo of 141 kg per Mt of sugarcane in

2007 to calculate C_L^{BR} as follows:

$$C_L^{BR}(R\$/ha) = Q_s(Mt/ha) \times ATR(kg/Mt) \times P^{ATR}(R\$/kg) - C_s \qquad (12)$$

where C_s is the operating cost per hectare, $Q_s = 75$ Mt/ha and $ATR = 141$ kg/Mt (CONAB 2008). The calculated value of C_L^{BR} is R\$182/ha or R\$0.11/gallon. By adding the operating cost and cost of land and management, a total feedstock cost of R\$3,074 per hectare or R\$1.9 per gallon is obtained (Table 3.2). The above approach provides the imputed opportunity cost of land for an independent producer of sugarcane who owns his own land and supplies sugarcane to a refinery at the market price of ATR. Mills that grow their own sugarcane typically lease the land at rates that are set by the market. The leasing rate is based on a fixed tonnage and ATR specified in the leasing contract. Using market data on leasing contracts in 2007, firms lease land at the value of 15 Mt of sugarcane per hectare with an ATR content of 121 kg per Mt of sugarcane. The latter is a determined by agreement between sugarcane mills and landowners. Thus, the leasing cost per hectare is:

$$\text{Leasing cost}(R\$/ha) = 15(Mt/ha) \times 121(kg/Mt) \times P^{ATR}(R\$/kg) \qquad (13)$$

At an ATR price of R\$0.29 per kg this leasing cost is calculated to be R\$526 per hectare or R\$0.3 per gallon (given a sugarcane yield of 81 Mt per hectare). Assuming that integrated production of sugarcane by the mills is at least as profitable as using purchased sugarcane from independent producers, the inferred operating cost of sugarcane production for mills is at most R\$1.6 per gallon, which is at least 10%

lower than the cost for independent growers.

Refinery cost

The refinery cost of ethanol production is obtained from the balance sheets of 20 mills producing ethanol and sugar in the state of São Paulo. The sample represents over 30% of installed capacity in Brazil in 2007 which totals 97 million Mt of crushing capacity (with more than 50 mills). As shown in Table 3.3, data on COGS (cost of goods sold) and SG&A (selling, general and administrative expenses) are used to obtain total cost of production for each mill. To obtain the per gallon cost of ethanol, the total cost for each mill is divided by the potential production of anhydrous ethanol, based on the mill's sugarcane milling capacity. The cost per gallon of ethanol is adjusted considering that mills also produce sugar and sugar production has a higher cost per Mt as well as higher revenue per Mt than ethanol production. Assuming that the cost and revenue for a mill producing only ethanol are equiproportionately lower than the cost and revenue for a mill producing both ethanol and sugar, respectively, and using data from a mill that produces only ethanol (100%E), the costs for the other mills are adjusted using the following equation:

$$Adj.Cost(R\$/gallon) = Cost(R\$/gallon) \times \frac{Revenue(R\$/\text{Milled cane}(Mt))}{Revenue^{100\%}(R\$/\text{Milled cane}(Mt))} \tag{14}$$

The total cost of ethanol production on average across these 20 mills is R$3.3 per gallon in 2007. By subtracting the average feedstock cost (estimated above as

R$1.9/gallon) from the total cost, the refinery cost (for industrial inputs, equipment, and management) is calculated to be R$1.4 per gallon. This is the refinery cost of a plant that does not generate co-products through the sale of excess electricity. This refinery cost includes the cost-savings due to electricity generation at the mill using baggasse [6]. To calculate the cost of imported ethanol at US ports, I assume that ethanol is transported 312 miles from the refinery to the port by truck at a cost of R$49 per cubic meter (TRANSPARANA 2006). From the port, ethanol is then transported by an ocean tanker 7,416 miles (approximate distance from São Paulo, BR port to Philadelphia, US port) at a cost of R$130 per cubic meter (ODJFELL 2006). The cost of transporting sugarcane ethanol is calculated to be R$0.68 per gallon which brings the total cost of sugarcane ethanol at US ports to R$3.9 per gallon.

3.3.2 Corn Ethanol

The cost components included for corn ethanol are similar to those for sugarcane ethanol. The total cost per gallon and the sub-total for each cost component are presented in the last column of Table 3.2. The per gallon cost is based on an ethanol yield of 1,107 gallons per hectare, which assumes a corn yield of 10 Mt per hectare (the average for Illinois in 2007) and an ethanol yield of 110 gallons per Mt of corn.

Feedstock cost

Feedstock cost is determined by the cost of production of corn produced using a

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[6] Based on market data for mills that sell electricity, co-generation could further reduce cost by R$0.07 per liter.

corn-soybean rotation. Production data are based on prices, input uses and yields for the state of Illinois as reported in 2007 Illinois crop budget and Illinois Agronomy Handbook (Schnitkey 2006; Hoeft and Nafziger 2009b). Fertilizer inputs include N, P, K and lime, and their per-hectare application rates based on the state average are 17 kg per unit of target yield in Mt for N, 8 kg for P, 5 kg for K, and 450 kg for lime (Hoeft and Nafziger 2009b). Feedstock transportation to the refinery is based on a round trip distance of 100 km at US$3.5 per Mt (McVey, Vaughn, and Baumel 2007). As shown in Table 3.2, the total operating cost of corn production is US$698 per hectare or US$0.65 per gallon of ethanol. Similar to independent sugarcane producers, the imputed cost of land and management (C_L^{US}) for corn producers is the residual profit of the corn producer, defined as the difference between the revenue per hectare from selling corn at the market price and the per hectare costs of corn production. The value of C_L^{US} is calculated as:

$$C_L^{US} = P_c Q_c - C_c \tag{15}$$

where P_c is the market price per unit of corn, Q_c is yield per hectare, and C_c is the operating cost per hectare. Using an average corn price for 2006-2008 of $144/ Mt, Qc = 10Mt/ha, and Cc = $698/ha, C_L^{US} is $745/ha or US$0.65 per gallon of ethanol. The total feedstock cost for corn ethanol is US$1443 per hectare or US$1.3 per gallon (see Table 3.2).

Refinery cost

Refinery cost is based on a 100 million-gallon per year dry-mill ethanol plant, and is calculated using the Ethanol Dry Mill Simulator (FARMDOC 2007). I use dry-milling process because a majority of ethanol produced in the US comes from dry-mill ethanol plants (Dale and Tyner 2006). The calculated cost of ethanol refining is $0.72 per gallon, which includes chemical and energy inputs, administrative costs, taxes, depreciation and amortization, and interest expenses. The refining cost used here is similar to that reported by (Eidman 2007). Other studies have reported a lower refining cost at $0.46 per gallon due to the exclusion of several administrative cost items (Hoeft and Nafziger 2009a). The ethanol dry-milling process generates a co-product called Dry Distiller's Grain (DDGS). I assume that 386 kg of DDGS are produced per Mt of corn processed into ethanol, and sold at a price of $130 per Mt [7]. The revenue generated from the sale of co-products is subtracted from the total cost of ethanol production. Adding the feedstock cost and refinery cost gives a total cost of US$2.01 per gallon. When the co-product credit of US$0.46 subtracted, the net cost of corn ethanol is US$1.56 per gallon (Table 3.2).

3.3.3 Comparison of Production Costs

As shown in Table 3.2, the cost of corn ethanol is higher or lower than the delivered cost of sugarcane ethanol depending on the exchange rate. At an exchange rate of US$1=R$1.81 the cost of sugarcane ethanol is $2.2 per gallon while at an exchange rate of US$1=R$3.11 it is $1.28 per gallon. Figure 3.5 shows the exchange rate at which the cost of production for US corn ethanol and Brazilian sugarcane ethanol would equalize. For 2006-2008 average corn and ATR prices, corn ethanol is less

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[7] The DDGS price is related to the price of corn using the following equation: DDGSPrice = 1.55 + 21.98*CornPrice + 0.205*SoybeanPrice, and is capped at US$140 per ton (FARMDOC 2007).

expensive than sugarcane ethanol up to an exchange rate of US$1=R$2.48, at which point sugarcane ethanol gains the cost advantage. The break-even exchange rate is 23% lower when the corn feedstock price is 50% higher, and 4% higher when the ATR price is 50% higher. Figure 3.1 shows that the years 2007-2008 have the lowest exchange rates in almost ten years, which could be attributed to macroeconomic conditions in the US and Brazil. Thus, if exchange rates were to revert to levels close to their historical high of over R$3 per one US dollar experienced from 2002-2004, it is expected that ethanol from Brazil would have a cost advantage over US ethanol.

Figure 3.4 shows the cost of corn ethanol and sugarcane ethanol at a US port, at the central value of the exchange rate of US$1=R$2.15, at which the net per gallon cost of corn ethanol of US$1.5 is less than that of sugarcane ethanol from Brazil, at a cost of US$1.8, delivered to the US port. From Table 3.2, feedstock costs account for 65% of total corn ethanol domestic cost, while refinery costs contribute 35% to the total cost of $2.01 per gallon of corn ethanol (excluding co-product credit). Among the feedstock costs, over 48% comes from operating expenses (consisting of fertilizers (32%), machinery (31%), chemicals (15%), seeds (16%) and transportation (5%)) while 52% of the feedstock costs are the cost of land and management. For sugarcane ethanol, feedstock and refinery costs account for 58% and 42%, respectively, of the total domestic cost of US$1.52 per gallon. For independent sugarcane producers, a majority of feedstock costs is from operating expenses (94%) while returns to land and management account for only 6% of the cost. For mills producing all their sugarcane, 84% is from agricultural operations while 16% is land leasing cost.

The main components of operating costs are machinery (51%), fertilizers (19%), and transportation (17%). Seeds and other chemical inputs make up the balance. Total operating cost per gallon of sugarcane ethanol is 29% higher than that of corn ethanol. The cost disadvantage for Brazilian ethanol in operating costs is due to higher machinery and transport costs from field to mill. Transportation of sugarcane is not as efficient as corn because only 15% of it is ATR content which is transformed into ethanol. The rest of the cane is composed of water (70%) and bagasse (15%). In the case of corn, 40% of its content is transformed into ethanol. Brazil has a cost advantage in its land cost which is significantly lower than in the US. The total cost of feedstock, including operating cost and cost of land, is 32% lower in Brazil. Industrial costs at the refinery are very similar in the US and Brazil. Cost of sugarcane ethanol within Brazil is 24% lower than the cost of corn ethanol in US. Even when transportation to the US is included, sugarcane ethanol still has a slight cost advantage compared to corn ethanol. However because corn ethanol production has a co-product credit, the net cost of ethanol produced in Brazil and delivered to US ports is 17% higher than US corn ethanol (with 1US\$ = R\$2.15).

3.4 Greenhouse Gas Emissions

GHG emissions from corn and sugarcane ethanol have been calculated separately by several studies using life cycle assessment (LCA) methods (for corn ethanol, see review in Farrell et al. (2006b); Wu, Wang, and Hou (2007); Liska et al. (2009); for sugarcane ethanol see Macedo, Seabra, and Silva (2008a); Macedo and Seabra (2008)). Several studies have also pointed to indirect land-use change (ILUC) as another source of emissions from biofuels. Searchinger et al. (2008) and Fargione et al. (2008) provide estimates of the GHG emissions caused by ILUC due to the production of corn ethanol in the US. Pacca and Moreira (2009) estimate the emissions due to land use changes caused by expansion of sugarcane production in Brazil. Due to a lack of consensus on methods to calculate ILUCs accurately for either feedstock (see for example Reilly, Gurgel, and Paltsev (2009)), they are not included in the GHG calculations in this analysis. I use the assumptions made above for feedstock production, industrial processes and transportation of feedstocks and finished products to estimate the above ground GHG emissions intensities of corn and sugarcane ethanol. To keep the estimates for corn ethanol and sugarcane ethanol comparable to each other, the same approach and energy and emission coefficients for variable inputs are used for both biofuels.

For U.S. corn ethanol, coefficients from the GREET model are used to calculate emissions from production inputs (ANL 2008). GHG emissions for corn ethanol are calculated using the input quantities listed above, multiplied by the appropriate emission factors from the GREET model. For nitrogen and lime, emissions include those during the production of these chemicals, as well as emissions from application. For farm machinery, the input quantity is the total weight divided by farm size and lifetime of machinery, which is multiplied by the GREET emission factor associated with the energy embodied in the farm machinery. For the refinery phase, data are from the California Air Resource Board GREET (CA-GREET) model (California Air Resources Board). Emissions from ethanol production at the refinery depend on the milling technology (wet-mill or dry-mill). Ethanol produced in a dry-mill refinery typically has 20% lower emissions than a wet-mill plant. Consistent with cost calculations, emissions from a dry-mill ethanol plant which uses 90% natural gas and 10% electricity are used. Emissions from chemical inputs, ash disposal, and effluent restoration as well as energy embodied in the physical ethanol plant are included in the calculations.

For sugarcane ethanol, the corresponding emission factors given by GREET are multiplied by the use rates given above to calculate emissions from fertilizer and chemical inputs. Similar to corn ethanol, nitrogen and lime emissions consist of emissions from production as well as from denitrification after application. I use emission values from Macedo and Seabra (2008) for machinery, labor, and hire; trash burning; feedstock transport; and refinery operations. For ethanol transport from the refinery in Brazil to US ports, coefficients provided by the CA-GREET model (California Air Resources Board) are used.

The findings on GHG emissions are summarized in Table 3.4. Corn ethanol emissions equal 4.45 kg CO2 equivalent (CO2-eq) per gallon using corn grown under a corn-soy rotation, while sugarcane ethanol emissions equal 2.09 kg CO2-eq per gallon. Emissions of CO2 from gasoline are 12 kg CO2-eq per gallon. The estimate of 4.45 kg CO2-eq per gallon of corn ethanol is higher than figures reported in the recent literature by Liska et al. (2009) whose estimate ranges from 3 - 4 kg CO2-eq, but lower that those reported in older studies (Farrell et al. 2006b; Wu, Wang, and Hou 2007). The latter ranges between 5.7 and 9.5 kg CO2-eq. The low estimates obtained by Liska et al. (2009) are based on mills that sell DDGS in its "wet" form thus saving energy used to dry the DDGS.

For sugarcane ethanol, the estimate of 2.09 kg CO2-eq per gallon falls between that of Macedo, Seabra, and Silva (2008a) who report emissions of 1.67 kg CO2-eq per gallon, and (California Air Resources Board) who report 2.32 kg CO2-eq per gallon. Differences in assumptions about sugarcane yield per hectare and ethanol yield per Mt of feedstock account for some of these differences. The estimate by Macedo, Seabra, and Silva (2008a) is lower than the estimate here because Macedo, Seabra, and Silva (2008a) do not include emissions from transport of ethanol from Brazil to US ports. When only emissions from agricultural and industrial production are considered, GHG emissions of sugarcane production in this study fall to 1.8 kg CO2-eq per gallon which is close to the estimate given by Macedo, Seabra, and Silva (2008a). On an energy-equivalent basis, corn ethanol decreases emissions by 44% compared to gasoline, while sugarcane ethanol reduces emissions by 74%. Sugarcane ethanol has 53% less emissions than corn ethanol. Recent estimates by US EPA shows that sugarcane ethanol from Brazil reduces GHG emissions by 61% compared to gasoline after including ILUCs. According to this, sugarcane ethanol would qualify as an advanced biofuel to meet the RFS. The EPA also lists reductions achieved by corn ethanol including ILUCs. EPA's estimates range from -1% for a new coal-fired ethanol refinery to 47% for a dry mill natural gas refinery with wet DDGS including ILUCs (EPA 2010).

3.5 Numerical Results

The ethanol cost data presented in section 3.3 is used to calibrate the numerical model described in section 3.1. This model is then used to quantify the market and welfare effects of the US biofuel mandate under various scenarios on the cost of importing ethanol from Brazil. The data on GHG emissons is also used to calculate the level of GHG emissions associated with each scenario.

Table 3.6 shows the various scenarios considered in the numerical simulation and the welfare and market effects associated with those scenarios. The numerical results for the mandate scenerio are presented using the central exchange rate of US\$1 = R\$2.15, as well as the minimum and maximum exchange rates observed from 1999 to 2009. The baseline scenario in 2015 with no biofuel mandate, but with a biofuel subsidy and import tariff is shown in the first column. As expected, without a biofuel mandate, total demand for ethanol is only 5.8 B gallons and demand for gasoline is 145 B gallons. With the biofuel mandate (Columns 2 - 5), ethanol consumption for traditional and advanced biofuel is fixed at the mandate, and gasoline demand is 6-8% lower. However, depending on the exchange rate and the presence of other biofuel policies, the share of corn and sugarcane ethanol varies.

With an exchange rate of US\$1 = R\$2.15, the cost of importing sugarcane ethanol is lower than the domestic production cost of corn ethanol [8]. Thus, US imports of sugarcane ethanol exceed the advanced biofuel mandate at 6.32 B gallon, and domestic production is 10.18 B gallons. The demand price of corn and sugarcane ethanol are equal at \$4.52 per gallon [9]. Similar to the case above, when the exchange rate increases by 40% to US\$1 = R\$3.11, the demand price of imported ethanol (\$3.34

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[8] The excess supply elasticity of sugarcane ethanol from Brazil is assumed to be more elastic than domestic corn ethanol supply. Thus, the cost of sugarcane ethanol is lower than corn ethanol in 2015 even through the reverse is true in 2007.

[9] Markups of ethanol producers in 2007 was at record levels. If mark-ups are lower in 2015, the price levels for ethanol would generally be lower than those reported here

per gallon) is lower than the domestic production cost of \$3.79 per gallon. However, since the price of imports is lower than in the previous case, imports increase to 9.12 B gallons of ethanol. On the other hand, when the exchange rate decreases by 16% to US\$1 = R\$1.81, the quantity of imported ethanol drops to 4.52 B gallons.

The last column shows market effects of removing the \$0.45 per gallon ethanol subsidy and the import tariff of \$0.54 per gallon plus 2.5% ad valorem. Ethanol imports are 7.58 B gallons, which is higher than the other cases where a subsidy and tariff are imposed, except for the case where the exchange rate is US\$1 = R\$3.11. Removing the subsidy and tariff increases the price of domestic ethanol, lowering its demand, and decreases the price of imported ethanol, increasing its demand. However, the drop in the demand price of ethanol in the case where the exchange rate is US\$1 = R\$3.11 is still greater than the case without the subsidy and tariff. The total consumption of miles increase due to the lower overall price of fuel. This result is driven by the lower gasoline price. Despite the mandate, gasoline still accounts for almost 90% of fuel use.

The welfare effect of the mandate is given in the third row from the bottom of Table 3.6. Given an exchange rate of US\$1 = R\$2.15, the welfare loss with the mandate compared to the 2015 baseline without a mandate is \$13.4 B. The loss in welfare is mainly due to the higher cost of ethanol inputs. With a higher exchange rate of US\$1 = R\$3.11, welfare increases by \$4.6 B with the mandate due to the availability of lower cost ethanol from Brazil. On the other hand, an unfavorable change in exchange rates to US\$1 = R\$1.81 reduces the purchasing power of the US dollar, leading to lower imports at higher prices. The result is that the welfare cost of the mandate increases to \$23 B. The last column shows the welfare effect of removing the existing biofuel subsidy and import tariff, while keeping the mandate. The loss in welfare is \$9 B, which shows that the presence of these policies exacerbate the welfare loss caused by the mandate.

The last two rows show the effect on GHG emissions. GHG emissions decrease with the mandate for all scenarios considered, with the greatest decrease occuring with an exchange rate of US\$1 = R\$3.11, which is consistent with the higher share of sugarcane ethanol. The increase in GHG emissions is consistent the result obtained by Ando, Khanna, and Taheripour (2010), who also consider the environmental effect of the EISA RFS mandate.

Table 3.7 shows the case with a less elastic excess supply curve. The price of domestic and imported ethanol are higher for all scenarios with the mandate. Quantities imported are also lower, which is consistent with the higher price. With an exchange rate of US\$1 = R\$1.81, the cost of imported ethanol is higher than domestically produced ethanol. Thus only the minimum required by the advanced biofuel mandate is imported. As expected, the welfare cost of the mandate for each of scenario is higher than in the previous case with a more elastic excess supply curve. Also since the excess supply is not very price responsive, changing exchange rates have a lesser impact on the welfare cost of the mandate.

Table 3.8 shows the sensitivity of the results to a the gasoline supply elasticity (ϵ^g). With $\epsilon^g = 10$, instead of $\epsilon^g = 2$ at the baseline, gasoline consumption decreases by 9-10% while gas prices decrease only slightly at 1%. The result is that ethanol has a higher share in fuel consumption. Because gasoline consumption is able to adjust more to the increase biofuel demand, miles consumption changes only slightly. As a result of the attenuated increase in miles demand, and the greater share of ethanol in the fuel mix, the decrease in GHG emissions is greater at 7-9%. Lower total expenditures on gasoline and greater GHG reduction lead to lower welfare losses with the mandate, and a higher welfare gain in the case with an exchange rate of US$2.15 = R$3.11.

3.6 Conclusions

The analysis in this chapter shows that the cost of importing ethanol from Brazil could have a substantial impact on the welfare cost of the US RFS mandate. The elasticity of Brazil's excess supply curve for sugarcane ethanol, and the prevailing exchange rate would determine th cost of sugarcane imports. Numerical simulations show that the welfare effect of the mandate in the ethanol market ranges from -$23 to +$5 Billion in 2015, given a range of exchange rates of US$1 = R$1.81 to US$1 = R$3.11.

In this chapter, detailed data on the cost of production of corn ethanol and sugarcane ethanol are presented, along with their corresponding GHG emissions. The results of this study reveal that the general perception that costs of sugarcane ethanol are lower than those of corn ethanol is not always valid and depends crucially on the prevailing exchange rate as well as the price of feedstocks, especially if one includes the cost of transportation of ethanol from Brazil to the US port and the co-product credits to US corn ethanol refineries. The analysis in this study suggests that at present, if prevailing market conditions continue, then the potential for sugarcane ethanol to meet the part of the RFS mandate allocated to "traditional biofuel" is limited.

Although the cost of importing sugarcane ethanol in 2006-2008 is close to the domestic cost of corn ethanol production, the cost of sugarcane ethanol in 2015 could be lower than that of corn ethanol if the excess supply elasticity of sugarcane ethanol is larger than that of corn ethanol. Even if the production cost of sugarcane ethanol is lower in 2015, changes in the exchange rate still affect the level of importation and the welfare effect of the US RFS mandate. In 2015, traditional biofuel would account for 42% of total biofuel demand while advanced biofuel would be 9% of total biofuel demand. As the share of the advanced biofuel mandate increases relative to domestically produced biofuel, the sensitivity of the cost of meeting the RFS mandate to the variability in the cost of importing sugarcane ethanol is likely to be amplified. A useful extension of this work is to incorporate uncertainty about future exchange rates or feedstock prices, in order to determine the likelihood of particular market and welfare outcomes due to the US RFS mandate.

The analysis here does not consider in-country transportation cost of ethanol within the US. It is possible that it is less costly to ship sugarcane ethanol (say to California) from Brazil rather than transport ethanol from the midwestern US. This may explain the imports observed in 2007. In addition, since ethanol demand was above the mandate in 2007, demand-side factors may be driving the ethanol price, instead of the cost of production. If the price of gasoline is high enough, it would be cost-effective to blend sugarcane ethanol with gasoline, even is sugarcane ethanol is more expensive than corn ethanol.

3.7 Figures and Tables

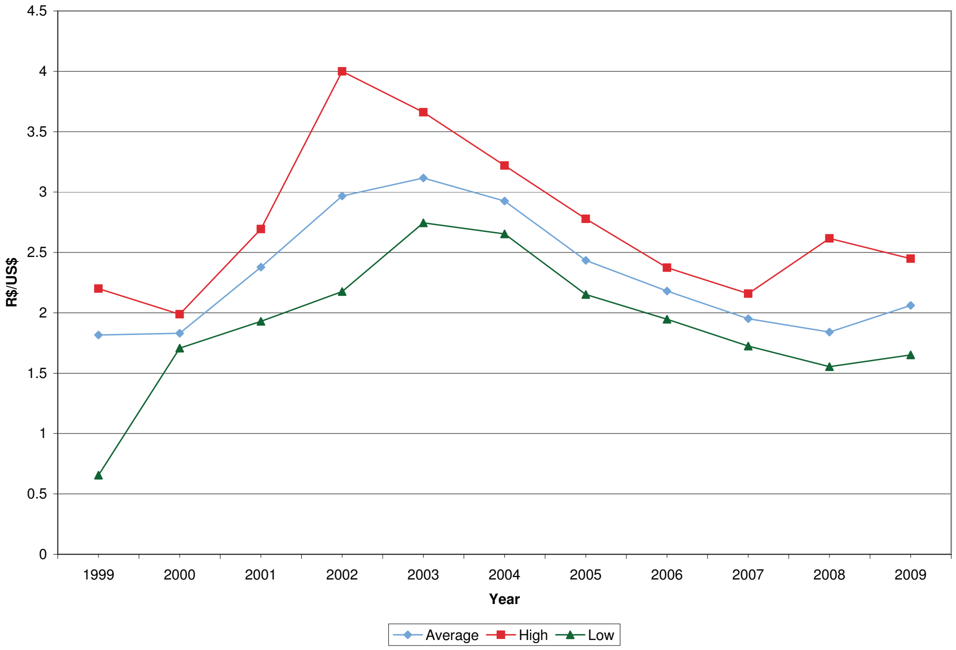

Figure 3.1: Exchange Rates for Brazilian *Reias* to US Dollars (1999-2009)

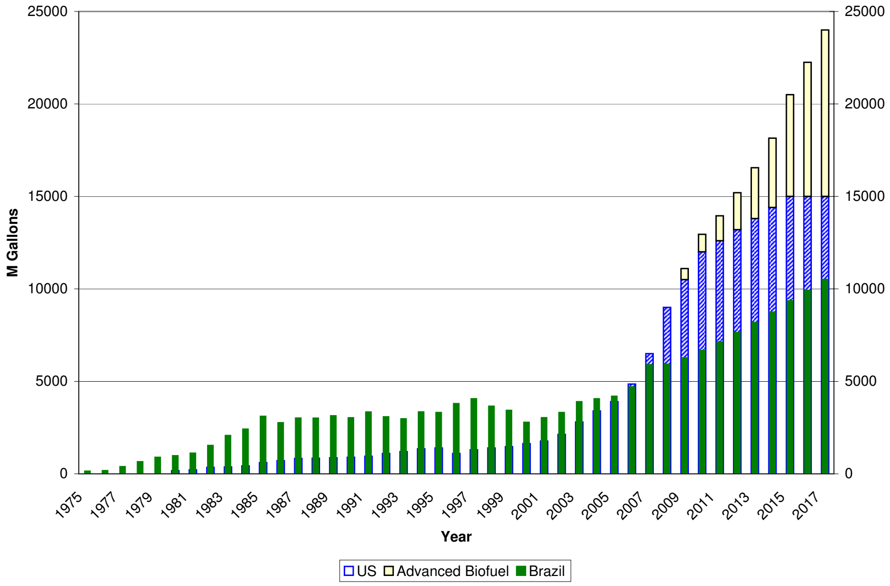

Figure 3.2: Historical and Projected Ethanol Production in the US and Brazil (Source: RFA, InfoFNP)

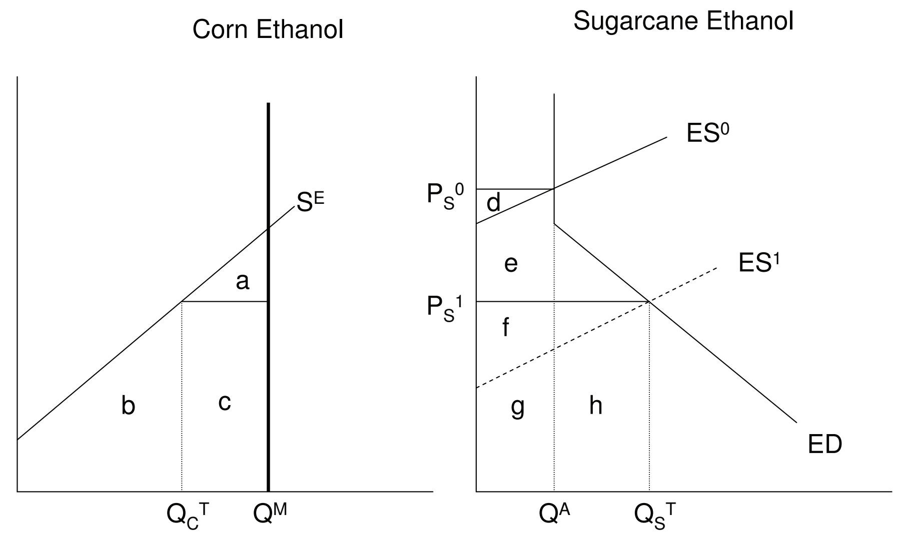

Figure 3.3: Welfare Cost of a Mandate

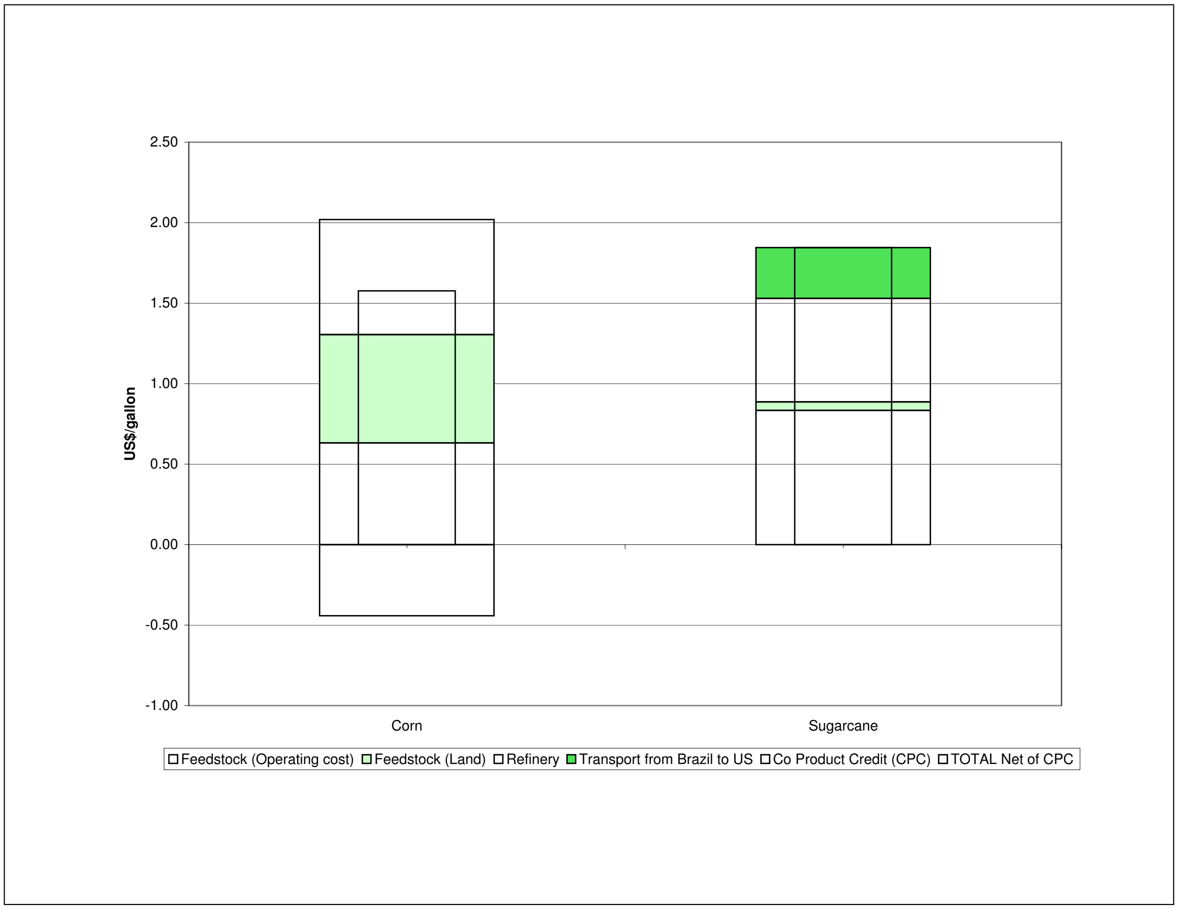

Figure 3.4: Cost of Ethanol Production (Data are from Present Research)

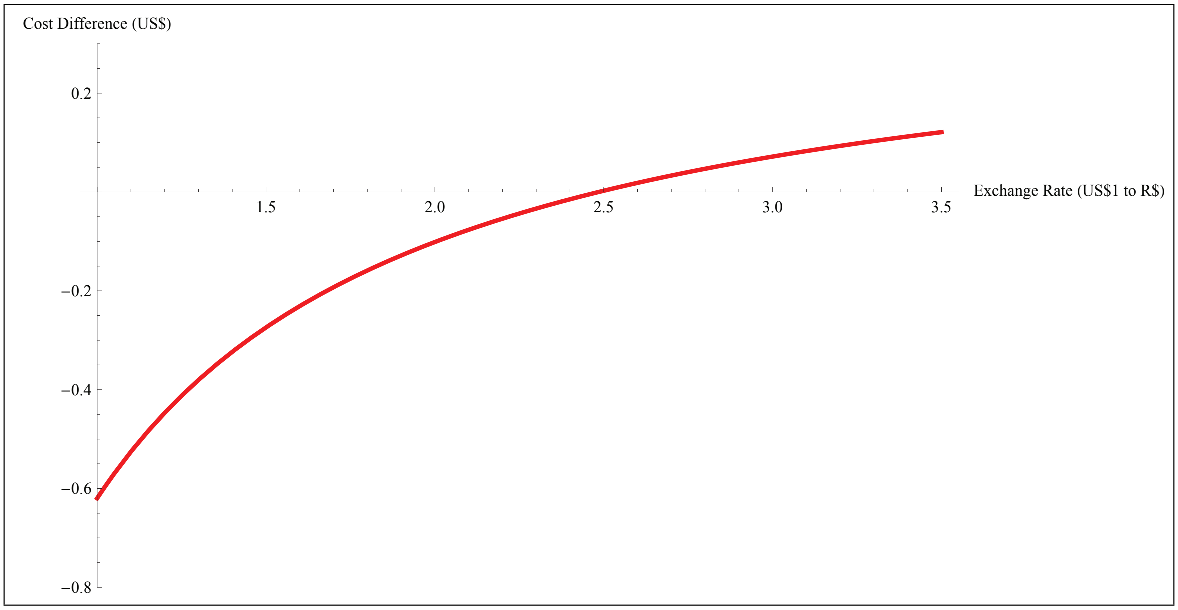

Figure 3.5: Sensitivity of Cost Difference to Exchange Rates

Table 3.1: Annual Costs of Sugarcane Production in So Paulo, Brazil (2007)

	Planting Year	1st Harvest	2nd Harvest	3rd Harvest	4th Harvest	5th Harvest	Average
Feedstock Yield (Mt per ha)	0	122.4	97.2	87.3	76.82	67.34	75.2
Ethanol Yield (L per ha)	0	10244.9	8135.6	7307	6429.8	5636.4	6134.4
Cost Items (R$ per ha)							
Fertilizers	643.95	526.5	526.5	526.5	526.5	526.5	546.1
Chemicals	413.28	184.85	184.85	184.85	184.85	184.85	222.9
Seed	868	0	0	0	0	0	144.7
Machinery and Hire	1572.64	1859.56	1544.82	1446.24	1274.87	1156.46	1475.8
Transportation to refinery	0	818.15	649.71	583.54	513.48	450.12	502.5
Total Operating Cost (R$ per ha)	3497.87	3389.07	2905.88	2741.13	2499.7	2317.93	2891.9
Total Operating Cost (R$ per gallon)							1.78

Source: InfoFNP, Market data

Table 3.2: Estimated Cost of Corn and Sugarcane Ethanol in the US and Brazil (2007)

	Feedstock				
	Sugarcane				Corn
	R$	US$	US$	US$	US$
Cost Items (per ha)		US$1=R$1.81	US$1=R$2.15	US$1=R$3.11	
Fertilizers	546.08	301.70	253.99	175.59	226.18
Nitrogen					134.22
Phosphorous					52.19
Potassium					29.89
Lime					9.88
Chemicals	222.92	123.16	103.68	71.68	106.26
Seed	144.67	79.93	67.29	46.52	110.78
Machinery, Repairs, Fuel, and Hire	1475.77	815.34	686.4	474.52	217.45
Transportation to refinery	502.5	277.62	233.72	161.58	37.36
Total Operating Cost per ha (a)	2891.93	1597.75	1345.08	929.88	698.03
Total Operating Cost per gallon	0.47	0.26	0.22	0.15	0.17
Return to Land and Management (b)	182.04	100.58	84.67	58.54	745.44
Total Feedstock Cost per ha (a+b)	3073.97	1698.33	1429.76	988.42	1443.47
Feedstock Cost per gallon	1.9	1.05	0.874	0.61	1.292
Refinery Costs per gallon (c)	1.368	0.76	0.646	0.44	0.722
Inputs	1.14	0.64	0.532	0.37	0.608
Depreciation	0.228	0.13	0.114	0.07	0.114
Total Domestic Cost (a+b+c)	3.268	1.82	1.52	1.06	2.014
Transport from Refinery to US Port (d)	0.684	0.38	0.304	0.22	N/A-
(Co-product Credit per gallon of Ethanol)	0	0.00	0	0.00	-0.456
Total Cost per gallon of Ethanol (a+b+c+d)	3.952	2.19	1.862	1.28	1.558

Table 3.3: Costs of Production of Sugarcane Mills

Company	Sugarcane Milling (Mt)	Net Sales (R$ M)	COGS (R$ M)	SG&A (R$ M)	Total Cost (R$ M)	Total Cost/ Anhydrous Equivalent Ethanol* (R$ per gallon)
Colombo	4.4	488	295	43	339	2.74
Bazan	3.4	370	223	44	267	2.81
Guarani	8.2	790	490	113	604	3.00
Generalco	1.2	100	69	8	76	3.00
Bela Vista	2.5	265	184	21	204	3.04
Santa Adlia	2.1	232	180	0	180	3.04
Alto Alegre	3	462	286	80	366	3.12
S. Js da Estiva	2.2	212	145	24	169	3.12
Equipav	4.4	424	285	55	341	3.15
Cosan	36.2	3,605	2,481	528	3,009	3.27
Pioneiros	1.3	142	102	17	120	3.31
So Martinho	9.3	827	571	130	701	3.34
Santa Isabel	2.5	228	177	19	196	3.38
Mandu	1.8	150	112	19	132	3.46
Nova Amrica	5.8	1,244	958	184	1,141	3.61
Furlan	1.5	116	102	5	107	3.65
Carolo	2.2	212	182	15	197	3.65
Itaiquara	2.2	253	183	59	242	3.72
Albertina	1.4	153	120	28	148	3.80
J. Pilon	1	80	66	14	80	3.91
Total	97	10,352	7,211	1,406	8,617	-
Average	4.8	518	360	70	431	3.27
Median	2.3	242	182	26	201	3.31

Source: Annual reports and financial statements from mills. * Cost adjusted for product mix.

Table 3.4: GHG Emissions from Corn and Sugarcane Ethanol (kg $CO_2 - eq$ per gallon)

INPUTS	Corn**	Sugarcane	Sources of data for Sugarcane
Fertilizers	1.86	0.80	
Nitrogen	1.48	0.49	Calculations using GREET 1.8
Phosphorous	0.08	0.04	Calculations using GREET 1.9
Potassium	0.04	0.04	Calculations using GREET 1.10
Lime	0.27	0.23	Calculations using GREET 1.11
Chemicals	0.04	0.04	
Herbicide	0.00	0.04	Calculations using GREET 1.8
Insecticide/Nematicide	0.00	0.00	Calculations using GREET 1.9
Ripener	0.00	0.00	
Seed	0.00	0.00	Calculations using GREET 1.9
Machinery repairs, fuel and hire	0.23	0.42	Macedo and Seabra (2008)
Trash Burning in field	0.00	0.30	Macedo and Seabra (2008)
Feedstock Total	2.13	1.60	
Transportation of feedstock to refinery	0.19	0.11	Macedo and Seabra (2008)
Refinery	3.08	0.08	Macedo and Seabra (2008)
Domestic Total	5.40	1.79	
Co-product Credit	-0.91	0.00	
Transportation from Refinery	N/A	0.30	Calculations using CA-GREET
to US Port (Philadelphia)	0.00	0.00	
TOTAL	4.45	2.09	

**Emissions for corn ethanol are based on the author's calculations using coefficients from GREET 1.8, except for Refinery and Co-product Credit which are from CA-GREET.

Table 3.5: Baseline Data and Parameters (2007)

	Unit	**Value**
Price of corn	US$	3.65
Price of ethanol (retail)	US$	2.41
Price of gasoline (retail)	US$	2.91
Qty corn produced	B bushels	13
Qty corn for ethanol	B bushels	3
Qty ethanol produced	B gallons	5.4
Qty ethanol imports	B gallons	0.3
Qty miles driven	B miles	3030
Price elasticities		
Corn supply		0.25
Ethanol supply		1.5
Gasoline supply		2
Ethanol import supply		10
Corn demand		−0.17
Miles demand		−0.40
GHG Intensities		
Gasoline	kg C/gallon	3.2
Corn ethanol	kg C/gallon	1.2
Sugarcane ethanol	kg C/gallon	0.60
Marginal Disutility of Carbon	US$/ton C	25.0

Table 3.6: Welfare Effect and Market Effects of Changes in Exchange Rate and Biofuel Policy, $\eta^{ES} = 10$

	No Mandate	Mandate	Mandate	Mandate	Mandate
		Base XR	High XR	Low XR	No Sub&Tar
		US$1=R$2.15	US$1=R$3.11	US$1=R$1.81	US$1=R$2.15
PRICES					
Corn	3.73	4.54	4.06	4.8	4.34
		0.22	*0.09*	*0.29*	*0.16*
Ethanol	2.64	4.52	3.34	5.25	4.45
		0.71	*0.27*	*0.99*	*0.69*
Imports	2.64	4.52	3.34	5.25	4.45
		0.71	*0.27*	*0.99*	*0.69*
Gasoline	3.03	2.9	2.9	2.89	2.9
		-0.04	*-0.04*	*-0.04*	*-0.04*
Miles	0.14	0.13	0.13	0.13	0.13
		-0.03	*-0.03*	*-0.03*	*-0.03*
QUANTITIES					
Corn	13.07	13.73	13.35	13.92	13.57
		0.05	*0.02*	*0.06*	*0.04*
EthanolDemand	5.79	16.5	16.5	16.5	16.5
		1.85	*1.85*	*1.85*	*1.85*
Ethanol Supply	5.77	10.18	7.38	11.98	8.92
		0.76	*0.28*	*1.08*	*0.55*
Ethanol Import	0.02	6.32	9.12	4.52	7.58
		301.06	*434.73*	*214.8*	*361.13*
Gasoline	144.62	134.68	133.23	135.26	134.61
		-0.07	*-0.08*	*-0.06*	*-0.07*
Miles	3270.85	3310.31	3317.42	3307.49	3310.63
		0.01	*0.01*	*0.01*	*0.01*
WELFARE and EMISSIONS					
WelfareChange		-13.99	4.57	-22.97	-8.95
GHG Emissions	0.47	0.447	0.441	0.45	0.446
		-0.05	*-0.06*	*-0.04*	*-0.05*

Numbers in italics are percent changes relative to the baseline.

Table 3.7: Welfare Effect and Market Effects of Changes in Exchange Rate and Biofuel Policy, $\eta^{ES} = 2.7$

	No Mandate	Mandate Base XR US\$1=R\$2.15	Mandate High XR US\$1=R\$3.11\$	Mandate Low XR US\$1=R\$1.81	Mandate No Sub&Tar US\$1=R\$2.15
PRICES					
Corn	3.73	5.16	4.96	5.23	5.11
		0.38	*0.33*	*0.4*	*0.37*
Ethanol	2.62	6.33	5.72	6.57	6.64
		1.42	*1.18*	*1.51*	*1.54*
Imports	2.62	6.33	5.72	7.19	6.64
		1.42	*1.18*	*1.75*	*1.54*
Gasoline	3.03	2.89	2.89	2.89	2.89
		-0.04	*-0.04*	*-0.04*	*-0.04*
Miles	0.14	0.14	0.13	0.14	0.14
		-0.02	*-0.03*	*-0.02*	*-0.02*
QUANTITIES					
Corn	13.07	14.17	14.04	14.22	14.14
		0.08	*0.07*	*0.09*	*0.08*
EthanolDemand	5.87	16.5	16.5	16.5	16.5
		1.81	*1.81*	*1.81*	*1.81*
Ethanol Supply	5.73	14.75	13.17	15	14.38
		1.57	*1.3*	*1.62*	*1.51*
Ethanol Import	0.14	1.75	3.33	1.5	2.12
		11.2	*22.26*	*9.48*	*13.79*
Gasoline	144.58	135.88	135.56	135.99	136.02
		-0.06	*-0.06*	*-0.06*	*-0.06*
Miles	3271.35	3304.45	3306.01	3303.94	3303.78
		0.01	*0.01*	*0.01*	*0.01*
WELFARE and EMISSIONS					
WelfareChange		-33.4	-27.82	-35.31	-27.92
GHG Emissions	0.47	0.454	0.452	0.454	0.454
		-0.03	*-0.04*	*-0.03*	*-0.03*

Numbers in italics are percent changes relative to the baseline.

Table 3.8: Welfare Effect and Market Effects of Changes in Exchange Rate and Biofuel Policy, $\epsilon^g = 10$

	No Mandate	Mandate Base XR US\$1=R\$2.15	Mandate High XR US\$1=R\$3.11\$	Mandate Low XR US\$1=R\$1.81	Mandate No Sub&Tar US\$1=R\$2.15
PRICES					
Corn	3.71	4.54	4.06	4.8	4.34
		0.22	*0.09*	*0.29*	*0.17*
Ethanol	2.6	4.52	3.34	5.25	4.45
		0.74	*0.29*	*1.02*	*0.71*
Imports	2.6	4.52	3.34	5.25	4.45
		0.74	*0.29*	*1.02*	*0.71*
Gasoline	2.94	2.9	2.9	2.9	2.9
		-0.01	*-0.01*	*-0.01*	*-0.01*
Miles	0.13	0.13	0.13	0.14	0.13
		0	*0*	*0*	*0*
QUANTITIES					
Corn	13.06	13.73	13.35	13.92	13.57
		0.05	*0.02*	*0.07*	*0.04*
EthanolDemand	5.7	16.5	16.5	16.5	16.5
		1.9	*1.9*	*1.9*	*1.9*
Ethanol Supply	5.68	10.18	7.38	11.98	8.92
		0.79	*0.3*	*1.11*	*0.57*
Ethanol Import	0.02	6.32	9.12	4.52	7.58
		355.77	*513.65*	*253.89*	*426.72*
Gasoline	146.49	132.87	131.49	133.42	132.81
		-0.09	*-0.1*	*-0.09*	*-0.09*
Miles	3309.89	3306.71	3314.93	3303.45	3307.08
		0	*0*	*0*	*0*
WELFARE and EMISSIONS					
WelfareChange		-9.08	9.57	-18.11	-4.03
GHG Emissions	0.476	0.441	0.435	0.444	0.44
		-0.07	*-0.09*	*-0.07*	*-0.08*

Numbers in italics are percent changes relative to the baseline.

Chapter 4: Carbon Abatement in the Fuel Market with Biofuels: Implications for Second-Best Policies

Reducing greenhouse gas (GHG) emissions is critical to mitigating climate change and achieving greater energy security. The transport sector accounts for about 30% of total emissions in the United States, with 97% coming from fossil fuel combustion. Thus, reducing emissions from the transport sector is crucial to reducing overall emissions. Studies have shown that a tax on fuel is an effective and efficient instrument for reducing environmental externalities, and several studies have proposed second-best optimal fuel tax rates for gasoline in the presence of a labor market distortion (West and Williams 2007; Parry and Small 2005a).

However, the availability of biofuel as a fuel source is likely to affect the design and magnitude of the optimal fuel tax. Since gasoline and biofuel have different emission intensities, a carbon-based tax would be more appropriate compared to a volumetric tax. A carbon-based tax on fuels will tax both fuels in proportion to their GHG intensity and lead to the the least-cost combination of fuel substitution and fuel reduction to reduce carbon emissions [10]. Biofuel production is also land intensive and competes with other land-using production activities like agriculture for limited land inputs. Thus, a tax-induced change in biofuel production could affect the price of land or land rent. A change in land rent would in turn affect income and the prices of commodities using land as an input. In the presence of a labor market distortion

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[10] GHG intensity is measured in carbon equivalent emissions per unit of fuel. The carbon tax is levied on carbon emissions (not carbon dioxide emissions).

such as a labor tax, changing commodity prices add to the adverse effects of higher fuel prices on real wages and on labor supply. Thus, with biofuels included in the fuel mix, the effect of the tax on fuel and labor markets, as well as agricultural markets are important considerations for setting an optimal fuel tax.

One of the main drawbacks of a carbon tax is that it may be politically infeasible to implement. Compared to other developed countries, the US has one of the lowest gasoline tax rates (Hoo and Ebel 2005). The lower carbon intensity of biofuel compared to gasoline expands the options for reducing carbon emissions from the transportation sector from simply reducing gasoline consumption and vehicle miles traveled to also displacing gasoline by biofuels. Unlike a tax, policies that encourage greater domestic biofuel production and consumption through the use of subsidies and mandates appear to garner more political support. Thus it is important to determine the welfare effects of these policies compared to a carbon tax, and examine to what extent these policies could achieve the objectives of a carbon tax.

The use of taxes to internalize externalities dates back to Pigou (1932) and was later applied more specifically to environmental externalities in the works of Baumol and Oates (1971) and Baumol (1972). In a first best setting with perfect markets and no other distortions other than a single externality, the optimal tax is the Pigouvian tax, which is equal to the marginal external damage (MED) of the externality. When other distortions persist, the best policy is a “second-best” policy because the true optimum cannot be attained.

More recent literature focuses on finding the second-best optimal tax, recognizing the interaction of an environmental tax with other market distortions (Goulder

1995a; Bovenberg and Goulder 1996; Bovenberg and van der Ploeg 1994). The double dividend literature, which explores the possibility of using revenues from environmental taxation to decrease an existing labor tax is closely related to the literature on optimal environmental taxes. If environmental taxes can lower the labor tax rate (i.e. generate a double dividend) the second-best optimal tax may exceed the Pigouvian tax rate. The current theoretical and empirical evidence suggests that in general, the optimal environmental tax is lower than marginal external damages (i.e no double dividend exists) because the welfare gains from using an environmental tax to reduce the labor tax is not sufficient to compensate for its negative impact of exacerbating the distortion in the labor market and reducing the allocative efficiency of consumption (see Goulder (1995b) and Bovenberg (1999) for a comprehensive discussion). However, Parry (1995) argues that it is possible to gain a double-dividend if the taxed commodity is a relatively weak substitute for leisure implying that the optimal environmental tax is above the MED. West and Williams (2007) and Parry and Small (2005a) derive the second-best optimal tax rate for gasoline and conclude that due to gasoline being a weak substitute for leisure (in Parry and Small (2005a)) or a complement to leisure (in West and Williams (2007)), the second-best optimal gas tax is above the Pigouvian tax rate.

Bento and Jacobsen (2007) and Bovenberg and Van der Ploeg (1998) also show that the use of a fixed input either in the production of a dirty good or together with a dirty input increases the likelihood of a double-dividend and contributes to raising the optimal tax above the Pigouvian rate by shifting the burden of the tax from labor to the fixed input [11]. In a model where a dirty input is used together with labor and a fixed input, Bovenberg and Van der Ploeg (1998) show that if labor is a better substitute for the dirty input compared to the fixed input, and the fixed input has a large share in total input use, a tax on the dirty input increases labor supply. In a framework with a dirty output that uses labor and a fixed factor (land), Bento and Jacobsen (2007) show that a tax on the dirty good leads to an increase in labor supply because part of the tax burden falls on the fixed input as demand for the fixed input falls when the dirty good is taxed. The price of the dirty good falls with the lower fixed input price, mitigating the tax-induced rise in prices that cause labor supply to decrease.

The purpose of this paper is to derive the second-best optimal carbon tax for gasoline and biofuel and determine the welfare effect of a revenue-neutral change in the carbon tax. The policy experiment considered is a revenue neutral increase in the carbon tax rate, with revenues from the carbon tax used to reduce the labor tax. I also consider a model in which a fixed biofuel subsidy also exists in addition to the carbon tax and labor tax.

This paper extends the literature on fuel taxation by examining the welfare effects and tax policy implications of including biofuels in the fuel mix. I extend the model developed by Parry and Small (2005a) to consider the inclusion of biofuels while recognizing the competition they pose for land use, and their implication for the price of other consumption goods using land as an input.

In addition, I also examine the effect of a marginal increase in a subsidy rate,

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[11] Both Bento and Jacobsen (2007) and Bovenberg and Van der Ploeg (1998) make the assumption that profits or rents from the fixed input cannot be fully taxed by the government.

holding revenue and the carbon tax rate fixed but allowing the labor tax to vary. Although previous studies show that deadweight losses result from the current biofuel subsidy, none of these studies have examined the interaction of these policies with the broader tax system, as I do in this paper (Elobeid and Tokgoz 2008; de Gorter and Just 2008). However, in the presence of a labor tax, an output subsidy could increase labor demand and lower the disortion in the labor market. Thus, it is important to determine whether this benefit exists and whether it is sufficient to yield an overall welfare gain, given that a subsidy would also affect land rent.

This paper also contributes to the literature on optimal environmental taxation and double-dividend, in particular, those that focus on the effect of using a fixed factor (land) on labor supply. The model presented here is comparable to that of Bento and Jacobsen (2007), although the model has two dirty goods with different pollution intensities. In addition, land use is fixed to the production of the less dirty good (biofuel) and the clean good (agricultural goods), but is mobile within the two production activities. I show that unlike the result obtained by Bento and Jacobsen (2007), a tax on dirty consumption could either raise or the lower the tax burden on land, so the effect of the tax on labor supply is ambiguous.

Applying the analytical model to the US fuel market, I find that the second-best optimal carbon tax is higher than the Pigouvian tax rate, due to the positive revenue recycling effect on labor supply which more than compensates for the negative tax interaction effect and commodity price effect on labor supply. The presence of biofuel in the fuel mix affects the value of the second-best optimal tax due to a commodity price effect which arises from tax-induced changes in land rent. The commodity price effect could exacerbate or attenuate the tax interaction effect caused by higher fuel prices, depending on the elasticity of substitution between gasoline and biofuel, the price elasticity of miles demand, and the relative emissions intensity of gasoline and biofuel. In addition, the existence of a fixed biofuel subsidy leads to a greater divergence between the value of the second-best optimal carbon tax with or without biofuels. Increasing the biofuel subsidy has a positive GHG reduction effect, but its negative impact on labor supply through changes in the labor tax rate more than offsets this positive effect.

The results of this paper highlight the importance of considering the impact of biofuel in designing policies in the fuel sector. Particularly, in setting a carbon tax rate, it is important to determine whether the carbon tax will lead to an increase or decrease in biofuel demand. The results of this study also strenghten the case for carbon taxes, since I find that even in the presence of other policy alternatives such as a biofuel subsidy, a tax on carbon is still the better policy option for reducing GHG emissions in the fuel sector.

The paper proceeds as follows : Section 4.1 presents the analytical model used to derive the second-best optimal carbon tax. In Section 4.2, I examine the effect of a biofuel subsidy on GHG emissions, labor supply, and welfare. Section 4.3 discusses data and parameters used in the numerical simulations. Section 4.4 presents estimates of the second-best optimal carbon tax and corresponding fuel taxes, as well as welfare effects of a carbon tax and biofuel subsidy. Section 4.5 concludes.

4.1 The Analytical Model

The representative consumer derives income from labor (L) provided to firms. Labor is equal to a fixed time endowment ($\overline{L}$) minus leisure ($\acute{L}$), $L = \overline{L} - \acute{L}$. Additionally, the consumer owns a fixed amount of land (K) and derives income from land rent (R). The tax rate on labor is denoted by T^L and the wage rate is W, which is set to unity and held constant. Thus the total income, I is:

$$I = (1 - T^L)WL + RK \tag{16}$$

The representative consumer derives utility from leisure ($\acute{L}$), and consumption of agricultural goods (A) which is a clean good, and gasoline (G) and biofuel (B) which are dirty goods used to produce miles (M). Additionally, consumers derive utility from public goods (Y) and disutilty from greenhouse gas (GHG) emissions which are an externality of gasoline and biofuel consumption. Let δ^G and δ^B denote the GHG intensity of gasoline and biofuel respectively, measured in carbon equivalents, where $\delta^G > \delta^B$ so that total emissions (E) is $E = \delta^G G + \delta^B B$.

The consumer's utility function is:

$$U = u(\acute{L}, M(G, B), A) - \phi E + Y \tag{17}$$

where u is strictly concave. The utility function exhibits weak separability between leisure and the consumption of miles and the agricultural good, and strong separability between those goods and externalities and public goods. The price per mile is $P^M = \frac{G}{M}(P^G + T^G) + \frac{B}{M}(P^B + T^B)$ where P^i and $T^i, i = G, B$ are gasoline and biofuel prices and per unit tax rates, respectively. The expression for P^M is derived using the homogeneity property of miles production and Euler's theorem. A fuel tax is levied on gasoline and biofuel such that the tax on each fuel is proportional to their GHG emissions, i.e., $T^i = T^C \delta^i$, $i = G, B$ and T^C is the carbon tax. The price of agricultural goods is denoted P^A.

Firms are owned by the representative consumer. Firms minimize cost and produce agricultural goods, gasoline and biofuel at zero profit. Gasoline is produced using only labor, while agricultural goods and biofuel are produced using labor and land. The production function for gasoline follows a one input production technology given by $G = G(L_G)$, while the production function for biofuel and agricultural goods are given by $B = B(L_B, K_B)$ and $A = A(L_A, K_A)$. The government taxes labor to provide public goods, and it engages in pollution abatement by taxing fuel accoring to their GHG intensity.

The consumer's maximization problem is:

$$\begin{aligned} &\max_{\acute{L},G,B,A} U = u(\acute{L}, M(G,B), A) - \phi E + Y \quad s.t. \\ &\lambda[I - (P^G + \delta^G T^C)G - (P^B + \delta^B T^C)B - P^A A] \end{aligned} \tag{18}$$

The first-order conditions (FOCs) of the utility maximization problem are:

$$L : u_L - \lambda(1 - T^L) = 0 \tag{19}$$

$$G : u_M M_G - \lambda(P^G + \delta^G T^C) = 0 \tag{20}$$

$$B : u_M M_B - \lambda(P^B + \delta^B T^C) = 0 \tag{21}$$

$$A : u_A - \lambda P^A = 0 \tag{22}$$

where subscripts denote partial derivatives. The FOCs above imply that the marginal utility from leisure and other goods is equated to their respective prices multiplied by λ, which can be interpreted as the marginal utility of income. For gasoline and biofuel, (20) and (21) show that their respective prices are equated to the contribution of each fuel to total utility, which is denoted by product of the marginal utility of miles and the marginal product of each fuel.

Substituting the solution of (18) in the utility function, the indirect utility function (V) is derived, with the carbon tax, T^C as its argument:

$$\begin{aligned} V(T^C) = u(\acute{L}^*, M(G^*, B^*), A^*) - \phi(E) + Y + \\ \lambda[I - (P^G + \delta^G T^C)G^* - (P^B + \delta^B T^C)B^* - P^A A^*] \end{aligned} \tag{23}$$

As shown in Appendix A, the effect of a marginal increase in T^C on V is given by the following equation:

$$\frac{dV(T^C)}{dT^C} = -\frac{\phi}{\lambda}\frac{dE}{dT^C} + T^C\frac{dE}{dT^C} + T^L\frac{dL}{dT^C} \tag{24}$$

The first term on the right hand side (RHS) is the marginal benefit of reducing the level of environmental externality. Using the definition of E provided above, $\frac{dE}{dT^C} = \delta^G \frac{dG}{dT^C} + \delta^B \frac{dB}{dT^C}$. The tax will decrease the level of gasoline consumption, since gasoline has a higher emissions intensity compared to biofuel. On the other hand, the tax could either increase or decrease the consumption of biofuel. Biofuel consumption increases as it is substituted for gasoline. However because of the tax on biofuel's emissions, demand could also decrease. Although the net effect of the tax on biofuel demand is ambigious, the overall effect of the tax on emissions is negative. The second and third terms reflect the change in the economy's tax base. The second term shows the decrease in the tax base for emissions, as fuel use decreases because of the carbon tax. The third term shows the change in labor tax revenues that results from a tax-induced change in labor supply. Labor supply is a function of the exogenous variables in the indirect utility function $(T^L, T^C, P^B(R), P^A(R), R)$. By taking the total differential of labor supply, the change in labor supply for a marginal change in T^C can be expressed as:

$$\frac{dL}{dT^C} = \frac{\partial L}{\partial T^L}\frac{dT^L}{dT^C} + \frac{\partial L}{\partial T^C} + (\frac{\partial L}{\partial R} + \frac{\partial L}{\partial P^A}\frac{dP^A}{dR} + \frac{\partial L}{\partial P^B}\frac{dP^B}{dR})\frac{dR}{dT^C} \tag{25}$$

The first term on the RHS is the *revenue recycling* effect that shows the effect of the carbon tax on labor supply due to a change in the labor tax rate. The use of the revenue from carbon taxes to reduce the tax rate on labor has a positive effect on labor supply. The second term is the *tax interaction* effect which is the partial differential of the labor supply with respect to the carbon tax. A tax on carbon increases the price of taxed goods, increasing leisure demand and decreasing labor supply. These two effects are what normally constitutes the labor market impact of an environmental tax, similar to the expression in Parry and Small (2004) [12]. However, because one of the taxed commodities uses land as an input, the environmental tax also affects land rent as shown by the third term [13]. A change in land rent will affect the price of commodities that use land as an input, and also affect land rent income. The change in prices and income would then affect labor supply. If leisure is a normal good, additional income and higher prices reduce labor supply (as else equal). The change in the price of land input as a result of levying an output tax is central to the study by Bento and Jacobsen (2007). However, in their model, the tax only works in one direction, that is, to decrease the price of land, since the tax decreases demand for the land-using dirty good. However, in the model presented here with two taxed commodities of differing pollution intensities, the tax could either increase or decrease the price of land. I discuss the determinants of the effect of the tax on land rent in the next section.

4.1.1 Effect of T^{C*} on Demand for Biofuel and Land Rent

From the discussion above, the effect of the tax on biofuel demand and land rent is important in determining the net labor market and welfare effect of a carbon tax. Without loss of generality, I assume that for the purpose of deriving the effect of T^C on land rent, labor supply and the labor tax rate are fixed [14].

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[12] see Appendix section.

[13] Here I abstract from the government's ability to tax land rent income. If the government is to tax all of rent income, then a price distortion will not occur.

[14] This assumption does not affect the derived results due to the separability of leisure from consumption. Appendix C provides additional discussion.

By total differentiation of the first order conditions of (18) and the additional constraint that land use is fixed to the production of biofuel and agricultural goods, the comparative static effects of a change in T^C on G, B, and A, as well as land rent (R) is derived.

Appendix C shows that the change in land rent for a marginal change in the carbon tax is given by:

$$\frac{dR}{dT^C} = -U_{AA}\frac{dB}{dT^C} \tag{26}$$

where:

$$\frac{dB}{dT^C} = -\frac{P^M}{|D|}[\frac{\sigma}{\eta^{MM}}\left\{\delta^G M_{GB} - \delta^B \frac{M_G M_{GB}}{M_B}\right\} + (\delta^G M_{BG} - \delta^B M_{GG})] \tag{27}$$

The slope of the demand curve for the agricultural good is U_{AA} and the change in biofuel demand due to the carbon tax is $\frac{dB}{dT^C}$. The sign of U_{AA} is negative, implying that the sign of (26) depends entirely on the whether the change in biofuel production due to the carbon tax is positive or negative. If $\frac{dB}{dT^C} > 0$, then (26) is positive, and vice-versa.

Equation (27) shows that the magnitude and sign of $\frac{dB}{dT^C}$, and thus $\frac{dR}{dT^C}$ depends on several parameters, including the the elasticity of substitution between gasoline and biofuel in the production of miles, given by $\sigma = \frac{M_G M_B}{M_{GB} M}$, the relative emissions intensity of gasoline (δ^G) and biofuel (δ^B), the price elasticity of miles demand (η^{MM}), and technological parameters[15].

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[15] The definition of σ is given by Floyd (1965). The technological parameters $(M_{GB}, M_G, M_B, M_{BG}, M_{GG})$ and the determinant $|D|$ are defined in Appendix C.

The elasticity of substitution affects the extent to which B can replace G in the consumer's production of miles. Because gasoline has a higher emissions intensity than biofuel, a carbon tax will cause a greater decrease in gasoline consumption, compared to biofuel. The extent to which biofuel can be substituted for gasoline will influence the post-tax level of biofuel demand. As shown in the first term in (27) a higher value of σ will lead to a greater change in $\frac{dB}{dT^C}$ as long as the ratio of emission intensities of gasoline and biofuel is greater than the ratio of their marginal products in miles production (i.e. $\frac{\delta^G}{\delta^B} > \frac{M_G}{M_B}$). Conversely, if $\sigma = 0$ (or gasoline and biofuel are perfect complements), a carbon tax will unambiguously decrease both gasoline and biofuel consumption.

Equation (27) also shows that the effect of σ is magnified the more price inelastic miles demand is. Taxing inputs needed to produce miles raises the overall cost of consuming miles. If miles demand is price inelastic, demand for miles and fuel inputs will not decrease as much as when miles demand is elastic. Since the per unit tax on gasoline is higher than the tax on biofuel, consumption will be biased towards biofuel due to its price advantage.

Assuming that σ has a positive value, a greater reduction in emissions from biofuel relative to gasoline also increases the positive impact of the tax on biofuel demand, because the post-tax price of biofuel relative to gasoline will be lower the more biofuel reduces emissions compared to gasoline.

Numerical simulations show that depending on the combination of parameter values, biofuel demand could increase or decrease. In general, what I find is that the tax increases biofuel demand given a combination of high emissions reduction from biofuel, high elasticity of substitution, and inelastic miles demand.

Equations (25) and (26) show that the uncertainty in the welfare effect of a carbon tax is due to the ambiguous effect of the tax on labor supply and land rent. Whether the impact of the tax on welfare is positive or negative is summarized by (24). Alternatively, a positive sign of the second-best optimal carbon tax, T^{C*} would imply that introducing a carbon tax would increase welfare. The equation for T^{C*} is derived by setting $\frac{dV}{dT^C} = 0$, yielding the following expression:

$$T^{C*} = \frac{\phi}{\lambda} - T^L \frac{\frac{dL}{dT^C}}{\frac{dE}{dT^C}} \tag{28}$$

Equation (28) shows the components of the second best optimal carbon tax [16]. The first term is the marginal external damage (MED) of a unit of GHG emission, which is positive. The second term is the change in labor tax revenues. If the change in labor tax revenues is positive, then T^{C*} will be higher than the MED. If it is negative, T^{C*} will be lower than the MED. Finally, in the case where the change in labor tax revenues is negative and exceeds the MED, T^{C*} is negative.

In order to sign T^{C*} or $(T^{C*} - MED)$, it is necessary to express (28) in terms of empirically measureable components. Appendix B shows that (28) can be expressed as:

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[16] This tax is necessarily second-best because other distortions exist in the economy. The first best tax rate is equal to the MED, with no other distortions present. Note also that this carbon tax rate corresponds to a second-best optimal labor tax rate, since both are jointly determined.

$$\begin{gathered} T^{C*} = \overbrace{\frac{1}{(MEB^L+1)}\frac{\phi}{\lambda}}^{Pigouvian} + \overbrace{\frac{-T^L}{1-T^L}[T^C\frac{\epsilon^{L^CL}(\eta^{MI}-1)}{\epsilon^{ET}}]}^{TaxInteration+RevenueRecycling} \\ \underbrace{\frac{-T^L}{1-T^L}((A+B)[\epsilon^{L^CL}(\eta^{MI}-1)+\epsilon^{LL}])\frac{\gamma^{RE}}{E/R}}_{LaborMarketCommodityPriceEffect} \end{gathered} \tag{29}$$

where:

$$MEB^L = -\frac{T^L\frac{\partial L}{\partial T^L}}{L+T^L\frac{\partial L}{\partial T^L}}; \quad (1+MEB^L) = \frac{L}{L+T^L\frac{\partial L}{\partial T^L}}$$

$$\epsilon^{L^CL} = \frac{\partial L^C}{\partial T^L}\frac{(1-T^L)}{L}; \quad \epsilon^{LL} = \frac{\partial L}{\partial T^L}\frac{(1-T^L)}{L} \quad \eta^{MI} = \frac{\partial M}{\partial I}\frac{(1-T^L)L}{L}$$

$$\epsilon^{ET} = \frac{\partial E}{\partial T^C}\frac{T^C}{E}; \quad \epsilon^{RT} = \frac{\partial R}{\partial T^C}\frac{T^C}{R}; \quad \gamma^{RE} = \frac{\epsilon^{RT}}{\epsilon^{ET}}$$

The compensated labor supply elasticity with respect to the labor tax is given by ϵ^{L^CL}, while ϵ^{ET} is the emissions elasticity at the optimum. The "T^C" term that appears on the right hand side of (29) is the MED of carbon, which is the closest approximation of the second-best optimal carbon tax. The first term in (29) is the Pigouvian component, which is the MED divided by the marginal cost of public funds $(1+MEB^L)$. The MED is divided by $(1+MEB^L)$ to reflect the cost of providing public goods such as environmental quality. If $MEB^L > 0$ or $(1+MEB^L) > 1$, public funds are scarcer than private funds. Bovenberg (1999) notes that "If public revenues become scarcer, as indicated by a higher marginal cost of public funds, the optimal tax system focuses more on generating revenues and less on internalizing pollution externalities." Thus, the Pigouvian tax decreases as $(1 + MEB^L)$ increases. The second term is the sum of the tax interaction and revenue recycling effects. Parry and Small (2005) show that if $\eta^{MI} < 1$ (or miles and leisure are weak substitutes), then the revenue recycling effect exceeds the tax interaction effect. Consistent with West and Williams (2007); Parry and Small (2005a), I assume that miles and leisure are weak substitutes so the second term is also positive. The only term left to be signed is the third term, which shows the effect of the tax on labor tax revenues due to changes in the land rent. As discussed previously, an increase in land rent has a negative impact on the labor supply due to a positive income effect. The sign of the third term could be positive or negative depending on whether the change in land rent that could be attributed to the decrease in emissions due to the tax (γ^{RE}) is positive or negative.

4.1.2 Second-Best Optimal Tax with a Subsidy

With a fixed biofuel subsidy (S) the government budget constraint changes to:

$$Y = T^L L + T^C E - SB \tag{30}$$

With the subsidy rate and government budget fixed, the corresponding change in the labor tax due to a marginal change in the carbon tax is:

$$\frac{dT^L}{dT^C} = -\frac{1}{L}(E + T^C \frac{dE}{dT^C} + T^L \frac{dL}{dT^C} - S \frac{dB}{dT^C}) \tag{31}$$

Following the derivation presented in Appendix B, the change in welfare with respect to a marginal change in the carbon tax is:

$$\begin{aligned}\frac{dV(T^C)}{dT^C} = &-\frac{\phi}{\lambda}\frac{dE}{dT^C} + T^C\frac{dE}{dT^C} + \frac{MEB^L}{\epsilon^{LL}}[E\epsilon^{L^CL}\left(\eta^{MI}-1\right)] + MEB^L T^C\frac{dE}{dT^C} \\ &+\frac{MEB^L}{\epsilon^{LL}}((A+B)[\epsilon^{L^CL}(\eta^{MI}-1)+\epsilon^{LL}])\frac{dR}{dT^C} - (1+MEB^L)S\frac{dB}{dT^C} \qquad (32)\end{aligned}$$

Setting the above equation to zero gives the second-best optimal carbon tax with a fixed subsidy:

$$\begin{aligned}T^{C*} = &\overbrace{\frac{1}{(MEB^L+1)}\frac{\phi}{\lambda}}^{Pigouvian} + \overbrace{\frac{-T^L}{1-T^L}[T^C\frac{\epsilon^{L^CL}(\eta^{MI}-1)}{\epsilon^{ET}}]}^{TaxInteration+RevenueRecycling} \\ &\underbrace{\frac{-T^L}{1-T^L}((A+B)[\epsilon^{L^CL}(\eta^{MI}-1)+\epsilon^{LL}])\frac{\gamma^{RE}}{E/R}}_{LaborMarketCommodityPriceEffect}\underbrace{+(1+MEB^L)S\frac{\frac{T^C}{B}}{R/E}\frac{\epsilon^{BT}}{\epsilon^{ET}}}_{SubsidyEffect} \qquad (33)\end{aligned}$$

where:

$$\epsilon^{BT} = \frac{dB}{dT^C}\frac{T^C}{B}; \quad \epsilon^{ET} = \epsilon^{BT}(\frac{\delta^B B}{E}) + \epsilon^{GT}(\frac{\delta^G G}{E}); \quad \epsilon^{GT} = \frac{dG}{dT^C}\frac{T^C}{G}$$

To the extent that the carbon tax changes biofuel demand, the expenditures that need to be allocated for the provision of the subsidy also changes. The presence of the subsidy as an additional distortion causes the last term to appear in (32). The multiplication of the marginal cost of providing the subsidy for an additional unit of biofuel with $(1+MEB^L)$ implies that the social cost of a marginal increase in biofuel demand is the actual expenditure plus the deadweight loss associated with raising the revenue needed to finance the subsidy.

If the carbon tax increases biofuel demand, then the carbon tax will also increase the burden of subsidy provision. In this case, the presence of the subsidy will decrease the second-best optimal tax by the last term in (33).

4.2 Welfare Effect of an Increase in the Biofuel Subsidy

The welfare effects of a marginal increase in the biofuel subsidy rate is discussed in this section. Government revenue is derived only from labor taxes, and part of the government revenue is used to finance the biofuel subsidy. The government revenue is assumed to be fixed, but the labor tax rate varies with the subsidy rate.

With a biofuel subsidy, the consumer maximization problem changes to:

$$\max_{\acute{L},G,B,A} U = u(\acute{L}, M(G,B), A) - \phi(E) + Y + \lambda[I - P^G G - (P^B - S)B - P^A A] \tag{34}$$

and the first-order conditions (FOCs) are:

$$L : u_L - \lambda(1 - T^L) = 0 \tag{35}$$

$$G : u_M M_G - \lambda P^G = 0 \tag{36}$$

$$B : u_M M_B - \lambda(P^B - S) = 0 \tag{37}$$

$$A : u_A - \lambda P^A = 0 \tag{38}$$

The indirect utility function is:

$$V(S) = u(\acute{L}^*, M(G^*, B^*), A^*) - \phi(E) + Y + \lambda[I - P^G G^* - (P^B - S)B^* - P^A A^*] \quad (39)$$

Public goods are financed by labor taxes net of subsidy expenditures so $Y = T^L L - SB$. Given that the level of public goods provision is fixed, the effect of the subsidy on the labor tax is given by:

$$\frac{dT^L}{dS} = -\frac{1}{L}(T^L \frac{dL}{dS} - B - S\frac{dB}{dS}) \quad (40)$$

The effect of a marginal increase in S on V, given below is obtained by dividing the total derivative of V with the total change in S and substituting (40) in the resulting expression.

$$\frac{dV(T^C)}{dS} = -\frac{\phi}{\lambda}\frac{dE}{dS} - S\frac{dB}{dS} + T^L \frac{dL}{dS} \quad (41)$$

The first term in (41) shows the effect of the subsidy on the level of externalities. Using the definition of $E = \delta^G G + \delta^B B$, the change in GHG emissions due to a change in the subsidy is given by $\frac{dE}{dS} = \delta^G \frac{dG}{dS} + \delta^B \frac{dB}{dS}$. The subsidy will increase the consumption of biofuel and decrease the consumption of gasoline. However, it is unclear whether the increase in the consumption of biofuel will be fully offset by the decrease in gasoline consumption. Khanna, Ando and Taheripour (2008) argue that by lowering the overall price of fuel, the subsidy could cause an increase in overall fuel consumption, and thus greater GHG emissions. The result will depend on the relative changes in the use of gasoline and biofuel and their emission intensities. Thus, the effect of the subsidy on externalities is ambigious.

The second and third terms reflect the effect of the subsidy on the economy's tax base. A marginal increase in the subsidy rate will increase consumption of biofuel thus increasing the government expenditures and lowering utility (second term). The last term is the effect of the subsidy on labor supply. Taking the total derivative of labor supply and substituting (40) gives:

$$\frac{dL}{dS} = \frac{-\frac{1}{L}\frac{\partial L}{\partial T^L}(-B - S\frac{dB}{dS}) + [\frac{\partial L}{\partial R} + \frac{\partial L}{\partial P^A}\frac{\partial P^B}{\partial R} + \frac{\partial L}{\partial P^A}\frac{\partial P^A}{\partial R}]\frac{dR}{dS} + \frac{\partial L}{\partial S}}{1 + \frac{T^L}{L}\frac{\partial L}{\partial T^L}} \tag{42}$$

which can also be expressed as:

$$\begin{aligned} T^L\frac{dL}{dT^C} = -\frac{MEB^L}{\frac{\partial L}{\partial T^L}}[L\frac{\partial L}{\partial S} + B\frac{\partial L}{\partial T^L}] - MEB^L S\frac{dB}{dS} + \\ (1 + MEB^L)T^L[\frac{\partial L}{\partial R} + \frac{\partial L}{\partial P^A}\frac{\partial P^B}{\partial R} + \frac{\partial L}{\partial P^A}\frac{\partial P^A}{\partial R}]\frac{dR}{dS} \end{aligned} \tag{43}$$

where:

$$L\frac{\partial L}{\partial S} + B\frac{\partial L}{\partial T^L} = -B\frac{\partial L^C}{\partial T^L}(\eta^{MI} - 1) \tag{44}$$

The first term in (43) is the sum of the marginal excess burden (deadweight loss) of labor taxation that is caused by the change in the subsidy rate and labor tax. This term is negative provided that $\eta^{MI} < 1$. The second term is the additional deadweight loss from the change in the quantity of biofuel, which is negative. The last term is the change in labor supply that results from the increase in the price of goods that use land as an input. The sign of this term is also negative. Thus, it is clear that an increase in biofuel subsidy leads to a decrease labor supply, which in turn decreases the indirect utility function. The result that labor supply decreases with the subsidy is different from the result suggested by Parry (1995) because biofuel is a weak substitute for leisure.

From the dicussion above the effect of the subsidy on utility is negative if $\frac{dE}{dS} > 0$. If $\frac{dE}{dS} < 0$, the effect of the subsidy on utility is positive if the first term in (43) is greater than the last two terms, and negative otherwise. That is, a subsidy will lead to an increase in utility if the welfare gain from reduced externality exceeds the welfare loss from increased expenditure for subsidy provision and reduction in labor supply.

The magnitude of the three terms above will depend on prevailing market conditions. To evaluate plausible cases, I also express (41) in empirically estimable terms as described below.

Substituting (44) in (43) and using results from Appendix B:

$$\begin{aligned} T^L\frac{dL}{dS} = {} & \frac{MEB^L}{\epsilon^{LL}}[B\epsilon^{L^C L}\left(\eta^{MI}-1\right)] - MEB^L S\frac{dB}{dS} \\ & +\frac{MEB^L}{\epsilon^{LL}}((A+B)[\epsilon^{L^C L}(\eta^{MI}-1)+\epsilon^{LL}])\frac{dR}{dS} \end{aligned} \tag{45}$$

Substituting (45) in Equation (41) gives:

$$\begin{aligned}\frac{dV(S)}{dS} = -\frac{\phi}{\lambda}\frac{dE}{dS} + \frac{MEB^L}{\epsilon^{LL}}[E\epsilon^{L^C L}\left(\eta^{MI} - 1\right)] \\ +\frac{MEB^L}{\epsilon^{LL}}S\frac{dB}{dS} + \frac{MEB^L}{\epsilon^{LL}}((A+B)[\epsilon^{L^C L}(\eta^{MI} - 1) + \epsilon^{LL}])\frac{dR}{dS}\end{aligned} \tag{46}$$

where:

$$\frac{dE}{dS} = \delta^G \frac{\epsilon^{GP^B}}{P^B/G} + \frac{\delta^B \epsilon^{BP^B}}{P^B/B} \tag{47}$$

$$\frac{dB}{dS} = \frac{-\epsilon^{BP}}{P^B/B} \tag{48}$$

$$\frac{dR}{dS} = \frac{\epsilon^{BP}}{\epsilon^{AP}}\frac{B}{A}\frac{P^A}{P^B} \tag{49}$$

The next section discusses the data and parameters used to quantify (29) and (33), and calculate welfare effects of deviating from the second-best optimal tax rate.

4.3 Data and Parameters

I use market data and elasticities from the literature. Parry and Small (2005a) present a thorough review of some of the parameters needed to quantify the second-best optimal gas tax. Whenever possible, I use values similar to theirs. Because biofuel is now part of the fuel mix, some of the parameters used by Parry and Small (2005) have to be modified, and new parameters need to be introduced.

4.3.1 Carbon Price and GHG Intensity of Fuels

Parry and Small (2005) review the existing literature on the cost of carbon emissions and conclude that a wide variety of estimates ranging from \$0.7 per ton more than \$100 per ton exists. I use the central value used by Parry and Small (2005) of \$25 per ton of carbon, as the marginal external cost of carbon emissions.

The externality impact of a gallon of fuel is measured using its GHG intensity, which is defined as the amount of GHG in carbon equivalents (C-eq) emitted per unit consumption of fuel. Unlike Parry and Small (2005) who used tailpipe emissions of gasoline, which amount to 0.0024 tons C-eq per gallon, I use emissions from Life Cycle Assessment (LCA) studies that measure emissions from "well-to-wheel" or from the production of inputs that go into fuel production, up to emissions from the combustion of the fuel. For gasoline, emissions include those from crude oil recovery, transport and refining, distribution to the pump , and end of pipe emissions. For biofuel, emissions include those from feedstock farming, biofuel production in the refinery, distribution, up through end of pipe emissions. Since the GHG reduction capacity of biofuel relative to gasoline is an important consideration, LCA provides a better meausure of the two fuels' relative GHG intensities. GHG emissions from gasoline are fairly well established. I use "well-to-wheel" emission from CARB (2009) of 12.05 kgCO2-eq (0.0032 tons C-eq) per gallon of gasoline. In the case of biofuel, LCA emissions are less certain. Emissions depend on the type of feedstock used, farming practices and the technology used for refining. In addition, because biofuel production uses land as input, some studies suggest that emissions from indirect land use change may be significant (Searchinger et al. 2008; Fargione et al. 2008).

Early studies showed that corn ethanol has 12-20% less emissions than gasoline (Farrell et al. 2006b; Wang, Wu, and Huo 2007). More recent studies with more technologically advanced refineries suggest a reduction of over 40% (Liska et al. 2009). Cellulosic ethanol from grasses and woody biomass offers even higher mitigation potential, with reductions up to 90% compared to gasoline (Wu, Wang, and Hou 2007).

To address the broad range of possibilities in GHG emissions from biofuel, I use a range suggested by current studies. In the low emission case, emissions from cellulosic biofuel with no land use change whose emissions have been measured at 1.5 kg CO2-eq (0.0004 tons C-eq) per gallon are used. In the central case, emissions from corn ethanol production in the Unites States with LCA emissions of 4.7 kgCO2-eq (0.0012 tons C-eq) per gallon are used. I abstract from indirect land use change emissions for now because consensus has not been reached on how much emissions should be attributed to biofuel because of this indirect impact. The low emission case suggests that on an energy equivalent basis, biofuel reduces emissions by 80%, whereas in the central case, the reduction is 40% compared to gasoline.

4.3.2 Fuel and Miles Market Parameters

Using the definition of total emissions, $E = \delta^B B + \delta^G G$, I define the elasticity of emissions as: $\epsilon^{ET} = (\frac{\delta^B B}{E})\epsilon^{BT} + (\frac{\delta^G G}{E})\epsilon^{GT}$ where $\epsilon^{BT} = \frac{dB}{dT^C}\frac{T^C}{B}$ and $\epsilon^{GT} = \frac{dG}{dT^C}\frac{T^C}{G}$. The elasticity of gasoline and biofuel demand to the carbon tax takes into account the change in demand due to the tax-induced price increase, the substitution of biofuel for gasoline, as well as the effect of changing miles demand. As shown in Appendix

C, the change in gasoline and biofuel demand depend on a few key parameters, such as the elasticity of substitution between biofuel and gasoline (σ), price elasticity of miles (η^{MM}), and the emissions intensity of biofuel (δ^{B}) relative to gasoline. I use the results of the comparative static analysis in Appendix C to determine the values of ϵ^{GT} and ϵ^{BT}, given different values of the elasticity of substitution between biofuel and gasoline , price elasticity of miles, and the emissions intensity of biofuel. Table 4.1 shows the range of values for ϵ^{ET}. Results are presented for the range of parameters used shown in Table 4.1.

Little empirical information exists for the cross price elasticity of gasoline demand with respect to biofuel price. If gasoline and biofuel are perfect substitutes, the cross price elasticity of gasoline to biofuel price will be equal to the negative of biofuel's own-price elasticity (i.e. $\epsilon^{GP^B} = 0.1$). On the other hand, if the elasticity of substitution between the two fuels is low, ϵ^{GP^B} will be close to zero. Thus I use a central value of $\epsilon^{GP^B} = 0.05$ but also evaluate results for the plausible range of 0 to 0.1.

For the expenditure elasticity of miles, which is functionally equivalent to an income elasticity, I use a value of $\eta^{MI} = 0.35$ based on Pickrell and Schimek (1997) who analyze trends in personal motor vehicle use based on the 1995 Nationwide Personal Transportation Survey (NPTS).

Market data for gasoline and biofuel consumption for 2008 is used. The Energy Infomation Agency reported that total gasoline use in 2008 was 125 B gallons, while the Renewable Fuels Association reported total ethanol demand to be 9 B gallons in the same year (Department of Energy 2009; RFA 2009a). The per gallon wholesale price of gasoline and ethanol are \$2.57 and \$2.47, respectively, according to the Nebraska Ethanol Board (NEB 2009). In the numerical simulation, quantities are scaled so that initial prices are equal to unity.

4.3.3 Land and Agricultural Markets

Using the definition of price elasticities, the change in land rent with respect to a change in the carbon tax is given by: $\frac{dR}{dT^C} = -\frac{\epsilon^{BT}}{\epsilon^{AP}} \frac{B}{A} \frac{P^A}{P^B}$, where the price elasticity of the agricultural good is $\epsilon^{AP} = \frac{dA}{dP^A} \frac{P^A}{A}$. Emipirical studies estimate that ϵ^{AP} = -0.2 (ERS 2003). The results are presented using a range of values for ϵ^{BT}, as discussed in the previous section.

From the US Census Bureau, the total spending for farm foods [17] in 2006 is \$880 Billion, with an increase of approximately \$40 Billion per year. Thus, I set the total expenditures on agricultural goods to \$960 Billion for 2008 (USCB 2009). Since prices are set to unity in the initial equilibrium, the quantity of agricultural goods is also 960 units.

4.3.4 Labor Market Parameters

For labor market parameters, I use values similar to Parry and Small (2005a). They use a central value of 0.2 for uncompensated elasticity and 0.35 for compensated elasticity based on Blundell, Duncan, and Meghir (1998) and Fuchs, Krueger, and Poterba (1998). Also, based on Parry (2001), the tax rate on labor, T^L is set to 0.39.

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[17] Farm foods are defined as products purchased by civilian consumers that are produced by US farms.

4.4 Results

4.4.1 Second-Best Carbon Tax

Values of the second-best optimal carbon tax (T^{C*}) are presented in Table 4.2 under various assumptions about the elasticity of substitution between biofuel and gasoline (σ), price elasticity of miles demand (η^{MM}) and the emissions intensity of biofuel (δ^B). These three parameters determine whether biofuel demand (and land rent) increases or decreases with the carbon tax. For a wide range of these parameters, the carbon tax increases biofuel demand. The carbon tax leads to a positive but small change in biofuel demand if the elasticity of substitution between biofuel and gasoline is very small ($\sigma < 0.1$), miles demand is very price inelastic ($\eta^{MM} > |-1|$), or biofuel has an emissions intensity close to that of gasoline. However, the change is small, with $\epsilon^{BT} < 0.001$. Thus, I only present results wherein the tax has a positive effect on biofuel demand.

The first column of Table 4.2 shows the per ton carbon tax, without considering the presence of biofuel in the fuel mix. The components of the carbon tax, namely the Pigouvian tax and the tax that accounts for the Labor Market Effect are shown below the second-best carbon tax rate (T^{C*}). The Labor Market Effect is also decomposed into its various components.

The Pigouvian tax is \$21.8 per ton carbon, which is the MED of a ton of carbon emissions divided by the marginal cost of public funds. The tax interaction effect lowers T^{C*} by \$5.6 per ton but it is more than offset by the revenue recyling effect, which is \$16.1 per ton, bringing the net labor market effect to \$10.5 per ton and the carbon tax to \$32.3 per ton.

The second to fourth columns show the components of the carbon tax when biofuel is included in the fuel mix, and the elasticity of substitution between gasoline and biofuel is 10. In the second column, where the price elasticity of miles and biofuel emissions intensity are -0.4 and 0.0012 respectively, the effect of increasing commodity prices on the labor market reduces the labor market effect by \$0.3. However, the addition of biofuel in the fuel mix decreases the emissions elasticity with respect to the carbon tax, increasing both the positive revenue-recyling effect and the negative tax interaction effect, so that the net results on the labor market is similar to the gas only case. If miles demand is more price inelastic, the negative commodity price effect is increased. The inelasticity of miles demand keep fuel use higher relative to the case where it is less inelastic; however, since biofuel is taxed less than gasoline, demand shifts toward biofuel and away from gasoline. The labor market effect is larger in this case because much more revenue is generated due to higher fuel demand and lower emissions elasticity. The result is a carbon tax that is 17% higher than the gas only case. With a lower biofuel emission intensity (Table 4.2, last column), the commodity price effect is relatively larger because biofuel demand increases due to the lower per gallon tax rate. However, since the tax base for carbon is decreased due to biofuel's low emission intensity, the labor market effect is attenuated as well. This scenario leads to the carbon tax rate that is 7% lower than the gas only tax.

The bottom half of Table 4.2 shows that with a positive effect of the tax on biofuel demand, a fixed biofuel subsidy decreases the carbon tax due to increased burden on the government to generate revenues from labor taxation.

Table 4.3 shows the values of the carbon tax with $\sigma = 100$. Compared to the case with $\sigma = 10$, carbon tax rates are generally lower because the greater elasticity of substitution results in a more tax elastic emissions, which lowers the tax base on emissions leading to lower tax interaction and revenue-recycling effects. The commodity price effect however, is relatively larger because a greater increase in biofuel demand is made possible by a higher elasticity of substitution.

On the other hand, with $\sigma = 2$ (Table 4.4), the tax interation and revenue recycling effects are relatively larger due to the small emissions elasticity (implying that the tax base remains large). However, because of the limited substitution possibility between biofuel and gasoline, the commodity price effect is fairly modest and the difference between the carbon tax rates with and without a fixed biofuel subsidy is small.

Table 4.5 shows fuel taxes corresponding to a range of values for the elasticity of substitution between gasoline and biofuel. Per gallon fuel taxes are computed by multipying T^{C*} with the respective GHG intensity of each fuel. Biofuel has a lower fuel tax compared to gasoline because its GHG intensity per gallon is lower. Consistent with the carbon tax results, the fuel taxes are larger the smaller the value of the elasticity of substitution. Gasoline taxes range from \$7.6 to \$11.7 per gallon, while biofuel taxes range from \$3.1 to \$4.8 per gallon. These values are much lower than the \$1.01 per gallon gas tax proposed by Parry and Small (2005). It is important to remember that the fuel taxes reported in Table 4.5 only account for externalities from GHG emissions, which are less than 10% of total fuel and miles externalities accounted for in the gas tax derived by Parry and Small (2005). If miles externalities could be internalized by a carbon tax, the value of the second-best optimal carbon tax would be significantly larger, and the implied fuel taxes would be closer to those reported by Parry and Small (2005).

These results show that the presence of biofuel in the blended fuel mix has a significant impact on the second-best optimal tax rate for carbon. Under different parameter assumptions, the effect of the tax on income, commodity prices and subsidy expenditures could either be positive or negative, thus increasing or lowering the value of the second-best optimal tax rate with gasoline and biofuel, relative to the case where only gasoline is used as fuel. The question then is: what set of parameters represent the current market condition? Very high levels of substitutability between gasoline and ethanol implies that biofuel is widely available and that the vehicle fleet is mostly flex fuel such that consumers can freely use one fuel or the other. This does not appear to be the case at present where biofuel comprises less than 5% of total fuel use and less than 1% of the vehicle fleet is flex fuel. However, current legislation will likely change the market conditions in the future. The EISA mandate of 36 B gallons of biofuel by 2022 will increase the share of biofuel by 20%. In order for this mandate to be met, the vehicle fleet would also need to change so that a larger percentage of cars would be flex fuel. Thus, it seems likely that in the short run, a carbon tax will have a small positive or negative effect on biofuel demand while in the long run a carbon tax will have a larger positive effect on biofuel demand, thus increasing the magnitude of the (negative) commodity price effect, and lowering the second-best carbon tax.

4.4.2 Welfare Effects of an Increase in the Biofuel Subsidy

The welfare effect of marginal increase in the biofuel subsidy is obtained by substituting market data and parameters in (46). Table 4.6 shows the welfare effect of a unit increase in the subsidy rate when the cross price of gasoline demand with respect to biofuel price (ϵ^{GP^B}) is equal to 0.05. The benefit from decreased GHG emissions are valued at \$1.21 Billion. However negative effect of increased distortion in the labor market and increased government expenditures result in an overall welfare reduction of \$3.87 Billion which is 1.13% of 2008 fuel expenditures.

Figure 4.1 shows the welfare change, given different values of $-\epsilon^{GP^B}$ (The negative of ϵ^{GP^B} is the elasticity of gasoline demand with respect to the biofuel subsidy.). The line labeled "EXT" refers to the welfare change due to changing levels of externalities, while "GOV" and "LAB" refer to welfare changes from government expenditures and labor market distortions, respectively. The results show that the subsidy does decrease externalities, for values of $-\epsilon^{GP^B} < -0.001$. The line labeled "EXT" on the graph below shows that as gasoline demand becomes more responsive to biofuel price (i.e. $-\epsilon^{GP^B}$ approaches -0.1), the welfare gain from the pigouvian portion of the tax increases. The welfare change for a unit increase in the subsidy ranges from $-\$5.1$ to $-\$2.6$ Billion or 0.7% to 1.5% of 2008 fuel expenditures.

4.5 Conclusions

This study shows that the advent of biofuel has significant implications for the second-best optimal tax rate for fuels. In particular, with a labor market distortion, the effect of a carbon tax on land rents could attenuate or exacerbate the impact of a revenue neutral carbon tax on labor supply. In addition, the presence of a fixed biofuel subsidy further differentiates the magnitude of the second-best carbon tax with biofuels, relative to the case with no biofuels in the fuel mix.

Applying the analytical framework to the US fuel market and using land as the common input for the production of biofuel and agricultural goods, I show that the effect of a carbon tax on biofuel demand and land rent depends on the elasticity of substitution between gasoline and biofuel, the demand elasticity of miles and the GHG intensity of biofuel relative to gasoline. If the elasticity of substitution is high, miles demand is very inelastic, and biofuel provides significant GHG reduction, biofuel demand increases and land rent increases as well. The increase in land rent leads to a positive income effect and a reduction in the real wage due to an increase in commodity prices, that in turn decreases labor supply. Thus, the second-best optimal carbon tax rate is reduced when the negative effect of increase in land rent on labor supply is taken into account. In addition, if a fixed subsidy exists, the tax-induced increase in biofuel demand increases the burden on the government to increase labor taxes to finance the subsidy, which further decreases labor supply, and the carbon tax.

On the other hand, if substitution between biofuel and gasoline is low, the added carbon tax decreases biofuel consumption and decreases land rent, thus decreasing income and lowering the price of goods that use land as an input. The latter result is similar to the finding of Bento and Jacobsen (2007) using a model with one polluting good that solely uses land as a fixed input, in which the pollution tax acts as a "surrogate tax" on land rent. The decrease in land rent has a positive effect on labor supply and increases the carbon tax rate. With a fixed biofuel subsidy, the tax-induced decrease in biofuel consumption eases the burden on the government to generate revenues. Hence, the presence of the subsidy leads to an increase in the carbon tax rate if the tax decrease biofuel demand.

The welfare analysis presented here strenghtens the case for carbon taxation because although both a carbon tax and a biofuel subsidy lowers GHG emissions, a carbon tax provides welfare gains while a subsidy results in welfare losses. However, the general equilibrium impact of a carbon tax on the labor market, as well as agricultual markets need to be carefully considered in setting a carbon-based tax for fuels.

4.6 Figures and Tables

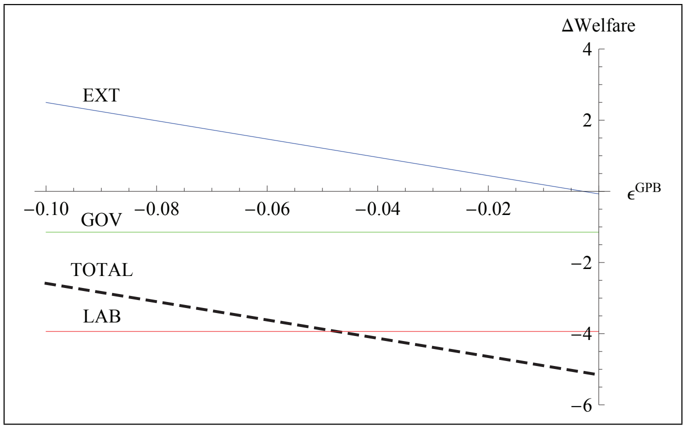

Figure 4.6: Welfare Effect of a Subsidy

Table 4.1: Range of Values for Emissions Elasticity (ϵ^{ET})

			ϵ^{ET}
$\sigma = 100$	$\eta^{MM} = -0.4$	$\delta^B = 0.0012$	-1.36
$\sigma = 100$	$\eta^{MM} = -0.2$	$\delta^B = 0.0012$	-1.21
$\sigma = 100$	$\eta^{MM} = -0.4$	$\delta^B = 0.0004$	-2.29
$\sigma = 10$	$\eta^{MM} = -0.4$	$\delta^B = 0.0012$	-0.33
$\sigma = 10$	$\eta^{MM} = -0.2$	$\delta^B = 0.0012$	-0.22
$\sigma = 10$	$\eta^{MM} = -0.4$	$\delta^B = 0.0004$	-0.42
$\sigma = 2$	$\eta^{MM} = -0.4$	$\delta^B = 0.0012$	-0.24
$\sigma = 2$	$\eta^{MM} = -0.2$	$\delta^B = 0.0012$	-0.13
$\sigma = 2$	$\eta^{MM} = -0.4$	$\delta^B = 0.0004$	-0.26

σ - elasticity of substitution between gasoline and biofuel
η^{MM} - price elasticity of miles
δ^B - emissions elasticity of biofuel

Table 4.2: Second-Best Carbon Tax Under Different Parameter Assumptions, $\sigma = 10$ (\$/ton)

	Gas Only	With Biofuel	With Biofuel	With Biofuel
		$\eta^{MM} = -0.4$	$\eta^{MM} = -0.2$	$\eta^{MM} = -0.4$
		$\delta^{BT} = 0.0012$	$\delta^{BT} = 0.0012$	$\delta^{BT} = 0.0004$
No fixed subsidy				
Second-best carbon tax rate (T^{C*})	32.3	32.3	37.8	29.9
Pigouvian	21.8	21.8	21.8	21.8
Labor Market Effect	10.5	10.5	16.	8.1
Tax Interaction	-5.6	-5.8	-8.8	-4.6
Revenue Recycling	16.1	16.6	25.2	13.1
Commodity Price	-	-0.3	-0.4	-0.4
With fixed subsidy				
Second-best carbon tax rate (T^{C*})	32.3	32.3	37.6	29.7
Pigouvian	21.8	21.8	21.8	21.8
Labor Market Effect	10.5	10.4	15.8.	7.9
Tax Interaction	-3.7	-3.7	-3.7	-3.7
Revenue Recycling	10.6	10.6	10.6	10.6
Commodity Price	-	-4.8	-1.6	1.6
Subsidy Effect	-	-0.1	-0.2	-0.2

Table 4.3: Second-Best Carbon Tax Under Different Parameter Assumptions, $\sigma = 100$ (\$/ton)

	Gas Only	With Biofuel	With Biofuel	With Biofuel
		$\eta^{MM} = -0.4$ $\delta^{BT} = 0.0012$	$\eta^{MM} = -0.2$ $\delta^{BT} = 0.0012$	$\eta^{MM} = -0.4$ $\delta^{BT} = 0.0004$
No fixed subsidy				
Second-best carbon tax rate (T^{C*})	24.4	23.8	24.	22.6
Pigouvian	21.8	21.8	21.8	21.8
Labor Market Effect	2.6	2.	2.2	0.8
Tax Interaction	-1.4	-1.4	-1.6	-0.9
Revenue Recycling	4.	4.1	4.6	2.4
Commodity Price	-	-0.7	-0.8	-0.8
With fixed subsidy				
Second-best carbon tax rate (T^{C*})	24.4	23.6	23.6	22.2
Pigouvian	21.8	21.8	21.8	21.8
Labor Market Effect	2.6	1.8	1.8	0.4
Tax Interaction	-1.4	-1.4	-1.6	-0.9
Revenue Recycling	4.	4.1	4.6	2.4
Commodity Price	-	-0.7	-0.8	-0.8
Subsidy Effect	-	-0.2	-0.4	-0.4

Table 4.4: Second-Best Carbon Tax Under Different Parameter Assumptions, $\sigma = 2$ (\$/ton)

	Gas Only	With Biofuel	With Biofuel	With Biofuel
		$\eta^{MM} = -0.4$ $\delta^{BT} = 0.0012$	$\eta^{MM} = -0.2$ $\delta^{BT} = 0.0012$	$\eta^{MM} = -0.4$ $\delta^{BT} = 0.0004$
No fixed subsidy				
Second-best carbon tax rate (T^{C*})	36.2	36.5	48.9	35.6
Pigouvian	21.8	21.8	21.8	21.8
Labor Market Effect	14.4	14.7	27.1	13.8
Tax Interaction	-7.7	-8.	-14.7	-7.5
Revenue Recycling	22.1	22.7	41.9	21.4
Commodity Price	-	0	-0.1	-0.1
With fixed subsidy				
Second-best carbon tax rate (T^{C*})	36.2	36.5	48.8	35.5
Pigouvian	21.8	21.8	21.8	21.8
Labor Market Effect	14.4	14.7	27	13.7
Tax Interaction	-7.7	-8.	-14.7	-7.5
Revenue Recycling	22.1	22.7	41.9	21.4
Commodity Price	-	0	-0.1	-0.1
Subsidy Effect	-	0	-0.1	-0.1

Table 4.5: Fuel Taxes, $\eta^{MM} = -0.4, \delta^{B} = 0.0012$ (cents/gallon)

	$\sigma = 2$		$\sigma = 10$		$\sigma = 100$	
	Gasoline	Biofuel	Gasoline	Biofuel	Gasoline	Biofuel
Fuel Tax	11.7	4.8	10.3	4.2	7.6	3.1
Pigouvian	7.	2.8	7.	2.8	7.	2.8
Labor Market Effect	4.7	1.9	3.4	1.4	0.6	0.3
Tax Interaction	-2.5	-1	-1.9	-0.8	-0.5	-0.2
Revenue Recycling	7.3	3	5.3	2.2	1.3	0.5
Commodity Price	0	0	-0.1	0	-0.2	-0.1

Table 4.6: Welfare Effect of a Biofuel Subsidy

Externality Effect (B $)	1.21
Labor Market Effect (B $)	-3.94
Government Expenditures (B $)	-1.14
Welfare Change (B $)	-3.87

Chapter 5: Conclusion

This dissertation examines market and external impacts of biofuel policies in the US, and determines the welfare implications of existing and alternative second-best policies. The main conclusion from the three chapters is that existing policies which include the corn ethanol blender subsidy, import tariff and RFS mandate for traditional and advanced biofuel are welfare decreasing and their effect on reducing environmental externalities, in particular GHG emissions, is limited. In constrast, taxing miles and fuels according to their marginal external damage provides welfare gains while significanly reducing environmental externalities. Considering that other distortions in the economy exist, a second-best optimal carbon tax for fuels that takes into account the interaction of a fuel tax with other existing distortions would yield the welfare maximizing outcome.

This study also derives second-best optimal policies, and uses them as benchmarks to evaluate existing policies. In Chapter 2, the optimal policy benchmark imposes a Pigouvian tax on miles and fuels, and an optimal tariff on imported ethanol. Comparing the welfare effect of the current subsidy and tariff policies to the optimal benchmark yields a substantially large increase in the welfare cost of these policies, compared to measuring welfare losses against a non-intervention benchmark. The main message is that quantifying the cost of externalities associated with biofuel policies provides a more accurate assessment of the welfare impact of biofuel policies.

This dissertation also offers several insights related to biofuels trade with Brazil. Chapter 2 shows that from the perspective of improving terms of trade, an ethanol tariff could be beneficial if the US could influence the world price through a tariff.

However, caution should be used in applying this finding. As discussed in Chapter 3, if there is a binding “mandate” on imports from Brazil, the tariff will only serve to increase the price paid by US consumers and would therefore be welfare decreasing. Chapter 3 also provides important insights on the cost competitiveness of biofuel from Brazil relative to domestically produced corn ethanol. Contrary to conventional belief, the cost of sugarcane ethanol from Brazil at US ports is not necessarily cheaper, and with recently observed exchange rates, is even more expensive than corn ethanol. The cost advantage for each type of biofuel is greatly dependent on the prevailing exchange rate. The effect of this exogenous factor on the welfare effect of the mandate is significant and shows that the cost of meeting the advanced biofuel mandate could be more costly than initially anticipated, especially if exchange rates continue at their current level.

Although Pigouvian taxes for fuels would increase welfare relative to status-quo and non-intervention policies, it is not the optimal tax rate if other distortions in the economy are present. With other distortions, the optimal tax is only “second-best” because the true optimum cannot be achieved. In order to derive the second-best optimal tax, the interaction of the tax with the overall fiscal system has to be considered. Chapter 4 examines the impact of a carbon tax for fuels, with a labor tax and fixed biofuel subsidy present. Chapter 4 shows that the presence of biofuel in the fuel mix influences the magnitude of the second-best optimal carbon tax for fuels. The link between the fuel sector and the agricultural sector causes policies in the fuel sector to affect land rent - which affects labor supply, and also the welfare of consumers. Whether the effect of the tax on land rent is positive or negative depends on whether the tax causes biofuel demand to increase or decrease. If a carbon tax increases the demand for biofuel, land rent increases, reducing labor supply and thus making the likelihood of a non-environmental welfare gain from a revenue neutral tax swap less likely. The effect of the tax on biofuel demand depends on the elasticity of substitution between gasoline and biofuel, and to a lesser extent, the price elasticity of miles demand and the GHG intensity of both fuels. Biofuel demand increases with the carbon tax with a higher elasticity of substitution. The elasticity of substitution between gasoline and biofuel is likely to be large in the long-run when ethanol pumps and flex-fuel vehicles are widely available. Thus it is likely that as biofuel use becomes more widespread, a carbon tax would lead to a greater impact on land rent and commmodity prices, which in turn would lower the second-best optimal carbon tax. This implies that ignoring the presence of biofuel in the fuel mix could lead to an overestimate of the optimal fuel tax, and would not maximize welfare gains from fuel taxation.

The findings in this dissertation point to several key areas of further research. Numerical simulations show that results are sensitive to several key parameters: the elasticity of substitution between ethanol and gasoline, the price elasticity of gasoline supply, the price elasticity of Brazil's excess supply for ethanol, and the price elasticity of miles demand. The importance of using parameters that accurately represent the markets being modeled provide rationale for more empirical analysis that provides better estimates of these parameters.

Another area of uncertainly that merits further investigation is the GHG intensity of biofuels, when indirect land use change (ILUC) is taken into account. Because of the remaining uncertainties associated with measuring emissions from ILUC associated with the different types of biofuel, the GHG intensities used in this research only reflect direct emissions. Further research on the magnitude of ILUC related to increasing biofuel demand in the US would improve estimates of the environmental effects of using biofuel.

The external effects of fuel consumption emphasized in this research are GHG emissions and miles externalities. Increased consumption of domestically produced biofuel also affects energy security. The results of welfare analyses conducted in the last three chapters suggest that on the basis of their effects on social surplus and GHG emissions, existing policies are not welfare increasing. A useful extension of this work is to examine how increasing production and consumption of biofuels affect energy security and whether the effect on energy security is enough to justify these policies, given the other negative impacts discussed in this research.

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Appendix A

Deriving the effect of the carbon tax on indirect utility (V):

The change in V for a marginal change in T^C is:

$$\frac{dV}{\lambda dT^C} = E + \frac{\phi}{\lambda}\frac{dE}{dT^C} - L\frac{dT^L}{dT^C} + (K - \frac{\partial P^B}{\partial R} - \frac{\partial P^B}{\partial R})\frac{dR}{dT^C} \tag{A.1}$$

Total differentiation of the government budget constraint given by:

$$Y = T^L L + T^C E \tag{A.2}$$

gives the expression for the change in labor tax for a marginal change in the carbon tax:

$$\frac{dT^L}{dT^C} = -\frac{1}{L}(E + T^C\frac{dE}{dT^C} + T^L\frac{dL}{dT^C}) \tag{A.3}$$

Substituting this in A.1 yields (24).

Appendix B

Deriving an empirical formula for the optimal carbon tax:

Substituting (A.3) in (25) gives:

$$\frac{dL}{dT^C} = \frac{-\frac{1}{L}\frac{\partial L}{\partial T^L}(E + T^C\frac{dE}{dT^C}) + [\frac{\partial L}{\partial R} + \frac{\partial L}{\partial P^A}\frac{\partial P^B}{\partial R} + \frac{\partial L}{\partial P^A}\frac{\partial P^A}{\partial R}]\frac{dR}{dT^C} + \frac{\partial L}{\partial T^C}}{1 + \frac{T^L}{L}\frac{\partial L}{\partial T^L}} \tag{B.1}$$

Noting the definitions for MEB^L and $1 + MEB^L$ given in reference to (29), B.1 can be written as:

$$\begin{aligned} T^L\frac{dL}{dT^C} = (1 + MEB^L)T^L\frac{\partial L}{\partial T^C} + MEB^L[E + T^C\frac{\partial E}{\partial T^C}] + \\ (1 + MEB^L)T^L[\frac{\partial L}{\partial R} + \frac{\partial L}{\partial P^A}\frac{\partial P^B}{\partial R} + \frac{\partial L}{\partial P^A}\frac{\partial P^A}{\partial R}]\frac{dR}{dT^C} \end{aligned}$$

Or alternatively:

$$\begin{aligned} T^L\frac{dL}{dT^C} = -\frac{MEB^L}{\frac{\partial L}{\partial T^L}}[L\frac{\partial L}{\partial T^C} - E\frac{\partial L}{\partial T^L}] + MEB^L T^C\frac{dE}{dT^C} + \\ (1 + MEB^L)T^L[\frac{\partial L}{\partial R} + \frac{\partial L}{\partial P^A}\frac{\partial P^B}{\partial R} + \frac{\partial L}{\partial P^A}\frac{\partial P^A}{\partial R}]\frac{dR}{dT^C} \end{aligned} \tag{B.2}$$

The following shows steps to express the terms inside the square brackets, in the first term of B.2 in the empirically measurable components:

Recall that a change in T^F affects labor through change in the tax-inclusive price of miles so that:

$$\frac{\partial L}{\partial T^C} = \frac{\partial L}{\partial P^M}\frac{\partial P^M}{\partial T^C} = \frac{\partial L}{\partial P^M}\frac{E}{M} \tag{B.3}$$

From the Slutsky equation:

$$\frac{\partial L}{\partial P^M} = \frac{\partial L^C}{\partial P^M} - \frac{\partial L}{\partial I}M \tag{B.4}$$

From the symmetry property of the substitution matrix, the effect of a change in the price of miles on compensated labor supply (L^C) is equal to the change in compensated miles demand (M^C) due to a change in the labor tax:

$$\frac{\partial L^C}{\partial P^M} = \frac{\partial M^C}{\partial T^L} \tag{B.5}$$

Parry and Small (2004) citing Deaton (1981, p. 1249) argue that since leisure is weakly separable in the utility function, the change in miles due to a change in the labor tax occurs only through a change in disposable income, $(1 - T^L)L$ [18]. Thus:

$$\frac{\partial M^C}{\partial T^L} = \frac{\partial M}{\partial I}(1 - T^L)\frac{\partial L^C}{\partial T^L} \tag{B.6}$$

The Slutsky equation (B.4), can thus be re-written as:

$$\frac{\partial L}{\partial P^M} = \frac{\partial M}{\partial I}(1 - T^L)\frac{\partial L^C}{\partial T^L} - \frac{\partial L}{\partial I}M \tag{B.7}$$

---

[18] Since the labor tax affects land rents only through changes in demand for biofuel and agricultural goods, the expected change in land rent income in response to a change in the labor tax is very small and can be ignored.

Substituting B.7 to B.3:

$$\begin{aligned}
\frac{\partial L}{\partial T^C} &= \left(\frac{\partial M}{\partial I}(1-T^L)\frac{\partial L^C}{\partial T^L} - \frac{\partial L}{\partial I}M\right)\frac{E}{M} \\
&= \left(\frac{\partial M}{\partial I}(1-T^L)\frac{\partial L^C}{\partial T^L}\frac{E}{M} - \frac{\partial L}{\partial I}E\right) \qquad \text{(B.8)}
\end{aligned}$$

Note also that:

$$\frac{\partial L}{\partial T^L} = \frac{\partial L^C}{\partial T^L} - \frac{\partial L}{\partial I}L \qquad \text{(B.9)}$$

Using B.8 and B.9,

$$\begin{aligned}
L\frac{\partial L}{\partial T^C} - E\frac{\partial L}{\partial T^L} &= L\left(\frac{\partial M}{\partial I}(1-T^L)\frac{\partial L^C}{\partial T^L}\frac{E}{M} - \frac{\partial L}{\partial I}E\right) - E\left(\frac{\partial L^C}{\partial T^L} - \frac{\partial L}{\partial I}L\right) \\
&= \left(\frac{\partial M}{\partial I}(1-T^L)\frac{\partial L^C}{\partial T^L}\frac{E}{M}L - \frac{\partial L}{\partial I}EL\right) - E\left(\frac{\partial L^C}{\partial T^L} - \frac{\partial L}{\partial I}L\right) \\
&= \frac{\partial M}{\partial I}(1-T^L)\frac{L}{M}\frac{\partial L^C}{\partial T^L}E - \frac{\partial L^C}{\partial T^L}E \\
&= E\frac{\partial L^C}{\partial T^L}\left(\eta^{MI} - 1\right) \qquad \text{(B.10)}
\end{aligned}$$

where:

$$\eta^{MI} = \frac{\partial M}{\partial I}\frac{(1-T^L)L}{M} \qquad \text{(B.11)}$$

Substitute B.10 to B.2 to get:

$$
\begin{aligned}
T^L \frac{dL}{dT^C} = -\frac{MEB^L}{\frac{\partial L}{\partial T^L}}[E\frac{\partial L^C}{\partial T^L}\left(\eta^{MI}-1\right)] + MEB^L T^C \frac{dE}{dT^C} - \\
\frac{MEB^L}{\frac{\partial L}{\partial T^L}} L(-\frac{\partial L}{\partial R} - \frac{\partial L}{\partial P^B}\frac{\partial P^B}{\partial R} - \frac{\partial L}{\partial P^A}\frac{\partial P^A}{\partial R})\frac{dR}{dT^C}
\end{aligned} \tag{B.12}
$$

Now, to express the last term in B.2 in empirical terms, note that

$$\frac{\partial L}{\partial P^B} = \frac{\partial L}{\partial P^M}\frac{\partial P^M}{\partial P^B} = \frac{\partial L}{\partial P^M}\frac{B}{M} \tag{B.13}$$

Recall the following identities:

$$\frac{\partial L}{\partial P^M} \equiv \frac{\partial L^C}{\partial P^M} - \frac{\partial L}{\partial I}M \tag{B.14}$$

$$\frac{\partial L^C}{\partial P^M} \equiv \frac{\partial M^C}{\partial T^L} \equiv \frac{\partial M}{\partial I}(1-T^L)\frac{\partial L^C}{\partial T^L} \tag{B.15}$$

$$\epsilon^{LL} \equiv \epsilon^{L^C L} - \eta^{LI} \tag{B.16}$$

where:

$$\eta^{LI} = \frac{\partial L}{\partial I}\frac{(1-T^L)L}{L}$$

B.13 can be expressed as

$$\begin{aligned}\frac{\partial L}{\partial P^B} &= [\frac{\partial L^C}{\partial P^M} - \frac{\partial L}{\partial I}M]\frac{B}{M} && \text{(B.17)}\\ &= [\frac{\partial M}{\partial I}(1-T^L)\frac{\partial L^C}{\partial T^L}\frac{B}{M} - \frac{\partial L}{\partial I}B] && \text{(B.18)}\\ &= [\eta^{MI}\frac{\partial L^C}{\partial T^L}\frac{B}{L} - \frac{\partial L}{\partial I}B] && \text{(B.19)}\\ &= \frac{B}{1-T^L}[\eta^{MI}\epsilon^{L^C L} - \eta^{LI}] && \text{(B.20)}\\ &= \frac{B}{1-T^L}[\epsilon^{L^C L}(\eta^{MI}-1) + \epsilon^{LL}] && \text{(B.21)}\end{aligned}$$

Similarly:

$$\begin{aligned}\frac{\partial L}{\partial P^A} &= [\frac{\partial L^C}{\partial P^M} - \frac{\partial L}{\partial I}M]\frac{A}{M} && \text{(B.22)}\\ &= \frac{A}{1-T^L}[\epsilon^{L^C L}(\eta^{MI}-1) + \epsilon^{LL}] && \text{(B.23)}\end{aligned}$$

Thus, $T^L\frac{dL}{dT^L}$ can be written as:

$$\begin{aligned}T^L\frac{dL}{dT^C} = -\frac{MEB^L}{\epsilon^{LL}}[E\epsilon^{L^C L}\left(\eta^{MI}-1\right)] +\\ MEB^L T^C\frac{dE}{dT^C} - \frac{MEB^L}{\epsilon^{LL}}\\ (-\frac{\partial L}{\partial R} - B[\epsilon^{L^C L}(\eta^{MI}-1)+\epsilon^{LL}]\frac{\partial P^B}{\partial R}\\ -A[\epsilon^{L^C L}(\eta^{MI}-1)+\epsilon^{LL}]\frac{\partial P^A}{\partial R})\frac{dR}{dT^C} && \text{(B.24)}\end{aligned}$$

Noting that empirical measures of labor response to non-wage income is quite small and oftentimes zero, I set $\frac{\partial L}{\partial R} = 0$ (Triest 1990; Blundell, Duncan, and Meghir

1998). Since wage rate is constant, the marginal cost of biofuel and agricultural goods increase only with the land rent, so that $\frac{\partial P^B}{\partial R} = \frac{\partial P^A}{\partial R} = 1$. Thus, the previous equation can be written as:

$$\begin{aligned} T^L \frac{dL}{dT^C} &= -\frac{MEB^L}{\epsilon^{LL}}[E\epsilon^{L^C L}\left(\eta^{MI}-1\right)] + MEB^L T^C \frac{dE}{dT^C} \\ &+ \frac{MEB^L}{\epsilon^{LL}}((A+B)[\epsilon^{L^C L}(\eta^{MI}-1)+\epsilon^{LL}])\frac{dR}{dT^C} \end{aligned} \tag{B.25}$$

Substituting B.25 to Equation (24) gives:

$$\begin{aligned} \frac{dV(T^C)}{dT^C} &= -\frac{\phi}{\lambda}\frac{dE}{dT^C} + T^C \frac{dE}{dT^C}\frac{MEB^L}{\epsilon^{LL}}[E\epsilon^{L^C L}\left(\eta^{MI}-1\right)] \\ +MEB^L T^C \frac{dE}{dT^C} &+ \frac{MEB^L}{\epsilon^{LL}}((A+B)[\epsilon^{L^C L}(\eta^{MI}-1)+\epsilon^{LL}])\frac{dR}{dT^C} \end{aligned} \tag{B.26}$$

Setting the above equation to zero gives the second-best optimal carbon tax, T^{C*}:

$$\begin{aligned} T^{C*} &= \frac{1}{(MEB^L+1)}\frac{\phi}{\lambda} + \frac{-T^L}{1-T^L}[T^C \frac{\epsilon^{L^C L}(\eta^{MI}-1)}{\epsilon^{ET}} \\ &\frac{-T^L}{1-T^L}((A+B)[\epsilon^{L^C L}(\eta^{MI}-1)+\epsilon^{LL}])\frac{\gamma^{RE}}{E/R} \end{aligned} \tag{B.27}$$

Appendix C

Comparative static effects of a carbon tax on consumption goods and land rent:

The total amount of land is equal to the demand for land for biofuel and agricultural production, i.e. $\overline{K} = L_B + L_A$. I define a unit of land as the input necessary to produce one unit of B or A so that $L_B = B$ and $L_A = A$ and $\overline{K} = B + A$. The rental rate of land (R) can be interpreted as the marginal cost of the land constraint. Thus, a higher demand for land from either biofuel or agricultural production will raise the value of R. In order to obtain an expression for $\frac{dR}{dT^C}$, the change in the equilibrium values of B and A given a marginal change in T^C and its resulting impact on R have to be determined.

For the purpose of deriving the change in land rate with respect to the carbon tax, I assume that labor and the labor tax rate are fixed [19].

Taking the total differential of the first order conditions of G,B, and A and the additional constraint that $\overline{K} = B + A$, the following system of equations is obtained:

---

[19] Recall that in the utility function, leisure is weakly separable from consumption goods. This implies that the marginal rate of substitution between biofuel and agricultural goods (or any pair of consumption goods) is independent of the quantity of leisure or labor. (see Goldman and Uzawa (1964) page 388). Thus, given a change in relative prices of biofuel and agricultural goods due to the carbon tax, the resulting change in demand for biofuel and agricultural goods will be independent of the level of labor. In the case of the labor tax, a change in the labor tax rate due to a change in the carbon tax rate will affect the level of labor and consumption only through an "income effect", or a change in the overall expenditure for consumption goods (Deaton and Muellbauer (1980) page 128). Therefore, assuming that the consumption sub-utility function is homothetic, a change in T^L is unlikely to have an effect on the relative demand for B and A. If B and A have identical production functions, then a proportional change in both demands will not change their input demands for land and labor relative to each other. This can be shown by comparing the input demands of two goods with idential production functions in which the ratio of input demands depends only on the ratio of output levels.

$$\begin{pmatrix} (U_M M_G)_G & (U_M M_G)_B & 0 & 0 \\ (U_M M_B)_G & (U_M M_B)_B & 0 & -1 \\ 0 & 0 & U_{AA} & -1 \\ 0 & 1 & 1 & 0 \end{pmatrix} \bullet \begin{pmatrix} \frac{dG}{dT^C} \\ \frac{dB}{dT^C} \\ \frac{dA}{dT^C} \\ \frac{dR}{dT^C} \end{pmatrix} \equiv \begin{pmatrix} \delta^G \\ \delta^B \\ 0 \\ 0 \end{pmatrix}$$

The determinant of the first matrix, above, is denoted by "$|D|$" and is positive due to the assumptions that utility is concave and the cost functions are convex. Using Cramer's rule, the unknowns in the system can be solved for. The reader can confirm that the following expressions hold:

$$|D| = (U_M M_B)_G (U_M M_G)_B - U_{AA}(U_M M_G)_G - (U_M M_B)_B (U_M M_G)_G \tag{C.1}$$

$$\frac{dG}{dT^C} = \frac{1}{|D|} U_{AA}\delta^G + \delta^G (U_M M_B)_B - \delta^B (U_M M_G)_B \tag{C.2}$$

$$\frac{dB}{dT^C} = -\frac{1}{|D|}\delta^G (U_M M_B)_G - \delta^B (U_M M_G)_G \tag{C.3}$$

$$\frac{dA}{dT^C} = \frac{1}{|D|}\delta^G (U_M M_B)_G - \delta^B (U_M M_G)_G \tag{C.4}$$

$$\frac{dR}{dT^C} = -\frac{U_{AA}}{|D|}\delta^G (U_M M_B)_G - \delta^B (U_M M_G)_G \tag{C.5}$$

Substituting (C.3) to (C.5) gives:

$$\frac{dR}{dT^C} = -U_{AA}\frac{dB}{dT^C} \tag{C.6}$$

Substituting $\sigma = \frac{M_G M_B}{M_{GB} M}$ to C.3 and C.2 yields:

$$\frac{dB}{dT^C} = -\frac{P^M}{|D|}\left[\frac{\sigma}{\eta^{MM}}\left\{\delta^G M_{GB} - \delta^B \frac{M_G M_{GB}}{M_B}\right\} + (\delta^G M_{BG} - \delta^B M_{GG})\right] \tag{C.7}$$

and

$$\frac{dG}{dT^C} = -\frac{1}{|D|}[\frac{1}{\epsilon^{AP}A}\delta^G + \frac{P^M\sigma}{\eta^{MM}}\delta^G\frac{M_{GB}M_B}{M_G} - \delta^B M_{GB} + P^M(\delta^G M_{BB} - \delta^B M_{GB})] \tag{C.8}$$

I derive an empirical formula for (C.7) to see how differences in parameter assumptions change the value of $\epsilon^{BT} = \frac{dB}{dTC}\frac{TC0}{B}$.

An expansion of C.3 gives:

$$\begin{aligned}
\frac{dB}{dT^C} &= -\frac{1}{|D|}\left[\delta^G(U_{MM}M_GM_B + U_MM_{BG}) - \delta^B(U_{MM}M_GM_GU_MM_{GG})\right] && \text{(C.9)}\\
&= -\frac{1}{|D|}\left[U_{MM}M_G(\delta^GM_B - \delta^BM_G) + U_M(\delta^GM_{BG} - \delta^BM_{GG})\right] && \text{(C.10)}
\end{aligned}$$

where:

$$\begin{aligned}
|D| = (U_{MM}M_GM_B + U_MM_{BG})(U_{MM}M_BM_G + U_MM_{GB})&\\
-U_{AA}(U_{MM}M_GM_G + U_MM_{GG})&\\
-(U_{MM}M_BM_B + U_MM_{BB})(U_{MM}M_GM_G + U_MM_{GG})& \qquad \text{(C.11)}
\end{aligned}$$

Floyd (1965) gives the following definitions:

$$M_{GG} = -(B/G)\frac{M_B M_G}{\sigma M} \tag{C.12}$$

$$M_{BB} = -(G/B)\frac{M_B M_G}{\sigma M} \tag{C.13}$$

$$M_{GB} = \frac{M_B M_G}{\sigma M} \tag{C.14}$$

$$U_M = P^M = \frac{B}{F}P^B + \frac{G}{F}P^G \tag{C.15}$$

$$U_{MM} = \frac{dP^M}{dM} = \eta^{MM}/(M/P^M) \tag{C.16}$$

$$U_{AA} = \frac{dP^A}{dA} = \eta^{AA}/(A/P^A) \tag{C.17}$$

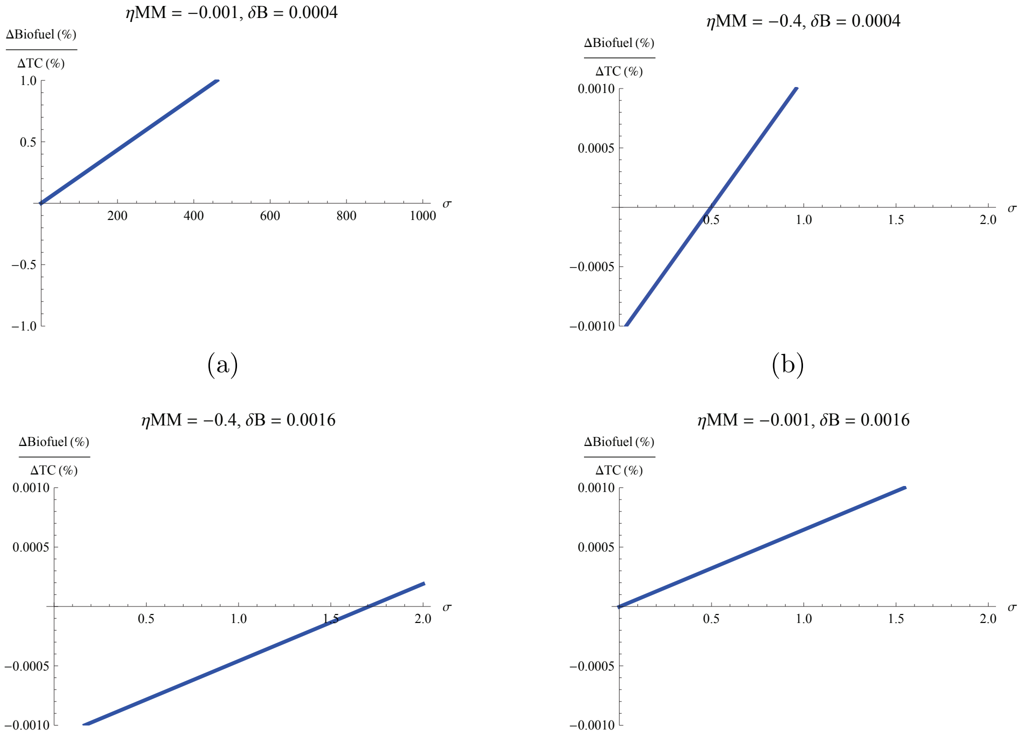
Where B, G, M, P^G, P^B and P^A are market parameters and η^{MM} and η^{AA} are elasticity estimates. Furthermore, M_B and M_G are miles per gallon estimates from biofuel and gasoline respectively and σ is the elasticity of substitution between the two fuels. Using market and empirical data described in the Data and Parameters section, the determinant can be numerically estimated.

Numerical simulations show that depending on the combination of parameter values, the sign of (C.7) could be positive or negative, as shown in the figures below.

Figures (C-1) show ϵ^{BT} as a function of the elasticity of substitution between biofuel and gasoline (σ) under different assumptions about the GHG reduction from biofuel and the price elasticity of miles demand. Figure (C-1a) shows that the higher the elasticity of substitution, the greater the value of ϵ^{BT}, and that the magnitude is greater the more inelastic miles demand is (see (C-1c) and (C-1d)), and the greater the GHG reduction of biofuel compared to gasoline (see (C-1b) and (C-1c)).

The next set of figures show the sensitivity of ϵ^{BT} to the GHG intensity of biofuel. Figure (C-2) shows that ϵ^{BT} decreases as δ^B increases, holding δ^G constant. The sign of ϵ^{BT} is more likely to be positive if the elasticity of substitution is high and miles is very inelastic. In Figure (C-2c) where miles is moderately inelastic and the elasticity of substitution is very low, ϵ^{BT} is negative regardless of the value of δ^B.

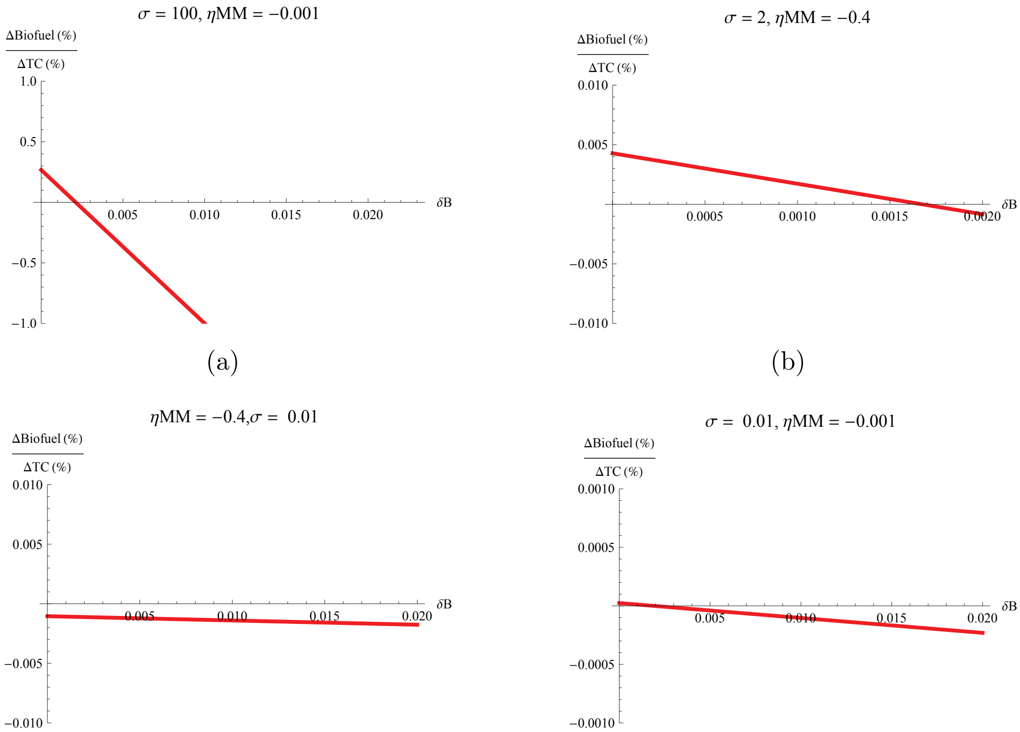
The change in ϵ^{BT} as miles demand elasticity changes is illustrated in Figure (C-3). For a very high elasticities of substitution (C-3a), ϵ^{BT} is positive regardless of miles elasticity. If $\sigma = 2$, as in Figure (C-3b), ϵ^{BT} could be positive or negative, depending on the miles elasticity. As miles demand becomes more inelastic, ϵ^{BT} is more likely to be positive. For low levels of substitution elasticity, Figures (C-3c) and (C-3d) show that ϵ^{BT} is likely to be negative, unless miles demand is close to being perfectly inelastic.



(a) (b)

(c) (d)

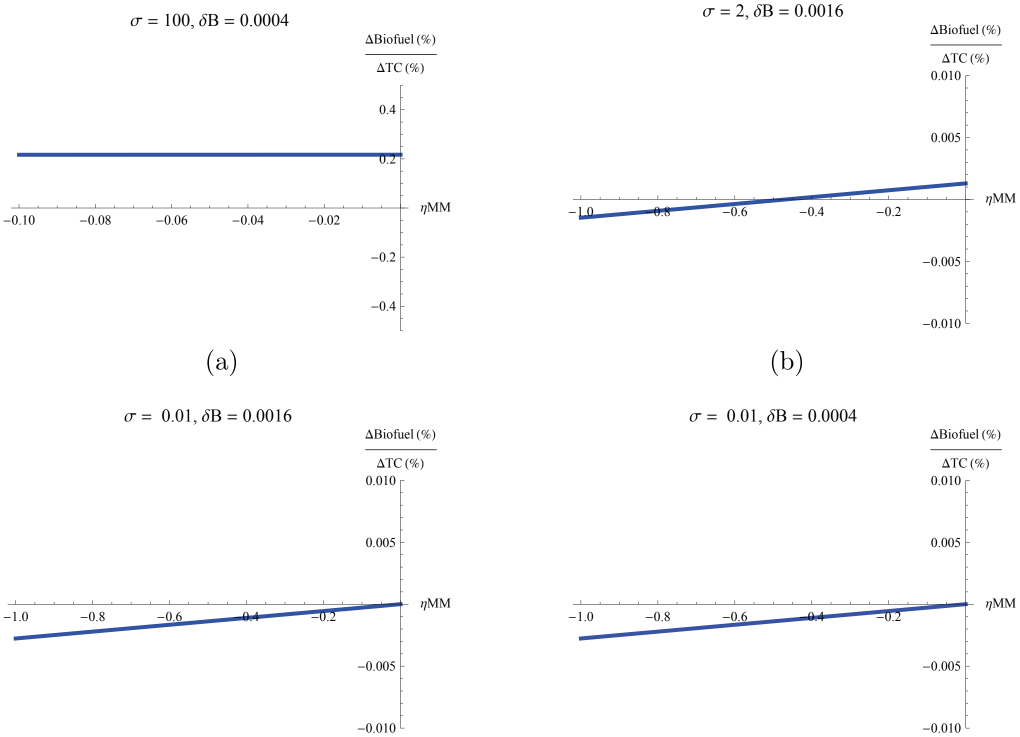
Figure C.1: Sensitivity of ϵ^{BT} to the Elasticity of Substitution



(a) (b)

(c) (d)

Figure C.2: Sensitivity of ϵ^{BT} to the Emission Intensity of Biofuel



(a) (b)

(c) (d)

Figure C.3: Sensitivity of ϵ^{BT} to the Price Elasticity of Miles Demand

Author's Biography

Marie Christine Dionela Lasco (now Marie Christine L. Crago) grew up in the town of Los Baños in the Philippines. Christine graduated with a BS Economics degree from the University of the Philippines (Los Baños) in 2001. She worked as an analyst/software engineer for Accenture in Manila, Philippines before starting her graduate education. She obtained her MS degree in Agricultural Economics from Michigan State University in 2005, and started her PhD studies the same year at the University of Illinois Urbana-Champaign. She is married to Neal C. Crago.