AgEcon SEARCH
RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search
http://ageconsearch.umn.edu
aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

No endorsement of AgEcon Search or its fundraising activities by the author(s) of the following work or their employer(s) is intended or implied.

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

Christine L. Crago (Corresponding author)
Department of Agricultural and Consumer Economics
Energy Biosciences Institute
1132 IGB Bldg., 1206 W Gregory Drive, Urbana, IL. 61801
Email: mlasco@illinois.edu
Phone: 217-721-3951
Fax: 217-244-3637
Madhu Khanna
Department of Agricultural and Consumer Economics
Energy Biosciences Institute
301A Mumford Hall, 1301 W Gregory Drive, Urbana, IL.

Paper prepared for presentation at the Agricultural & Applied Economics Association 2010 AAEA,CAES, & WAEA Joint Annual Meeting, Denver, Colorado, July 25-27, 2010

Copyright 2010 by Christine L. Crago and Madhu Khanna. All rights reserved. Readers may make verbatim copies of this document for non-commercial purposes by any means, provided that this copyright notice appears on all such copies.

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

Abstract

A carbon tax would penalize carbon intensive fuels like gasoline and shift fuel consumption to less carbon intensive alternatives like biofuels. Since biofuel production competes for land with agriculture, a carbon tax could raise land rents, divert land towards fuel production, and raise agricultural prices. This paper analyzes the welfare effect of a carbon tax on fuel with gasoline and biofuel as available fuel choices, in the presence of a labor tax and biofuel subsidy. The second-best optimal carbon tax is also quantified. Findings show that when biofuels 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 biofuel is high, miles is more price inelastic, and the GHG intensity of biofuel is lower compared to gasoline. 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. 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.
Keywords: carbon tax, optimal fuel tax, biofuel

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 2005).

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 [1]. 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 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

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

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 de Mooij 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 (2005) 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 (2005)) 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 [2]. 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

[2] 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.

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 (2005) 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, 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.

0.1 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:

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

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:

$$U = u(\acute{L}, M(G, B), A) - \phi E + Y \tag{2}$$

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:

$$\begin{aligned} \max_{\acute{L},G,B,A} U = u(\acute{L}, M(G,B), A) - \phi E + Y \quad s.t. \\ \lambda[I - (P^G + \delta^G T^C)G - (P^B + \delta^B T^C)B - P^A A] \end{aligned} \tag{3}$$

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

$$L : u_L - \lambda(1 - T^L) = 0 \tag{4}$$

$$G : u_M M_G - \lambda(P^G + \delta^G T^C) = 0 \tag{5}$$

$$B : u_M M_B - \lambda(P^B + \delta^B T^C) = 0 \tag{6}$$

$$A : u_A - \lambda P^A = 0 \tag{7}$$

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, (5) and (6) 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 (3) in the utility function, the indirect utility function (V) is derived, with the carbon tax, T^C as its argument:

$$V(T^C) = u(\acute{L}^*, M(G^*, B^*), A^*) - \phi(E) + Y + \lambda[I - (P^G + \delta^G T^C)G^* - (P^B + \delta^B T^C)B^* - P^A A^*] \tag{8}$$

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

$$\frac{dV(T^C)}{dT^C} = -\frac{\phi}{\lambda}\frac{dE}{dT^C} + T^C\frac{dE}{dT^C} + T^L\frac{dL}{dT^C} \tag{9}$$

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:

$$\frac{dL}{dT^C} = \frac{\partial L}{\partial T^L}\frac{dT^L}{dT^C} + \frac{\partial L}{\partial T^C} + (\frac{\partial L}{\partial R} + \frac{\partial L}{\partial P^A}\frac{dP^A}{dR} + \frac{\partial L}{\partial P^B}\frac{dP^B}{dR})\frac{dR}{dT^C} \tag{10}$$

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) [3]. 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 [4]. A change in land rent will affect the price of commodities that use land as an input, and also affect land rent income.

[3]see Appendix section.

[4]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.

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.

0.1.1 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 [5].

By total differentiation of the first order conditions of (3) 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:

$$\frac{dR}{dT^C} = -U_{AA}\frac{dB}{dT^C} \tag{11}$$

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

where:

$$\frac{dB}{dT^C} = -\frac{P^M}{|D|}[\frac{\sigma}{\eta^{MM}}\left\{\delta^G M_{GB} - \delta^B \frac{M_G M_{GB}}{M_B}\right\} + (\delta^G M_{BG} - \delta^B M_{GG})] \quad (12)$$

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 (11) 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 (11) is positive, and vice-versa.

Equation (12) 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[6].

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 (12) 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

[6]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.

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 (12) 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 (10) and (11) 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 (9). 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:

$$T^{C*} = \frac{\phi}{\lambda} - T^L \frac{\frac{dL}{dT^C}}{\frac{dE}{dT^C}} \tag{13}$$

Equation (13) shows the components of the second best optimal carbon tax [7]. 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 (13) in terms of empirically measureable components. Appendix B shows that (13) can be expressed as:

$$T^{C*} = \overbrace{\frac{1}{(MEB^L + 1)}\frac{\phi}{\lambda}}^{Pigouvian} + \overbrace{\frac{-T^L}{1-T^L}[T^C \frac{\epsilon^{L^C L}(\eta^{MI} - 1)}{\epsilon^{ET}}]}^{TaxInteration+RevenueRecycling} \tag{14}$$
$$\underbrace{\frac{-T^L}{1-T^L}((A+B)[\epsilon^{L^C L}(\eta^{MI} - 1) + \epsilon^{LL}])\frac{\gamma^{RE}}{E/R}}_{LaborMarketCommodityPriceEffect}$$

[7] 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.

where:

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

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

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

The compensated labor supply elasticity with respect to the labor tax is given by $\epsilon^{L^C L}$, while ϵ^{ET} is the emissions elasticity at the optimum. The "T^C" term that appears on the right hand side of (14) is the MED of carbon, which is the closest approximation of the second-best optimal carbon tax. The first term in (14) 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 (2005), 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.

0.1.2 Second-Best Optimal Tax with a Subsidy

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

$$Y = T^L L + T^C E - SB \tag{15}$$

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:

$$\frac{dT^L}{dT^C} = -\frac{1}{L}(E + T^C \frac{dE}{dT^C} + T^L \frac{dL}{dT^C} - S \frac{dB}{dT^C}) \tag{16}$$

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

$$\frac{dV(T^C)}{dT^C} = -\frac{\phi}{\lambda}\frac{dE}{dT^C} + T^C\frac{dE}{dT^C} + \frac{MEB^L}{\epsilon^{LL}}[E\epsilon^{L^C L}\left(\eta^{MI} - 1\right)] + MEB^L T^C\frac{dE}{dT^C}$$
$$+\frac{MEB^L}{\epsilon^{LL}}((A+B)[\epsilon^{L^C L}(\eta^{MI}-1)+\epsilon^{LL}])\frac{dR}{dT^C} - (1+MEB^L)S\frac{dB}{dT^C} \quad (17)$$

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

$$T^{C*} = \overbrace{\frac{1}{(MEB^L+1)}\frac{\phi}{\lambda}}^{Pigouvian} + \overbrace{\frac{-T^L}{1-T^L}[T^C\frac{\epsilon^{L^C L}(\eta^{MI}-1)}{\epsilon^{ET}}]}^{TaxInteration+RevenueRecycling}$$
$$\underbrace{\frac{-T^L}{1-T^L}((A+B)[\epsilon^{L^C L}(\eta^{MI}-1)+\epsilon^{LL}])\frac{\gamma^{RE}}{E/R}}_{LaborMarketCommodityPriceEffect} \underbrace{+(1+MEB^L)S\frac{\frac{T^C}{B}}{R/E}\frac{\epsilon^{BT}}{\epsilon^{ET}}}_{SubsidyEffect} \quad (18)$$

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 (17). 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 (18).

0.2 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:

$$\max_{\acute{L},G,B,A} U = u(\acute{L}, M(G,B), A) - \phi(E) + Y + \lambda[I - P^G G - (P^B - S)B - P^A A] \tag{19}$$

and the first-order conditions (FOCs) are:

$$L : u_L - \lambda(1 - T^L) = 0 \tag{20}$$

$$G : u_M M_G - \lambda P^G = 0 \tag{21}$$

$$B : u_M M_B - \lambda(P^B - S) = 0 \tag{22}$$

$$A : u_A - \lambda P^A = 0 \tag{23}$$

The indirect utility function is:

$$V(S) = u(\acute{L}^*, M(G^*, B^*), A^*) - \phi(E) + Y + \lambda[I - P^G G^* - (P^B - S)B^* - P^A A^*] \quad (24)$$

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:

$$\frac{dT^L}{dS} = -\frac{1}{L}(T^L \frac{dL}{dS} - B - S\frac{dB}{dS}) \quad (25)$$

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 (25) in the resulting expression.

$$\frac{dV(T^C)}{dS} = -\frac{\phi}{\lambda}\frac{dE}{dS} - S\frac{dB}{dS} + T^L \frac{dL}{dS} \quad (26)$$

The first term in (26) 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 (25) gives:

$$\frac{dL}{dS} = \frac{-\frac{1}{L}\frac{\partial L}{\partial T^L}(-B - S\frac{dB}{dS}) + [\frac{\partial L}{\partial R} + \frac{\partial L}{\partial P^A}\frac{\partial P^B}{\partial R} + \frac{\partial L}{\partial P^A}\frac{\partial P^A}{\partial R}]\frac{dR}{dS} + \frac{\partial L}{\partial S}}{1 + \frac{T^L}{L}\frac{\partial L}{\partial T^L}} \tag{27}$$

which can also be expressed as:

$$\begin{aligned} T^L\frac{dL}{dT^C} = -\frac{MEB^L}{\frac{\partial L}{\partial T^L}}[L\frac{\partial L}{\partial S} + B\frac{\partial L}{\partial T^L}] - MEB^L S\frac{dB}{dS} + \\ (1 + MEB^L)T^L[\frac{\partial L}{\partial R} + \frac{\partial L}{\partial P^A}\frac{\partial P^B}{\partial R} + \frac{\partial L}{\partial P^A}\frac{\partial P^A}{\partial R}]\frac{dR}{dS} \end{aligned} \tag{28}$$

where:

$$L\frac{\partial L}{\partial S} + B\frac{\partial L}{\partial T^L} = -B\frac{\partial L^C}{\partial T^L}(\eta^{MI} - 1) \tag{29}$$

The first term in (28) 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 (28) 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 (26) in empirically estimable terms as described below.

Substituting (29) in (28) and using results from Appendix B:

$$
\begin{aligned}
T^L \frac{dL}{dS} = {} & \frac{MEB^L}{\epsilon^{LL}} [B\epsilon^{L^C L} \left(\eta^{MI} - 1\right)] - MEB^L S \frac{dB}{dS} \\
& + \frac{MEB^L}{\epsilon^{LL}} ((A + B)[\epsilon^{L^C L} (\eta^{MI} - 1) + \epsilon^{LL}]) \frac{dR}{dS}
\end{aligned} \tag{30}
$$

Substituting (30) in Equation (26) gives:

$$\frac{dV(S)}{dS} = -\frac{\phi}{\lambda}\frac{dE}{dS} + \frac{MEB^L}{\epsilon^{LL}}[E\epsilon^{L^C L}\left(\eta^{MI} - 1\right)] \tag{31}$$
$$+\frac{MEB^L}{\epsilon^{LL}}S\frac{dB}{dS} + \frac{MEB^L}{\epsilon^{LL}}((A+B)[\epsilon^{L^C L}(\eta^{MI} - 1) + \epsilon^{LL}])\frac{dR}{dS}$$

where:

$$\frac{dE}{dS} = \delta^G \frac{\epsilon^{GP^B}}{P^B/G} + \frac{\delta^B \epsilon^{BP^B}}{P^B/B} \tag{32}$$

$$\frac{dB}{dS} = \frac{-\epsilon^{BP}}{P^B/B} \tag{33}$$

$$\frac{dR}{dS} = \frac{\epsilon^{BP}}{\epsilon^{AP}}\frac{B}{A}\frac{P^A}{P^B} \tag{34}$$

The next section discusses the data and parameters used to quantify (14) and (18), and calculate welfare effects of deviating from the second-best optimal tax rate.

0.3 Data and Parameters

I use market data and elasticities from the literature. Parry and Small (2005) 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.

0.3.1 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. 2006; 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.

0.3.2 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 1 shows the range of values for ϵ^{ET}. Results are presented for the range of parameters used shown in Table 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 2009). 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.

0.3.3 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 [8] 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.

0.3.4 Labor Market Parameters

For labor market parameters, I use values similar to Parry and Small (2005). 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.

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

0.4 Results

0.4.1 Second-Best Carbon Tax

Values of the second-best optimal carbon tax (T^{C*}) are presented in Table 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 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 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 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 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), 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 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 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.

0.4.2 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 (31). Table 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.

0.5 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.

0.6 Figures and Tables

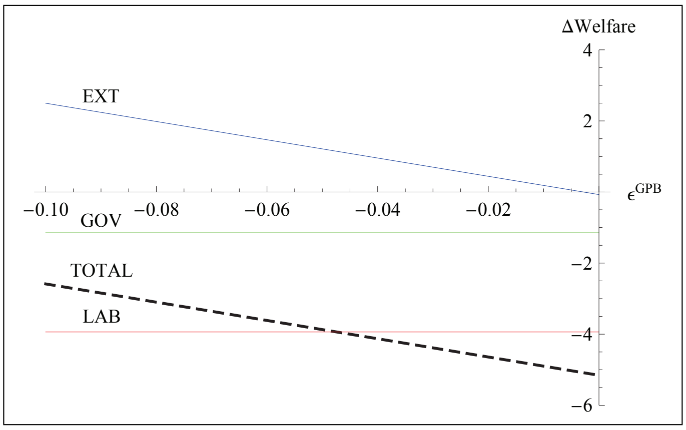

Figure 1: Welfare Effect of a Subsidy

Table 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

References

Baumol, W. 1972. "On Taxation and the Control of Externalities." *American Economic Review* 62:307–22.

Baumol, W., and W. Oates. 1971. "The Use of Standards and Prices for Protection of the Environment." *Swedish Journal of Economics* 73:42–54.

Bento, A., and M. Jacobsen. 2007. "Ricardian rents, environmental policy and the double-dividend hypothesis." *Journal of Environmental Economics and Management* 53(1):17–31.

Blundell, R., A. Duncan, and C. Meghir. 1998. "Estimating labor supply responses using tax reforms." *Econometrica* 66:827–861.

Table 2: Second-Best Carbon Tax Under Different Parameter Assumptions, $\sigma = 10$ (\$/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*})	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 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: 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 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 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

Bovenberg, A. 1999. "Green tax reforms and the double dividend: an updated reader's guide." *International Tax and Public Finance* 6:421–443.

Bovenberg, A., and R. de Mooij. 1994. "Environmental levies and distortionary taxation." *The American Economic Review* 84:1085–1089.

Bovenberg, A., and L. Goulder. 1996. "Optimal environmental taxation in the presence of other taxes: general-equilibrium analyses." *The American Economic Review* 86:985–1000.

Bovenberg, A., and F. Van der Ploeg. 1998. "Consequences of environmental tax reform for unemployment and welfare." *Environmental and Resource Economics* 12:137–150.

CARB. 2009. "Detailed CA-GREET Pathway for California Reformulated Gasoline Blendstock for Oxygenate Blending (CARBOB) from Average Crude Refined in California.", pp. .

de Gorter, H., and D.R. Just. 2008. "The Welfare Economics of a Biofuel Tax Credit and the Interaction effects with Price Contingent Farm Subsidies." *American Journal of Agricultural Economics* 90:in press.

Deaton, A., and J. Muellbauer. 1980. *Economics and consumer behavior*. Cambridge Univ Pr.

Department of Energy. 2009. "Estimated Petroleum Consumption: Transportation Sector, 1949-2008."

Elobeid, A., and S. Tokgoz. 2008. "Removing Distortions in the U.S. Ethanol Market: What Does It Imply For the United States and Brazil?" *American Journal of Agricultural Economics* 90:918–932.

ERS. 2003. "Commodity and Food Elasticities:Demand Elasticities from Literature for US Grain." $http://www.ers.usda.gov/Data/Elasticities/query.aspx$.

Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne. 2008. "Land clearing and the biofuel carbon debt." *Science* 319:1235.

Farrell, A., R. Plevin, B. Turner, A. Jones, M. O'hare, and D. Kammen. 2006. "Ethanol can contribute to energy and environmental goals." *Science* 311:506.

Floyd, J. 1965. "The effects of farm price supports on the returns to land and labor in agriculture." *The Journal of Political Economy* 73:148–158.

Fuchs, V., A. Krueger, and J. Poterba. 1998. "Economists' views about parameters, values, and policies: Survey results in labor and public economics." *Journal of Economic Literature* 36:1387–1425.

Goldman, S., and H. Uzawa. 1964. "A note on separability in demand analysis." *Econometrica* 32:387–398.

Goulder, L. 1995a. "Effects of carbon taxes in an economy with prior tax distortions: An intertemporal general equilibrium analysis." *Journal of Environmental economics and Management* 29:271–297.

—. 1995b. "Environmental taxation and the double dividend: a reader's guide." *International Tax and Public Finance* 2:157–183.

Hoo, S., and R. Ebel. 2005. "An International Perspective on Gasoline Taxes." *Tax Notes*, pp. .

Liska, A., H. Yang, V. Bremer, T. Klopfenstein, D. Walters, G. Erickson, and K. Cassman. 2009. "Improvements in life cycle energy efficiency and greenhouse gas emissions of corn-ethanol." *Journal of Industrial Ecology* 13:58–74.

NEB. 2009. "Ethanol and Gasoline Wholesale Prices." requested data.

Parry, I. 2001. "Comparing the marginal excess burden of labor, petrol, cigarette, and alcohol taxes: An application to the United Kingdom." *Resources for the Future Inc., Discussion Paper 00-33REV*, pp. .

—. 1995. "Pollution taxes and revenue recycling." *Journal of Environmental Economics and Management* 29(3):64–77.

Parry, I., and K. Small. 2004. "Does Britain or the United States have the right gasoline tax?" *RFF Discussion Paper*, pp. .

—. 2005. "Does Britain or the United States have the right gasoline tax?" *American Economic Review* 95:1276–1289.

Pickrell, D., and P. Schimek. 1997. "Trends in personal motor vehicle ownership and use: Evidence from the nationwide personal transportation survey." In *US Federal Highway Administration, Proceedings from the Nationwide Personal Transportation Survey Symposium*. vol. 17, pp. 85–127.

Pigou, A. 1932. "The economics ofwelfare." *Mac Millan, London*, pp. .

RFA. 2009. "Renewable Fuels Association Ethanol Industry Overview."

Searchinger, T., R. Heimlich, R. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T. Yu. 2008. "Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change." *Science* 319:1238.

Triest, R. 1990. "The effect of income taxation on labor supply in the United States." *Journal of Human Resources*, pp. 491–516.

USCB. 2009. "Civilian Consumer Expenditures For Farm Foods." *http://www.census.gov/compendia/statab/cats/agriculture.html*.

Wang, M., M. Wu, and H. Huo. 2007. "Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types." *Environmental Research Letters* 2:024001.

West, S., and R. Williams. 2007. "Optimal taxation and cross-price effects on labor supply: Estimates of the optimal gas tax." *Journal of Public Economics* 91:593–617.

Wu, M., M. Wang, and H. Hou. 2007. "Fuel-cycle assessment of selected bioethanol production." Working paper, ANL/ESD/06-7, Argonne National Laboratory (ANL).

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 (9).

Appendix B. Deriving an empirical formula for the optimal carbon tax

Substituting (A.3) in (10) 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 (14), 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, $(1 - T^L)L$ [9]. 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:

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

[9] 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:

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

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 (9) gives:

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

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 [10].

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:

[10] 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:

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

and

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

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:

$$\begin{aligned} \frac{dB}{dT^C} &= -\frac{1}{|D|}\left[\delta^G(U_{MM}M_G M_B + U_M M_{BG}) - \delta^B(U_{MM}M_G M_G U_M M_{GG})\right] && (C.9) \\ &= -\frac{1}{|D|}\left[U_{MM}M_G(\delta^G M_B - \delta^B M_G) + U_M(\delta^G M_{BG} - \delta^B M_{GG})\right] && (C.10) \end{aligned}$$

where:

$$\begin{aligned} |D| = (U_{MM}M_G M_B + U_M M_{BG})(U_{MM}M_B M_G + U_M M_{GB}) \\ -U_{AA}(U_{MM}M_G M_G + U_M M_{GG}) \\ -(U_{MM}M_B M_B + U_M M_{BB})(U_{MM}M_G M_G + U_M M_{GG}) \quad (C.11) \end{aligned}$$

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.

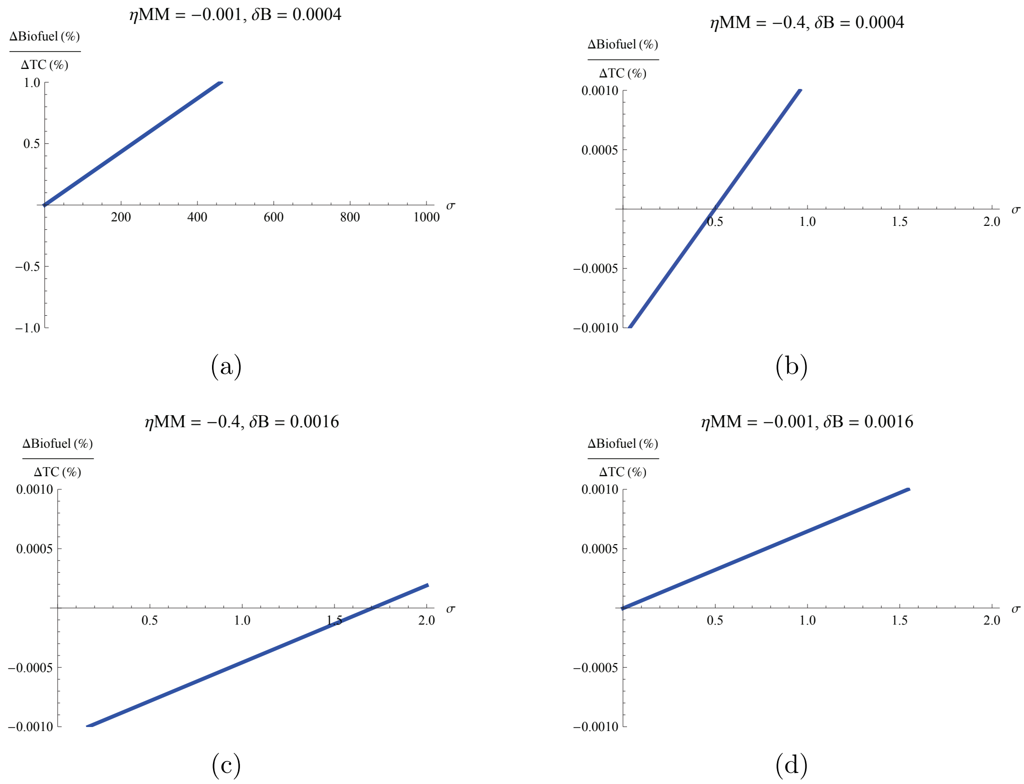

Figure C.1: Sensitivity of ϵ^{BT} to the Elasticity of Substitution

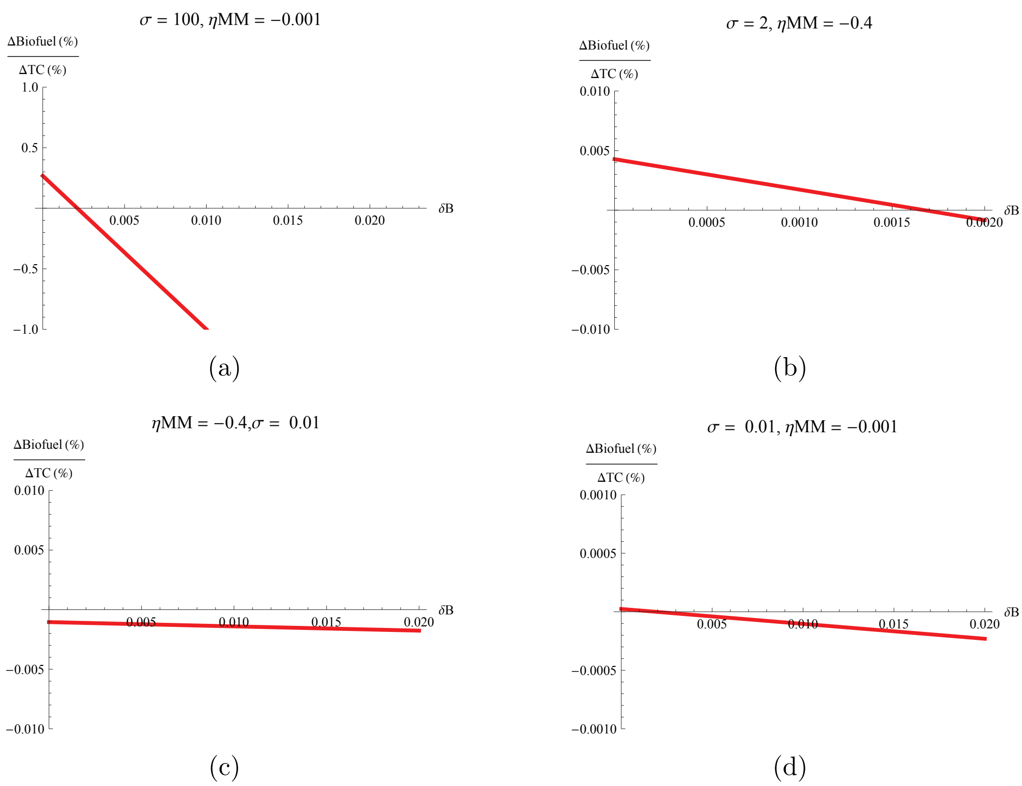

Figure C.2: Sensitivity of ϵ^{BT} to the Emission Intensity of Biofuel

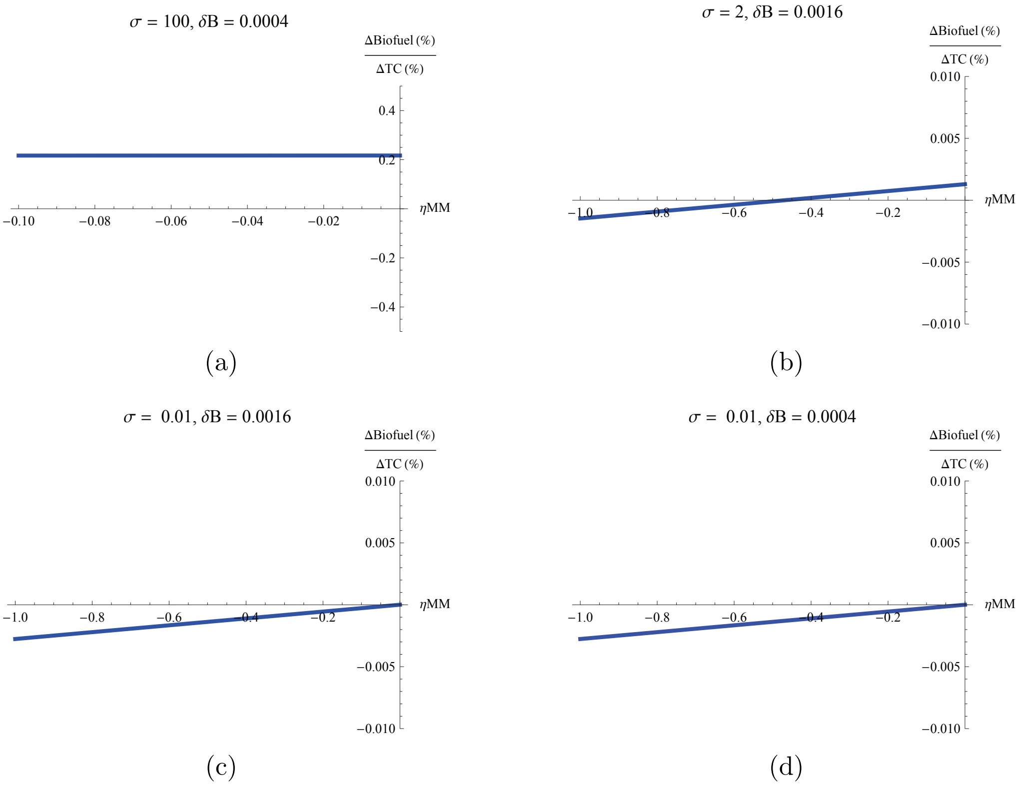

Figure C.3: Sensitivity of ϵ^{BT} to the Price Elasticity of Miles Demand