Welfare Effects of Biofuel Policies in the Presence of Fuel and Labor Taxes*

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Abstract

A tractable general equilibrium model is developed to analyze the welfare implications of a biofuel blend mandate and consumption subsidy in the presence of pre-existing labor and fuel taxes. The tax interaction and revenue recycling effects are significant relative to the overall costs of the policies and to previous partial equilibrium studies. We estimate the welfare effects of removing a tax credit which is used in combination with a binding mandate, which mirrors the expiration of the U.S. blender's tax credit at the end of 2011. Because the mandate was binding, removing the tax credit yields a net welfare gain of only $9 million, which is significantly less than the welfare gain of $357 million due to fiscal interaction effects. We find that the welfare cost of the blend mandate alone is $8.3 billion, which includes a tax interaction effect of $1.54 billion. We also find empirically that the tax credit is welfare superior to the mandate for a given level of ethanol consumption because the fuel tax is above the external costs of GHG emissions. This result is robust to the presence or absence of the labor tax.

Key words: biofuel policies, blend mandate, blender's tax credit, gasoline tax, greenhouse gas emissions, renewable fuel standard, second-best.

JEL *Classification*: H2, Q4.

I. Introduction

Biofuel blend mandates and consumption subsidies are used throughout the world. Although the U.S. blender's tax credit expired at the end of 2011, many other countries continue to employ tax-exemptions at the gasoline pump. In this paper, we derive and compare the welfare costs and benefits of biofuel blend mandates, consumption subsidies, and their combination using a closed-economy, general equilibrium model. This allows us to focus on the interactions of biofuels policies with the labor market and fixed fuel tax. Following other studies, (e.g., Cui et al. 2011, Lapan and Moschini 2012), we assume the only environmental benefit of the ethanol policies is to reduce the greenhouse gas (GHG) intensity of the fuel blend.[1] Unlike Cui et al. (2011) and Lapan and Moschini (2012), we keep the price of gasoline fixed and ignore terms of trade effects in oil imports and corn exports. This allows us to isolate the tax interaction and revenue recycling effects and compare their relative importance.

The first part of our paper develops a theoretical general equilibrium model with a pre-existing labor tax which can be used to analyze the fiscal interaction effects of U.S. ethanol policies and their implications for the policies' welfare effects. The model also includes a volumetric fuel tax. A rich literature in public finance and environmental economics has shown that the interaction of environmental policies with the broader fiscal system can significantly affect welfare measures in the context of environmental externalities (e.g., Bovenberg and de Mooij 1994, Parry 1995, Goulder et al. 1999, Parry and Small 2005, West and Williams 2007).

The tax interaction effect arises when biofuel policies change the relative commodity prices (corn and fuel, in our model) with respect to the price of labor which in turn affects

[1] This simplifying assumption ignores other environmental externalities associated with fuel consumption, including traffic congestion, motor vehicle accidents, or local air pollution (Parry and Small 2005, Parry et al. 2007, Khanna 2008; de Gorter and Just 2009b; 2010a; 2010b), as well as the concerns related to energy security.

demand for leisure, labor's substitute. This first-order welfare effect due to a change in the labor tax base occurs because of the pre-existing distortion in the labor market (Browning 1987, Parry 1995). The revenue-recycling effect arises because biofuel policies affect government revenue from the fuel market, and fuel market revenue is a substitute for labor tax revenue. Assuming that the level of total government spending will be held fixed, a biofuel policy which increases (decreases) government revenue from the fuel market will cause a decrease (increase) in the labor tax rate. The welfare effect of such a change in the labor tax is known as the "revenue-recycling effect" (Goulder 1995).

In the second part of the paper, we use a numerical version of the model that is calibrated to the U.S. in 2009 to investigate how important fiscal effects are relative to the overall welfare effects of the biofuel policies. If fiscal interaction effects are relatively large, research efforts which ignore them may overestimate the net benefits of the policies (if the fiscal interaction effects are negative), or underestimate the benefits (if the policies yield a "double dividend" – i.e., their net fiscal interaction effects are positive (Bento and Jacobsen 2007, Parry and Bento 2000).

In our first stage of analyzing the numerical model, we determine the optimal level of the tax credit or mandate, and we find that both policies would optimally be zero. This result is primarily due to rectangular deadweight costs (RDC) resulting from 'water' in the ethanol price premium (the gap between the free market ethanol price and the intercept of the ethanol supply curve).

We perform three other types of policy analysis using the numerical model. First, we study the welfare effects of removing a tax credit which is used in combination with a binding mandate (which mirrors the expiration of the U.S. blender's tax credit at the end of 2011). We find that removing the tax credit while keeping the mandate in place results in a welfare improvement of $9 million. Next, we analyze the welfare effects of the blend mandate alone. We find that the mandate imposes a welfare cost of $8.3 billion relative to an equilibrium where there is no ethanol policy. In these policy analyses, we make use of results from our theoretical model which allows us to separate the total welfare effect into four components: the primary distortion, the two fiscal interaction effects, and an externality effect. We find that most of the mandate's cost can be attributed to the primary distortion, although the tax interaction effect of $1.54 billion is also significant. Our finding that the status quo policies incur significant welfare costs corroborates our finding that the optimal policies are both zero.

Our third policy analysis compares the welfare with a blend mandate to the welfare with a tax credit that yields the same ethanol production. The question of which policy is superior has important implications for all countries which use biofuel policies, and our paper is the first to compare them in a general equilibrium framework. Theoretical partial equilibrium models (Lapan and Moschini 2012, de Gorter and Just 2010b) have shown that the mandate is superior to the tax credit on a welfare basis. Lapan and Moschini (2012) derive the first-best combination of fuel tax and ethanol subsidy and the second-best optimal ethanol subsidy or mandate alone. They find that the optimal second-best mandate (expressed as a combination of a fuel tax and ethanol subsidy) welfare dominates the optimal second-best subsidy alone. We cannot compare the mandate and the tax credit on the basis of welfare at their optimal levels – as analyzed by Lapan and Moschini (2012) – because we find both policies to be zero in the optimum due to RDC.

When we compare the welfare associated with the tax credit and mandate for the same ethanol production, we find empirically that the blender's tax credit is welfare superior to the mandate. This ordering is found to hold regardless of RDC. This is a novel result, since de Gorter and Just (2010) conclude that a mandate always welfare dominates the tax credit, given the same ethanol production. Our finding that the tax credit welfare dominates the mandate is driven by the fact that the fuel tax exceeds the marginal external cost of GHG emissions and so is superoptimal. Because the mandate by itself acts as an implicit tax on fuel consumption, its implementation on top of a superoptimal fuel tax makes it even more distortionary. On the other hand, because the tax credit lowers the fuel price, it works in the opposite direction and brings the effective fuel tax closer to its optimal level. When we compare the policies in a framework where there is no fuel tax, we find that the mandate is slightly superior to the tax credit.

Previous research has shown that differences in environmental policies' effects on government revenue can influence their welfare ordering (Goulder et al. 1997, Goulder et al. 1999). There are several inherent differences between biofuel blend mandates and consumption subsidies that make their fiscal interaction effects likely to differ. For example, although both the tax credit and mandate are revenue-requiring policies for a given level of ethanol (since fuel tax revenue declines with a mandate), the relative fiscal effects are *a priori* indeterminate. Fuel prices are always relatively higher under a mandate, and corn prices are the same for a given level of ethanol production, which implies that the mandate has a more costly tax interaction effect. We compare the mandate to the tax credit in a framework with a fuel tax but no pre-existing labor tax, and we find that the tax credit is still superior in this case.

The majority of literature studying the welfare effects of biofuel policies has taken a partial equilibrium approach (Rajagopal et al. 2007, Khanna et al. 2008, de Gorter and Just 2009b, Cui et al. 2011, Lapan and Moschini 2012). Several partial equilibrium studies numerically estimate optimal biofuel policies and find varying results, due largely to their inclusion of different externalities. For example, Khanna et al. (2008) use a partial equilibrium model to analyze the first and second best policies to address congestion and emissions externalities arising from consumption of vehicle-miles-traveled (VMT), including various combinations of the ethanol subsidy, fuel tax, and a VMT tax. They find that the first-best policy combination includes a negative ethanol subsidy – a $0.04/gallon tax – and that introducing an ethanol subsidy of $0.51/gallon (in place in 2008) decreases welfare if the fuel tax is held constant, since the ethanol subsidy decreases the price of the fuel blend and worsens the congestion externality. On the other hand, Vedenov and Wetzstein (2008) assume that ethanol consumption improves environmental quality and fuel security relative to gasoline; they follow an approach similar to Parry and Small (2005) and find that the optimal ethanol subsidy is $0.22/gallon.

Cui et al. (2011) analyze optimal biofuel policy in the presence of an emissions externality only and find that the optimal tax credit is $0.67/gallon in 2009 (35 percent greater than its actual level of $0.49/gallon) and that the optimal mandate yields even greater ethanol production than the optimal tax credit. Although our empirical model includes the same externality and is calibrated to 2009 U.S. data, we find the optimal tax credit or mandate to be zero. There are three main drivers of this difference. First, ethanol polices in the Cui et al. model derive additional benefits from the terms of trade effects in the oil and corn markets.[2] Because ours is a closed economy model, we do not capture these effects. On the other hand, we focus on understanding the relative importance of fiscal interaction effects – a welfare component not analyzed in Cui et al. (2011). Second, our ethanol policies have greater welfare costs because we

[2] Previous literature about the welfare effects of biofuel policy has also discussed the issue of "leakage" in the corn (e.g., Al-Riffai et al. 2010) and ethanol (Drabik et al. 2010; Rajagopal et al. 2011; Khanna 2012) markets and suggested that the leakage may be a significant component of welfare. Although we do not analyze leakage in this paper, in Section VI we do discuss the implications of leakage on the change in fuel tax revenue due to biofuel policies.

interact them with a pre-existing labor tax and fixed government revenue requirement. Finally, the status quo ethanol policies in Cui et al. (2011) are associated with lower deadweight costs because of the absence – relative to our model – of RDC.

Although the literature on fiscal interaction effects is extensive, few papers have measured the fiscal interaction effects of biofuel policies.[3] Crago and Khanna (2012) study the welfare effects of a carbon tax where a pre-existing ethanol subsidy and labor tax may be present; our approach here is to study the welfare effects of ethanol policies directly. Devadoss and Bayham (2010) also use a general equilibrium model to analyze welfare effects in biofuels markets, but they study the effect of the U.S. crop subsidy rather than the biofuel policy directly, and they do not have a labor market distortion.

Taheripour and Tyner (2012) analyze the welfare effects of an ethanol quantity mandate in an open-economy general equilibrium framework using the GTAP-BIO-AEZ Model. They model the mandate by imposing one of three combinations of market incentives necessary to induce the mandated quantity of ethanol: (*i*) a revenue-neutral combination of fuel tax and ethanol subsidy, (*ii*) eliminating agricultural production output subsidies while changing the ethanol subsidy and fuel tax, (*iii*) eliminating agricultural production output subsidies and paying for the ethanol subsidy with an income tax increase. In this paper, we use a different approach and implement the blend mandate directly—that is, we do not require any additional policies to impose the policy.

Overall, our paper contributes to the biofuels policy literature in two ways. First, we estimate the welfare effects of the tax credit and mandate using a general equilibrium model that allows us to estimate the fiscal interaction effects of each policy. We find that the fiscal

[3] Studies that have analyzed the fiscal interaction effects of agricultural policies include Parry (1999) and Taheripour et al. 2008).

interaction effects are significant relative to the overall costs of the policies. Because the tax credit was not the binding policy in most of 2009, its removal yields a total welfare gain of only \$9 million; however, the net fiscal interaction effect of this policy shock is considerably higher and represents a gain of \$357 million. The welfare cost of the remaining mandate is \$8.3 billion, which includes a tax interaction effect of \$1.54 billion. Our second finding is that the tax credit is welfare superior to the mandate for the same ethanol production when the fuel tax is superoptimal. This extends the partial equilibrium results of de Gorter and Just (2010b).

The remainder of the paper is organized as follows. In the next section, we build an analytical closed economy general equilibrium model with corn and labor as inputs, ethanol and gasoline as intermediate goods, and corn, fuel, and a numeraire good as the final goods. The model captures the trade-off between corn used to produce fuel and corn used for direct consumption. In Section III, we derive analytical expressions for the marginal welfare effects of each biofuel policy independently as well as effects of the tax credit applied in the presence of a binding mandate. Section IV presents a numerical version of the model; the data and calibration method for the numerical model are presented in Section V. Section VI presents our results, and Section VII provides some concluding discussion and remarks.

II. Analytical Model

The Representative Consumer

The representative consumer consumes fuel F, corn C, numeraire good x, and leisure N.[4] Leisure is assumed to be weakly separable from consumption of goods in utility. The consumer receives disutility σ (.) from an externality R associated with fuel consumption; the externality is separable from consumption in utility. The utility function is given by

[4] Fuel is a mixture of ethanol and gasoline. Because one gallon of ethanol has lower energy content than the same amount of gasoline, we measure fuel consumption in gasoline energy-equivalent gallons (GEEGs).

$$U = \varphi\left(u\left(F, C, x\right), N\right) - \sigma\left(R\right) \tag{1}$$

where φ (.) denotes utility from the consumption goods and leisure.

Production

Labor is the only factor of production, and the representative consumer's time endowment is $\bar{L}$. The consumer allocates his time between labor L and leisure such that $L + N = \bar{L}$. Labor is used in the production of gasoline G, ethanol e, corn supply C^S, and the numeraire good. The quantities of labor used to produce each good are L_G, L_e, L_C, and L_x, respectively. The wage rate is denoted by w.

Gasoline and the numeraire are produced by constant returns-to-scale production technologies. We assume perfect competition in the production of both goods, so the prices of gasoline and the numeraire depend only on the wage rate. Corn is produced using labor according to a decreasing returns-to-scale technology f (.)

$$C^S = f\left(L_C\right) \tag{2}$$

Profits from corn production are denoted by π_C and are returned lump-sum to the consumer.[5]

Ethanol e (quantity measured in physical gallons) is produced from corn and labor according to a fixed coefficients production process

$$e = \min\left\{e_C C^e, e_L L_e\right\} \tag{3}$$

where C^e is the residual corn supply after corn consumption demand is met: $C^e \equiv C^S - C$; the parameter e_C denotes total gallons of ethanol produced from one bushel of corn, and e_L denotes gallons of ethanol produced per unit of time. When calibrating the model to observed data, we

[5] Positive profits in corn production follow from our definition of the ethanol supply curve as the horizontal difference between the corn supply curve and the non-ethanol demand curve for corn. The positively sloped corn supply curve implies positive profits.

assume that the co-product from ethanol production (Dried Distillers Grains with Solubles) is a perfect substitute for corn.

The zero profit condition for ethanol production determines the link between ethanol and corn prices, denoted by P_e and P_C, respectively[6]

$$P_e = \frac{P_C}{e_C} + \frac{w}{e_L} \tag{4}$$

The link between the amount of labor and corn needed to produce *e* gallons of ethanol is obtained from cost minimization

$$e = e_C C^e = e_C \left(C^S - C \right) = e_L L_e \tag{5}$$

The consumer buys a blend of gasoline and ethanol. We assume that the consumer values fuel for miles traveled. Since one gallon of ethanol yields fewer miles traveled than a gallon of gasoline, we let γ denote the ratio of miles traveled per gallon of ethanol and gasoline. Total fuel consumption measured in gasoline energy-equivalent gallons (GEEGs) is then given by $F = G + \gamma e$. Following de Gorter and Just (2008), in our numerical model we assume that $\gamma = 0.7$. Throughout our analysis we use $E = \gamma e$ to denote ethanol measured in GEEGs. We assume that the fuel blend is produced by competitive blenders earning zero profits who face exogenous gasoline market price P_G and the ethanol market price $P_E = P_e/\gamma$, where P_E denotes the ethanol price in \$/GEEG.

Externalities

Fuel consumption is assumed to produce only one externality, carbon dioxide (CO_2) emissions; we allow the emissions per consumed GEEG to differ between ethanol and gasoline.[7] We normalize the units of CO_2 emissions so the externality can be written as

[6] The parameter e_C takes into account the effect of the ethanol co-product on the corn price.

$$R(G,E) = G + \xi E \tag{6}$$

where ξ denotes relative emissions of ethanol per GEEG. In the numerical part of the paper, we assume $\xi = 0.8$, meaning that one GEEG of ethanol emits 20 percent less CO_2 than gasoline.

Government

The government employs a volumetric fuel tax t, a proportional tax on labor earnings t_L, and either a volumetric ethanol blender's tax credit t_c or an ethanol blend mandate θ which dictates the minimum share of ethanol in the fuel (ethanol and gasoline) blend. Profits from corn production are not taxed. Real government revenue Γ is a fixed lump-sum transfer to consumers, and the government's budget is balanced and satisfies

$$\Gamma = t_L wL + t(G+e) - t_c e \tag{7}$$

The first term on the right-hand side of equation (7) represents government receipts from taxing labor; the second term denotes tax revenues from fuel consumption; the final term denotes expenditures on the tax credit.

Because the real lump-sum transfer Γ is assumed to be fixed, the labor tax is adjusted whenever labor supply or gasoline consumption, or ethanol consumption change in response to a policy change (i.e., when either the tax credit or the mandate is changed). We hold the fuel tax constant when ethanol policies change.

Equilibrium

The assumption of perfect substitutability between gasoline and ethanol (on a miles-traveled basis) implies the following relationship between prices if the tax credit is the only binding biofuel policy (de Gorter and Just, 2009a; Cui at al., 2011; Lapan and Moschini, 2012)

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[7] Other externalities associated with fuel consumption, such as traffic congestion or motor vehicle accidents, arise from vehicle-miles traveled (VMT) rather than fuel combustion. If ethanol is measured in GEEG, its VMT externalities do not differ from those of gasoline. In our model, the only potential benefit from ethanol relative to gasoline is reducing emissions (see also footnote 1). In our numerical model, we find that an extremely high MEC of carbon would make the optimal ethanol policies positive.

$$P_F = P_G + t = P_E + \frac{t}{\gamma} - \frac{t_c}{\gamma} \tag{8t}$$

Recall that the volume of one GEEG of ethanol is more than one gallon; since the fuel tax and ethanol tax credit are both volumetric, adjusting them by γ converts them to \$/GEEG units.

In the situation when the blend mandate θ (in energy terms) determines the ethanol price, the fuel price paid by consumers is a weighted average of the ethanol price and gasoline price[8]

$$P_F = \theta\left(P_E + \frac{t}{\gamma} - \frac{t_c}{\gamma}\right) + (1-\theta)(P_G + t) \tag{8m}$$

A key difference between the binding tax credit and the binding blend mandate model is how the corn price is determined. With a tax credit, corn prices are directly linked to the gasoline price. Combining equations (4) and (8t) and invoking $P_e = \gamma P_E$, we see that the tax credit directly affects the corn price:

$$P_C = e_C\left[\gamma P_G - (1-\gamma)t + t_c\right] - \frac{e_C w}{e_L} \tag{9}$$

With a binding mandate, corn-market clearing determines the corn price P_C, where the corn output supply function, denoted by $g(P_C)$ in equation (10), equals the sum of consumer demand for corn and the corn required for ethanol production (where ethanol production in turn depends on fuel demand)

$$g(P_C) = \frac{\theta F(P_C,\cdot)}{\gamma e_C} + C(P_C,\cdot) \tag{10}$$

The dot in equation (10) denotes all remaining arguments of the corn demand function. Note that with either policy in place, corn producer's profits can be expressed as a function of the corn price and the wage rate

[8] The blend mandate in energy terms denotes a share of the energy of ethanol in the total energy of the fuel.

$$\pi_C = P_C g(P_C) - f^{-1}(g(P_C))w \equiv \pi_C(P_C, w) \tag{11}$$

where f^{-1} denotes the inverse of function defined by equation (2).

We close the model by specifying the labor market clearing condition

$$L_G + L_x + L_C + L_e = L \tag{12}$$

and the representative consumer's budget constraint

$$P_F F + P_C C + P_x x + \omega N = \omega \bar{L} + \Gamma + \pi_C \tag{13}$$

Consumer wealth, on the right-hand side of equation (13), includes (*i*) the after-tax value of the labor endowment, where $\omega = (1 - t_L)w$ denotes the after-tax wage, (*ii*) the government transfer, and (*iii*) profits from corn production; all three terms are exogenous from the perspective of the consumer.

III. Marginal Welfare Effects of Biofuel Policies

In this section, we present analytical formulas to identify (and later quantify) the marginal welfare effects of the biofuel policies. In our welfare effect expressions, we use the term M to denote the marginal excess burden of taxation in the labor market, which is defined for a marginal change in the labor tax rate as the ratio of the marginal change in the "wedge" distortion (numerator) and the marginal change in labor tax revenue (denominator):

$$M = -\frac{t_L \dfrac{\partial L}{\partial t_L}}{L + t_L \dfrac{\partial L}{\partial t_L}} \tag{14}$$

Derivations of the welfare formulas can be found in Appendices 1 to 3.

Marginal welfare effects of the blender's tax credit

The marginal welfare effect of the blender's tax credit is given by

$$
\begin{aligned}
-\frac{1}{\lambda}\frac{dV}{dt_c} = & -\underbrace{\left[\left(t-t_c\right)\frac{de}{dt_c}+t\frac{dG}{dt_c}\right]}_{\text{Primary distortion effect}}-\underbrace{\left(M+1\right)t_L e_C\left(\frac{\partial L}{\partial P_C}+C^S\frac{\partial L}{\partial \pi_C}\right)}_{\text{Tax-interaction effect}} \\
& +\underbrace{M\left[e-\left(t-t_c\right)\frac{de}{dt_c}-t\frac{dG}{dt_c}\right]}_{\text{Revenue-recycling effect}}+\underbrace{\frac{\sigma'}{\lambda}\left(\frac{dG}{dt_c}+\xi\gamma\frac{de}{dt_c}\right)}_{\text{Externality effect}}
\end{aligned}
\tag{15}
$$

The first component on the right-hand side of equation (15) represents *primary distortions* or "wedges" in the fuel market caused by the fuel tax and the tax credit. It corresponds to the deadweight loss associated with the volumetric fuel tax levied on all fuel. Because the fuel is a mixture of ethanol and gasoline, the first term, (t - t_c) x de/dt_c represents the part of the change in the primary distortion effect attributable to ethanol while the term t x (dG/dt_c) represents gasoline's portion. Note that (t - t_c) denotes the net volumetric fuel tax to ethanol which is ambiguous in sign and depends on the relative size of the fuel tax and the tax credit; this term is negative in our empirical analysis.

The second component in equation (15), labeled as the *tax interaction effect*, represents the change in the labor supply (i.e., labor tax base) due to a change in the price level in the economy. When the prices of consumption goods change, the consumer reallocates the time endowment between leisure and labor. Recall that in our model the fuel price under the tax credit does not respond to shocks in this policy because it is directly linked to the exogenous gasoline price. Moreover, the price of the numeraire is normalized to unity which means that the price level in this policy scenario is changed only by the corn price. Labor supply depends on the prices of other goods, consumer wealth, and the after-tax wage rate (where the term t_L represents the wedge between pre-tax and after-tax wages). A change in the corn price due to the tax credit directly affects labor supply through the term $\partial L/\partial P_C$. The corn price change also affects corn production profits, which leads to an indirect income effect on labor supply; this is reflected in the term C^S x $\partial L / \partial \pi_C$, where $C^S = d\pi(P_C) / dP_C$ by Hotelling's lemma.

The third component represents the *revenue-recycling* effect of the tax credit. A change in the policy gives rise not only to the primary distortion effect (in the form of a change in the deadweight loss due to the fuel tax), but also gives rise to a change in fuel tax revenue. In our model, any change in revenue gets recycled in a revenue-neutral manner in the labor market, hence the similarity between the primary distortion and the revenue-recycling effects in equation (15).[9] It should be noted that if the tax credit is increased (reduced), it applies to the entire new equilibrium quantity of ethanol, not only the incremental amount. This is why the term *e* is present; it represents the initial amount of ethanol in the revenue-recycling component of equation (15).

The last component in equation (15) reflects the externality effect of a change in the tax credit. The bracketed term accounts for the change in the total carbon emissions due to a change in the tax credit. We assume that one gasoline energy-equivalent gallon of ethanol (adjusted from gallons of ethanol by the parameter γ) emits only ξ = 80 percent of carbon emissions relative to the same amount of gasoline. This value is close to the central estimate of 0.75 used in Cui et al. (2011). The term σ'/λ represents the marginal dollar value of a unit of the externality.

Marginal welfare effects of a binding blend mandate, holding the tax credit fixed

Unlike the blender's tax credit case, where the ethanol and fuel prices are directly linked to the price of gasoline, under the blend mandate both prices are endogenously determined in the market equilibrium. This implies additional complexity for the formula (16) that decomposes the welfare effects of the blend mandate, as well as for formula (17) that parcels out the effects of

[9] This also applies to equations (16) and (17).

the tax credit for a given mandate level. Because not all the welfare effects in equations (16) and (17) can be algebraically simplified by decomposing the total fuel into gasoline and ethanol (as was the case for the tax credit), we express all the effects in terms of fuel quantity *F*.

$$
\begin{aligned}
-\frac{1}{\lambda}\frac{dV}{d\theta} = & \underbrace{\left[F\frac{dP_F}{d\theta} - e\gamma\frac{dP_E}{d\theta} + t\left(1-\frac{1}{\gamma}\right)\left(F+\theta\frac{dF}{d\theta}\right) - t\frac{dF}{d\theta} + t_c\frac{de}{d\theta}\right]}_{\text{Primary distortion effect}} \\
& \underbrace{-\left(1+M\right)t_L\left[\left(\frac{\partial L}{\partial P_C} + C^S\frac{\partial L}{\partial \pi_C}\right)\frac{dP_C}{d\theta} + \frac{\partial L}{\partial P_F}\frac{dP_F}{d\theta}\right]}_{\text{Tax interaction effect}} \\
& \underbrace{+M\left\{t\left(1-\frac{1}{\gamma}\right)\left(F+\theta\frac{dF}{d\theta}\right) - t\frac{dF}{d\theta} + t_c\frac{de}{d\theta}\right\}}_{\text{Revenue recycling effect}} \\
& \underbrace{+\frac{\sigma'}{\lambda}\left(\frac{dF}{d\theta} + \gamma\left(\xi-1\right)\frac{de}{d\theta}\right)}_{\text{Externality effect}}
\end{aligned}
\tag{16}
$$

The primary distortion effect of the blend mandate in equation (16) can be thought of as the sum of three separate effects. First, the mandate by itself acts as an implicit tax on fuel; a change in the mandate also changes the effective fuel tax which corresponds to a price component of primary distortion represented by the term $F\frac{dP_F}{d\theta} - e\gamma\frac{dP_E}{d\theta}$. The second impact of increasing the mandate is that the volume of fuel which is taxed to meet a fixed fuel demand in GEEGs must be increased, since the energy content of ethanol is lower than that of gasoline; this is reflected in the term $t\left(1-\frac{1}{\gamma}\right)\left(F+\theta\frac{dF}{d\theta}\right)$. The third impact is a quantity distortion effect, represented by $t_c\frac{de}{d\theta} - t\frac{dF}{d\theta}$; it captures the marginal deadweight loss from the tax credit and fuel tax which result from ethanol and fuel quantities responding to the policy change.

The tax interaction effect in equation (16) is akin to that in equation (15), with the exception that the mandate also affects the fuel price which in turn partially influences labor supply via the real wage. The interpretations of the revenue-recycling and externality effects in equation (16) are parallel to those for equation (15).

Marginal welfare effects of the tax credit, holding the binding blend mandate fixed

Most countries have had biofuel consumption subsidies combined with binding mandates.[10] As these subsidies can vary over time (e.g., the tax exemption for biodiesel in Germany has been gradually reduced), it is important to understand the welfare effects of a change in the subsidy coupled with a binding blend mandate. For example, we use equation (17) to analyze the effects of allowing the U.S. tax credit to expire, as it has been the case at the end of December 2011.

$$
\begin{aligned}
-\frac{1}{\lambda}\frac{dV}{dt_c} = & \underbrace{\left\{ F\frac{dP_F}{dt_c} - e\gamma\frac{dP_E}{dt_c} + e + t_c\frac{de}{dt_c} - t\frac{dF}{dt_c} + t\theta\left(1-\frac{1}{\gamma}\right)\frac{dF}{dt_c} \right\}}_{\text{Primary distortion effect}} \\
& \underbrace{-(1+M)t_L\left[\left(\frac{\partial L}{\partial P_C} + C^S\frac{\partial L}{\partial \pi_C}\right)\frac{dP_C}{dt_c} + \frac{\partial L}{\partial P_F}\frac{dP_F}{dt_c}\right]}_{\text{Tax interaction effect}} \\
& \underbrace{+M\left\{ e + t_c\frac{de}{dt_c} - t\frac{dF}{dt_c} + t\theta\left(1-\frac{1}{\gamma}\right)\frac{dF}{dt_c} \right\}}_{\text{Revenue recycling effect}} \\
& \underbrace{+\frac{\sigma'}{\lambda}\left(\frac{dF}{dt_c} + \gamma(\xi-1)\frac{de}{dt_c}\right)}_{\text{Externality effect}}
\end{aligned}
\qquad (17)
$$

The primary distortion effect in equation (17) follows a similar pattern to that of equation (16); the tax credit induces both price distortion effects (reflected by $F\frac{dP_F}{dt_c} - e\gamma\frac{dP_E}{dt_c}$) and

[10] Although the U.S. corn ethanol blender's tax credit expired on December 31, 2011, many EU countries still use tax exemptions.

quantity distortion effects (reflected by $e + t_c \frac{de}{dt_c} - t\frac{dF}{dt_c}$). The tax credit also affects the distortion between the taxed volume of fuel and consumed GEEGs of fuel, as reflected by the term $t\theta\left(1-\frac{1}{\gamma}\right)\frac{dF}{dt_c}$; note that the magnitude of this impact is proportional to the fixed mandate level. It is interesting to note that the tax credit when combined with a binding mandate can affect the fuel price, unlike when the tax credit is the binding policy. Like equation (16), the equation (17) tax interaction effect includes the labor supply response to the fuel price as well as the corn price, and the remaining two welfare effects in equation (17) have parallel interpretations to their equation (15) counterparts.

IV. Numerical Model

To estimate and empirically analyze the welfare effects of a change in the U.S. biofuel policies, we develop a numerical version of the analytical model presented in Section II and calibrate it to the U.S. economy in 2009.

Consumption

We assume a nested constant elasticity of substitution (CES) utility function

$$U = U\left(F, C, x, N, R\right) = \left(\alpha_N N^{\frac{\delta-1}{\delta}} + (1-\alpha_N) X^{\frac{\delta-1}{\delta}}\right)^{\frac{\delta}{\delta-1}} - \sigma\left(R\right)$$

where α_N is a share parameter, δ denotes elasticity of substitution between leisure and the composite consumption good, X (i.e., the CES aggregator). The composite good includes fuel, corn, and the numeraire good

$$X \equiv \sigma_X \left(\alpha_F F^{\frac{\delta_x-1}{\delta_x}} + \alpha_C C^{\frac{\delta_x-1}{\delta_x}} + \left(1-\alpha_F-\alpha_C\right) x^{\frac{\delta_x-1}{\delta_x}}\right)^{\frac{\delta_x}{\delta_x-1}}$$

where σ_X is a scale parameter and δ_x reflects the elasticity of substitution among fuel, corn, and the numeraire good.

The consumer maximizes his utility subject to the budget constraint

$$P_F F + P_C C + P_x x + \omega N = \omega \overline{L} + P_X \Gamma + \pi_C$$

where P_X denotes the price index of the composite consumption good and Γ is the real government transfer. Derivations of the demand functions and other elements of the numerical model can be found in Appendix 4.

Production

1. Corn Production

Corn is produced by a decreasing returns to scale technology of the form $C^S = AL_C^{\varepsilon_S}$, where A is a scale parameter and $\varepsilon_S \in (0,1)$. The parameter ε_S implies that the corn supply curve is upward sloping; hence, corn producers earn positive profits. Profit maximization implies the following labor demand function L_C, output supply function C^S, and profit function π_C:

$$L_C = \left(\frac{w}{\varepsilon_S AP_C}\right)^{\frac{1}{\varepsilon_S - 1}}; C^S = A\left(\frac{w}{\varepsilon_S AP_C}\right)^{\frac{\varepsilon_S}{\varepsilon_S - 1}}; \pi_C = w\left(\frac{1}{\varepsilon_S} - 1\right)\left(\frac{w}{\varepsilon_S AP_C}\right)^{\frac{1}{\varepsilon_S - 1}}$$

2. Ethanol Production

The ethanol production function is the same as in the analytical section of the paper, and it implies the following cost-minimizing factor demands.

$$L_e = \frac{e}{e_L} \text{ and } C^e = \frac{e}{e_C}$$

The zero-profit condition for ethanol production establishes the link between corn and ethanol prices.

$$P_C = e_C P_e - \frac{w e_C}{e_L}$$

3. Gasoline and Fuel Production

We assume that gasoline is produced by a linear production technology $G = BL_G$, where B is a scale factor. Perfect competition and zero profits in the production of gasoline imply $P_G = w/B$. Fuel blenders face the gasoline price P_G. Price linkages between fuel, gasoline, and ethanol under a binding tax credit and blend mandate are given by equations (8t) and (8m), respectively.

4. Numeraire Production

The numeraire good is produced by a linear technology $x = kL_x$, where k is a scaling constant. Perfect competition and zero profits imply $P_x = w/k$.

Government

The government's real lump-sum transfer to the consumer is fixed at Γ, and the governmental budget constraint is given by

$$P_X \Gamma = t_L w\left(\overline{L} - N\right) + t\left[F - e\left(\gamma - 1\right)\right] - t_c e$$

where P_X denotes the price deflator on consumption.

Equilibrium

For any policy choice, the labor market must clear according to

$$L_G + L_x + L_c + L_e = \overline{L} - N$$

V. Data and Calibration

We now calibrate the closed-economy general equilibrium numerical model from Section IV to reflect the realities of the U.S. economy in 2009. The observed data and parameter assumptions used in our calibration can be found in Appendix 6- Table A1, together with their sources. To consistently model the relationships in the fuel market, all prices and quantities are expressed in gasoline energy-equivalent gallons.

Because both the blender's tax credit and a blend mandate were in place in 2009, it is important to determine which policy established the ethanol market price. We follow the reasoning presented in de Gorter and Just (2010b) and calibrate the model to a binding blend mandate. We calculate the ethanol blend mandate as the share of ethanol consumed in the United States and the total U.S. fuel consumption; this gives the mandate of $\theta = 0.06$. The ethanol blender's tax credit of \$0.498/gallon consists of the federal part of \$0.45/gallon and the average of state tax credits of \$0.048 (Koplow 2009).

We assume that the Unites States faces a perfectly elastic supply of gasoline; hence, the gasoline price, P_G = \$1.76/gallon, is exogenous in our model. The observed ethanol market price of \$1.79/gallon corresponds to \$2.56/GEEG, reflecting lower mileage of ethanol relative to gasoline. The final fuel price, P_F = \$2.27/GEEG, is equal to the weighted average of the ethanol and gasoline market prices adjusted for the fuel tax (\$0.49/gallon) and the tax credit; the weights represent the (energy-equivalent) shares of ethanol and gasoline, respectively, in the fuel blend. In calculating the fuel price, we recognize that both the fuel tax and the blend mandate are volumetric which requires adjusting the levels of these policies for the energy content of ethanol, hence the γ term in the equation defining P_F in Table A1.

We follow Ballard (2000) in determining the 'time endowment' ratio (i.e., labor endowment divided by labor supply), Φ, that makes our model yield estimates of the income elasticity and uncompensated elasticity of labor supply which are consistent with those found in the literature. Data from the U.S. Bureau of Economic Analysis indicate that the share of labor in the U.S. GDP was 0.57 in 2009. Normalizing the wage rate to unity, the previous ratio then determines the number of hours of labor. The total time endowment is in turn calculated by multiplying the parameter Φ by the number of hours spent working. The leisure demand is computed as the residual between the total time endowment and labor. Following the literature (e.g., Goulder et al. 1999; Parry 2011), we assume the (*ad valorem*) U.S. labor tax to be 40 percent. Following the Ballard procedure and using parameter and variable values detailed in Table A1, we arrive at $\Phi = 1.19$, which is close to Ballard's estimate of 1.21. Full details about our use of Ballard's procedure can be found in Appendix 5.

In our model, the representative consumer's decisions can be thought of as occurring in two stages. First, based on exogenous wealth and market prices he decides how much leisure and composite good to consume. Recall that the composite good is an aggregator of fuel, corn, and the numeraire good which proxies for everything else. The price of the composite good thus serves as a price index for the economy. Second, the quantity of the composite good from the first stage is allocated optimally between fuel, corn, and the numeraire. We normalize the price of the numeraire to unity. By setting the price of the composite good to unity in the baseline (though it varies in the simulations), we assume a unitary real wage rate equal to the nominal wage in the baseline.

We choose the elasticity of substitution among consumption goods to be 0.3 which results in own price elasticities of demand for fuel and corn to be -0.289 and -0.299, respectively. Our fuel demand elasticity is close to that reported by Hamilton (2009) (-0.26) and also to the long-run elasticity reported by a recent meta-analysis by Havránek et al. (2012). The corn demand elasticity is close to that used by de Gorter and Just (2009a) and Cui et al. (2011).

To evaluate the effect of ethanol policies on the consumer's welfare from the environmental externality of CO_2, we assume that ethanol emits 20 percent less carbon emissions relative to gasoline, in line with de Gorter and Just (2010b). We assume that the marginal external cost of CO_2 emissions is \$0.06/GEEG (Parry and Small 2005).

VI. Results

Using the calibrated model above, we first determine the optimal blender's tax credit and mandate (individually) by maximizing the social welfare (representative consumer's utility). Unlike other studies (e.g., Khanna 2008, Cui et al. 2011), we find that both policies should be set to zero at the optimum. The most important factor contributing to this result is the presence of 'water' in the biofuel policy price premium and associated rectangular deadweight costs (RDC).[11] The following sub-section explains and quantifies this welfare cost.

'Water' in the Biofuel Policy Price Premium[12]

The ethanol industry competes for corn with other industries that use the feedstock for feed/food purposes. In our model, the amount of corn available for ethanol is given by the difference between corn supply and the non-ethanol corn demand at any corn market price. Thus, the intercept of the ethanol supply coincides, after a unit adjustment, with the equilibrium corn price when no ethanol is produced.[13] Denoting this threshold price (intercept of the ethanol supply curve) as P_{NE}, from our simulations we obtain P_{NE} = \$2.07/GEEG. The 'no policy' ethanol price, P_E^*, denotes a market price of ethanol assuming no biofuel policy (i.e., a tax credit or mandate) in place.[14] Our model shows that without 2009 biofuel policies, no ethanol would be

[11] For example, Cui et al. (2011) calibrate their model to a tax credit which in their case necessitates adjusting the observed gasoline price up by \$0.32/gallon. This results in no 'water' in their model. Moreover, we note that non-linear demand/supply curves, as it is the case in our model, make the presence of 'water' more likely.
[12] Explanation of 'water' in biofuel policy price premium and related concepts can be found in greater detail in Drabik (2011).
[13] In a partial equilibrium framework, this point is given by the intersection of the corn supply curve and the non-ethanol demand curve.
[14] Note that assuming no ethanol production is not synonymous to assuming no biofuel policy. While the former, by definition, implies zero ethanol production, the latter may result in positive ethanol production. Drabik (2011) shows that ethanol production could occur even in the absence of biofuel policies, provided that consumers are able to choose between ethanol and gasoline, and the oil price is sufficiently high and/or the fuel tax is sufficiently low.

produced in 2009: the ‘no policy’ ethanol price P_E^* = \$1.55/GEEG is below the intercept of the ethanol supply curve.[15]

The gap between the intercept of the ethanol supply curve and the ‘no policy’ ethanol price represents ‘water’ in the biofuel price premium (de Gorter and Just 2008; Drabik 2011), and, in our case, is equal to \$2.07/GEEG - \$1.55/GEEG = \$0.52/GEEG.[16] It can be thought of as representing the waste of societal resources because gasoline is less costly and yet production of more costly ethanol is incentivized through biofuel policies. The estimated ‘water’ represents more than a fifth of the observed market price of ethanol in 2009. This is one of the reasons why both the optimal tax credit and the blend mandate are found to be zero in 2009 – the prevailing market conditions made it very inefficient to produce ethanol from corn.[17] Notice also that our (general equilibrium) estimate of ‘water’ in the biofuel policy price premium is similar to the partial equilibrium estimate of \$0.76/GEEG reported by Drabik (2011).[18] This indicates that the presence of ‘water’ in the biofuel policy price premium is not due only to our model specification. Quantifying the RDC associated with the status quo ethanol production entails multiplying the level of ‘water’ by the amount of ethanol produced. In 2009, we find the RDC is \$4 billion (= \$0.52/GEEG x 7.73 billion GEEGs).[19] In sum, for any optimal biofuel policy to induce positive ethanol production, the ethanol price premium would have to exceed the ‘water’.

[15] This price is calculated using equation (8t) and assuming a zero tax credit.
[16] The ethanol price premium is equal to the difference between the observed ethanol price and the ‘no policy’ ethanol price.
[17] In contrast, Cui et al. (2011) find that there would be ethanol production even in the absence of the mandate and tax credit in 2009. The difference arises because their linear partial equilibrium model is calibrated assuming the tax credit is the binding policy, while we calibrate the model to a binding blend mandate coupled with a tax credit (see our reasoning in Section 5). The presence of ‘water’ is also determined by the curvature of the supply and demand curves; the non-linear relationships in our model make ‘water’ more likely, other things being equal.
[18] That our estimate of water is lower than that in Drabik (2011) is consistent with the empirical observation that general equilibrium effects tend to be smaller relative to those obtained from a partial equilibrium analysis.
[19] 7.73 billion GEEGs correspond to 11.038 billion gallons of ethanol in the first column in Table A2.

To measure the welfare effects of the biofuel policies, we analyze three policy simulations: the status quo scenario (i.e., a binding blend mandate coupled with a tax credit); a scenario where the blend mandate is held at its status quo level but the tax credit is removed (the removal of the tax credit in this scenario mimics the policy change that occurred in January 2012 when the U.S. ethanol blender's tax credit expired but the corn ethanol mandate under the Renewable Fuel Standard remained in place); and a scenario with no ethanol policies. The results of these policy simulations are shown in Table A2 in Appendix 6.

Welfare Effects of the Tax Credit with a Binding Mandate

In the status quo scenario, ethanol production is determined by a binding blend mandate of 5.88 percent combined with a blender's tax credit of $0.498/gallon. Table 1 decomposes the total welfare change from the tax credit removal into the four components identified in Section II: the primary distortion effect, tax interaction effect, revenue recycling effect, and externality effect. The welfare effects presented in Table 1 correspond to a policy change from the status quo to the "tax credit removed" scenario in Table A2.

Table 1. Welfare Effects of Removing the Tax Credit but Keeping the Mandate

Welfare Component	Welfare Change ($ billion)
Primary Distortion	-0.328
Tax Interaction Effect	-0.063
Revenue Recycling Effect	0.360
Externality Effect	0.040
Total Change in Welfare	0.009

Source: calculated

The primary distortion effect (due to the fuel tax and tax credit) in the fuel market is estimated to be a loss of $328 million. To better understand its origin, consider Figure 1 where P_G denotes the exogenous gasoline market price, and $P_G + t$ is the consumer price of fuel (gasoline) under no biofuel policies. The Harberger deadweight loss triangle associated with the fuel tax t is area *abc*. The fuel (ethanol and gasoline) price under a blend mandate θ alone (i.e., absent of the fuel tax and tax credit) is denoted by $P_F(\theta)$. When a tax credit t_c and a fuel tax t are added to the blend mandate, the fuel price increases to $P_F(\theta, \mathrm{t_c}, \mathrm{t})$; the effective fuel tax is thus equal to $P_F(\theta, \mathrm{t_c}, \mathrm{t}) - P_F(\theta)$, corresponding to distance *fd* in Figure 1. The distortion associated with this fuel tax is therefore triangle *def*.

Because a mandate *per se* works as an implicit fuel tax (de Gorter and Just 2010b; Lapan and Moschini 2012), before being removed the tax credit was suppressing the full effect of the implicit tax by lowering the price of the fuel blend.[20] The elimination of the tax credit increases the fuel price to $P_F(\theta, \mathrm{t})$, thus increasing the distortion in the fuel market to be area *geh*. The trapezoid *gdfh* then represents the primary distortion effect of removing the blender's tax credit.[21]

The fuel price increase lowers the real wage and causes the representative consumer to substitute leisure for consumption goods, thus shifting the labor supply curve to the left.[22] The contraction of the labor tax base results in a welfare loss due to the tax interaction effect of $63 million.

When the blender's tax credit is abandoned, the government revenue from the fuel tax decreases by $349 million (see Table A2). However, the government saves $5.5 billion by no longer having to pay for the tax credit, so the overall revenue from the fuel market increases by $5.15 billion. This additional revenue is "recycled" – the labor tax rate can be reduced while the

[20] de Gorter and Just (2009a) show that the tax credit in combination with a binding mandate acts as a fuel consumption subsidy. Similarly, Drabik (2011) and Lapan and Moschini (2012) show that for a given blend mandate, an increase in the blender's tax credit decreases the fuel price, but increases the gasoline price.

[21] The tax credit does not cause any primary distortion in the corn market because corn is not taxed in our model.

[22] Although the corn price decreases by $0.007/bushel, this effect is more than offset by an increase in the fuel price by $0.041/GEEG such that the overall price index rises from 1 to 1.001.

real government transfer is held constant. The revenue-recycling effect of alleviating the pre-existing distortion in the labor market yields a benefit of $360 million.

The last welfare component in Table 1 is the positive externality effect of $40 million. This benefit is due to a decrease in fuel consumption of 710 million gallons (Table A2), caused by the elimination of the tax credit.

In total, we estimate that removing the tax credit improves social welfare by $9 million. This result is consistent with earlier findings from partial equilibrium models (e.g., de Gorter and Just 2010b), although the magnitude of the total welfare effect is perhaps smaller than a partial equilibrium model would predict. The welfare improvement is rather small because the tax credit's removal causes a significant increase in the primary distortion in the fuel market.

The main result from Table 1 is that the removal of the tax credit (while keeping the mandate) costs $63 million (the tax interaction effect) but there is a much bigger welfare gain due to the revenue recycling effect of $360 million. This means the *net* fiscal interaction welfare effect is large compared to the total welfare gains and is approximately equal to the welfare loss of the primary distortion effects.

In standard models of environmental taxation, the revenue recycling effect only exceeds the tax interaction effect in magnitude if the taxed good is a relatively weak substitute for leisure (Parry 1995). The nested-CES functional form for utility in our model imposes that all goods are equal (and hence all average) substitutes for leisure, so our finding that the revenue recycling effect exceeds the tax interaction effect in magnitude is perhaps surprising. However, since the tax credit was imposed on top of a binding mandate in this model, the standard model prediction does not necessarily apply and the relative size of the two fiscal interaction effects was *a priori* indeterminate.

The results presented in Table A2 also provide interesting insights into how biofuel policies affect the fuel tax revenue. To see this, consider the addition of the tax credit to a blend mandate (the second *versus* the first column in Table A2). The increase in the tax revenue from $65.7 billion (= 130.04 x 0.49) to $66.1 billion (= 134.75 x 0.49) is only due to higher fuel consumption. This means one gasoline energy-equivalent gallon of ethanol replaces less than one gallon of gasoline; thus, leakage of a biofuel policy in the fuel market is a condition for higher tax revenues.

To further analyze the role of the fiscal interaction effects in the welfare change due to the tax credit removal, we set the labor tax to zero (thus eliminating the fiscal interaction effects) and recalculate the primary distortion and externality effects (results not reported in a table). The primary distortion and externality effects are similar to those reported in Table 1—a loss of $355 million and a gain of $44 million, respectively. Owing to the absence of the fiscal interaction effects, however, the elimination of the tax credit results in a welfare loss of $311 million. This indicates that when the labor tax cannot be adjusted in response to a change in the net fuel tax revenue and when the real government transfer is not held constant, adding a tax credit to a binding mandate may indeed be welfare improving. In this case, the welfare improvement occurs only due to higher fuel tax revenue which is transferred lump sum to the representative consumer.[23] Because the ethanol price is determined by the mandate, the addition of the tax credit has only a marginal effect on ethanol consumption, and (mostly) gasoline consumption is subsidized instead. This gives rise to higher fuel tax revenues.

Welfare Effects of Blend Mandate Removal

[23] This is analogous to Cui et al. (2011) where the status quo versus a tax credit results in significant welfare gains due to increased tax revenues.

We now quantify how welfare would change if the status quo blend mandate were removed, and no tax credit was in place. This is the welfare effect of a change from the second scenario in Table A2 (*Tax Credit Removed*) to the third scenario (*No Ethanol Policy*). We anticipate that removing the mandate will cause welfare gains since we find that the optimal blend mandate is zero. Table 2 presents our estimates of the total welfare effect as well as its components. The last row of Table 2 does indeed confirm that overall welfare improves by $8.28 billion when the mandate is removed.

Table 2. Welfare Effects of Removing the Mandate after Tax Credit is Removed

Welfare Component	Welfare Change ($ billion)
Primary Distortion	6.974
Tax Interaction Effect	1.544
Revenue Recycling Effect	-0.063
Externality Effect	-0.173
Total Change in Welfare	8.282

Source: calculated

The primary distortion effect is the most significant component (about 85 percent) of the total welfare change. This reflects in large part the elimination of the RDC due to 'water' in the ethanol price premium ($4 billion). Welfare gains also arise because eliminating the mandate decreases both price and quantity distortions. The fuel price decreases from $2.31/GEEG to $2.25/GEEG, and the amount of fuel in energy-equivalent terms increases by 1.10 billion GEEGs (Table A2). In Figure 1, this is depicted as the transition from area *geh* to area *abc*, yielding a welfare gain (i.e., reduction in the distortion) equal to the difference between the two triangles.

The decrease in the fuel and corn prices after the mandate is removed increases the real wage; this shifts the labor supply curve to the right, as depicted in panel (a) of Figure 2.[24] Keeping the labor tax rate at its original level t_L^0, rectangle *lopm* represents a positive tax interaction effect that we estimate to be \$1.54 billion (17 percent of the total welfare change). This effect is positive because the mandate removal causes an expansion of the labor tax base.

Although the quantity of fuel in energy terms increases, its volume measured in gallons actually decreases. This happens because in the absence of the mandate, no ethanol is consumed and the fuel consists exclusively of gasoline. Because gasoline has lower volume than the same energy-equivalent of ethanol, the total volume of fuel decreases. This decrease results in a reduction in the fuel tax revenue because the fuel tax is levied on a volumetric basis. In order to be able to depict this situation in panel (b) of Figure 2, we have to convert the volumetric fuel tax into its energy-equivalent. Denoting t_F as the common energy-based fuel tax for ethanol and gasoline, it has to satisfy $t_F F = (t/\gamma)E + tG$, from which $t_F = \theta(t/\gamma) + (1-\theta)t$, where F, E, and G, where $F = E + G$, denote quantities of fuel, ethanol, and gasoline, respectively, and $\theta = E/F$ denotes the blend mandate.

The initial fuel tax revenue in panel (b) of Figure 2 corresponds to the rectangle *abcd*. (Price P_{F0} represents a fuel price in the absence of the fuel tax t). When the mandate is removed, the consumer price of fuel falls to $P_G + t$, earning tax revenue of area *efgh* (area *efgh* is smaller than area *abcd*). The loss of fuel tax revenue must be compensated by increasing the labor tax to keep the real government transfer to consumers constant. This is depicted in panel (a) of Figure 2, where the increase in the labor tax corresponds to a lower after tax wage $w - t_L^1$ (holding the

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[24] $S_L(P_{F1})$ denotes labor supply curve when the price of fuel is P_{F1} (i.e., with the mandate), and $S_L(P_G + t)$ denotes the labor supply curve after the mandate has been abandoned. Demand for labor is assumed to be perfectly elastic in Figure 2.

labor supply curve at its original position). This yields labor tax revenue equal to area *qrsn* which must be larger than the original revenue of *klmn*. The positive difference between these two areas offsets the revenue loss in the fuel market. Because the labor market distortion has increased, the revenue recycling effect is equal to -\$63 million. The amount of labor L_1 is only hypothetical, however, because it assumes no tax-interaction effect (in reality, these effects happen simultaneously).

Our simulation shows that the final labor tax rate decreases from 0.3996 to 0.3983, and labor tax revenue also decreases. In panel (a), this is depicted as a shift up of the after-tax wage: from $w - t_L^0$ to $w - t_L^2$. This happens because the tax interaction effect outweighs the revenue recycling effect. The final labor tax revenue is represented by area *tuvn,* which must be smaller than area *klmn*. Note also that because the real wage rate increases, the demand for fuel (and corn for non-ethanol use) increases, which is depicted by the demand curve $D_F(w - t_L^2)$ in panel (b). The final labor tax t_L^2 solves: $t_F F_0 + t_L^0 L_0 = tG_2 + t_L^2 L_2$.

Eliminating the mandate yields a welfare loss of \$173 million from the externality effect. The welfare losses arise from two sources: the share of the dirtier fuel (gasoline) in the blend increases, and fuel demand increases due to the fuel price decrease.

The main result from Table 2 is that the tax interaction effect of removing the mandate results in a welfare gain of \$1.54 billion which is partially offset by a welfare loss of \$63 million due to the revenue recycling effect. This means the *net* fiscal interaction welfare effect is again significant in magnitude, although the magnitude is not large relative to the primary distortion or total welfare gain.[25] The net welfare gain associated with the abolition of the blend mandate is largely due to elimination of the RDC worth $4 billion.

Welfare Comparison of a Tax Credit and a Mandate

This section is motivated by a recent literature which shows that in a partial equilibrium framework an optimal biofuel (consumption) mandate is welfare superior to an optimal tax credit not only with a suboptimal fuel tax (de Gorter and Just 2010b), but also without it (Lapan and Moschini, 2012). Because in our model both optimal policies are zero (due to RDC), we do not perform a general equilibrium welfare comparison analogous to the above studies. Instead, we fix the blend mandate at its status quo level (5.88 percent) and calculate a tax credit that by itself would generate an equivalent quantity of ethanol. We then study the welfare effects of removing both policies. To see how the presence of the fuel and labor taxes affects the welfare outcome, we consider three cases summarized in Table 3: (*i*) both taxes exist, (*ii*) fuel tax only and (*iii*) labor tax only.

Table 3. Welfare Effects of Removing Status Quo Mandate vs. an Equivalent Tax Credit

	Welfare change ($ billion)	
Pre-Existing Distortion Scenario	Mandate	Tax credit
Fuel tax and labor tax	7.096	6.607
Fuel tax*	6.296	5.693
Labor tax	7.227	7.269

* The value of the government transfer is allowed to freely adjust in these simulations
Source: calculated

Consider first the case where both the fuel and labor taxes are present, and the ethanol quantity under the mandate and tax credit alone is 10.98 billion gallons (Table A3). When each

[25] Compare this net fiscal interaction gain of $0.91 billion (= 1.54-0.63) with the welfare loss of $7.13 billion due to deterioration of the terms of trade in oil imports and corn exports implied for the removal of the binding tax credit in Cui et al. (2011).

policy is eliminated, ethanol production in both cases falls to zero because the existing 'water' prevents any ethanol production without a biofuel policy. Although the decrease in ethanol production is the same for both policies (10.98 billion gallons), the removal of the mandate yields a greater total welfare gain ($7.096 billion) than the removal of the tax credit ($6.607 billion). Alternatively, these welfare changes can be interpreted as follows: the introduction of a biofuel mandate reduces welfare by $7.1 billion, while the introduction of the same quantity of ethanol through a tax credit reduces welfare by only $6.6 billion. This implies the tax credit is welfare superior to the mandate. But this result needs to be interpreted cautiously.

Because we do not compare optimal policy levels, our finding does not violate the theoretical conclusion of Lapan and Moschini (2012) about the superiority of the mandate. But even when the tax credit and the mandate are compared for the same level of ethanol production, de Gorter and Just (2010b) show theoretically that the mandate welfare dominates the tax credit and more so if both policies are coupled with a suboptimal fuel tax. However, the results presented in the first set of columns in Table 3 are clearly not in line with this prediction.

The explanation is quite simple and intuitive: our fuel tax of $0.49/gallon is not *suboptimal* (i.e., less than the external cost of the externality of $0.06/gallon reported in Table A1), but it is *superoptimal*, meaning higher than the marginal external cost.[26] Because the mandate by itself acts as an implicit tax on fuel consumption (in the form of a higher fuel price), the addition of a superoptimal fuel tax makes it even more distortionary. On the other hand, because the tax credit lowers the fuel price, it works in the opposite direction and brings the effective fuel tax closer to its optimal level.

[26] Like us, Cui et al. (2011) also consider only one externality – carbon (CO_2) emissions. They assume a marginal emissions damage of $20/t$CO_2$. Parry et al. (2007) assume the marginal external damage due to carbon emissions to be $25/t$CO_2$, which corresponds to $0.06/gallon. Therefore, the marginal emissions damage of $20/t$CO_2$ in Cui et al. (2011) translates into $0.048/gallon which is less than the fuel tax of $0.39/gallon they use. Hence, their fuel tax is superoptimal.

This explanation also holds for the case when only the fuel tax is present, as seen in the second row of Table 3. However, as shown in the third row, the mandate becomes superior to a tax credit in the absence of the fuel tax (with only the labor tax in place). This is consistent with the explanation above as well as the prediction of de Gorter and Just (2010b) because the (zero) fuel tax is suboptimal. In this scenario, when the mandate implicitly taxes gasoline consumption to pay for higher ethanol prices, it is beneficially compensating for the suboptimal fuel tax.

To test the impact of RDC on the results in Table 3, we artificially increase the gasoline price (to $2.41/gallon) such that 'water' in the ethanol price premium is eliminated. The welfare gains from removing the policies given this assumption are reported in Table 4. The welfare gains are significantly smaller than their counterparts in Table 3, largely because the RDC of $4 billion is now absent. However, the results in Table 4 are qualitatively unchanged from Table 3, so we conclude that the presence of 'water' has no qualitative impact on the welfare superiority of a tax credit over a mandate (for the same ethanol production) under a superoptimal fuel tax.

Table 4. Welfare Effects of Removing Status Quo Mandate vs. an Equivalent Tax Credit: the 'No Water' Case

	Welfare change ($ billion)	
Pre-Existing Distortion Scenario	Mandate	Tax credit
Fuel tax and labor tax	1.507	1.381
Fuel tax*	0.506	0.300
Labor tax	1.035	1.045

* The value of the government transfer is allowed to freely adjust in these simulations
Source: calculated

The central message of the analysis above is that in countries which have a superoptimal fuel tax, like Great Britain (Parry and Small 2005), a tax credit will be welfare superior to a mandate when comparison is made for the same ethanol production.

VII. Conclusion

Although several earlier works have studied the welfare effects of the U.S. biofuel policies, the analyses have primarily been done in a partial equilibrium framework. These models are thus unable to capture general equilibrium fiscal interaction effects of biofuel policies. In this paper, we build a tractable general equilibrium model of the U.S. economy to analyze the welfare effects of a change in (or a complete removal of) the U.S. biofuel policies, a tax credit and a blend mandate. More specifically, we assume the government keeps the real transfer to consumers fixed and adjusts the labor tax whenever a change in a biofuel policy occurs. This enables us to study two interactions of biofuel policies with the broader fiscal system.

First, the tax interaction effect arises when the price of corn or fuel increases (decreases) as a result of a biofuel policy change, making the real wage decrease (increase) and thus contracting (expanding) the labor supply curve . The ensuing loss (gain) in labor tax revenue – holding the labor tax constant – represents the tax interaction effect. Second, a change in the biofuel policy affects the government fuel tax receipts. If the biofuel policy change yields greater (lesser) fuel tax revenue, this additional revenue is used to reduce (increase) the pre-existing labor tax to keep the real transfer to the consumer fixed; depending on the change in the labor tax, the pre-existing distortion in the labor market can either increase or decrease. The direction of the net fiscal interaction effect depends on the direction and magnitude of its tax interaction and revenue recycling components.

To mirror the recent expiration of the U.S. corn-ethanol tax credit, we simulate the welfare effects of removing the tax credit, keeping the blend mandate unchanged. Eliminating the tax credit yields a small gain in total welfare of $9 billion, but the fiscal interaction effects are more pronounced. Because the fuel price increases when the tax credit is removed, the tax interaction effect is estimated to be a loss of $63 million. But because the fiscal savings due to the absence of the tax credit can be used to reduce the labor tax, the revenue recycling effect of this policy change is a welfare gain of $360 billion. This implies that the *net* fiscal interaction welfare effect is large compared to the total welfare change, and it is approximately equal to the welfare loss of the primary distortion effect.

Motivated by our finding that the optimal mandate (as well as the tax credit) is zero, we analyze the welfare effects of the elimination of the status quo mandate. We indeed find that the current blend mandate is not optimal as its abandonment results in a total welfare gain of more than $8 billion. Significant welfare gains come from the elimination of the RDC (estimated to be $4 billion), as well as from a positive tax interaction effect of $1.54 billion. However, the welfare gains from the tax interaction effect are partially offset by a loss of $63 million due to the revenue recycling effect. In sum, the *net* fiscal interaction welfare effect of removing the mandate is significant in magnitude, although the magnitude is smaller relative to the primary distortion or total welfare gain.

For the same ethanol production, a blender's tax credit is empirically found to be welfare superior to a mandate. This ordering is found to hold regardless of the presence of 'water' in the ethanol price premium (i.e., the gap between the free market ethanol price and the intercept of the ethanol supply curve). This is a novel result, since previous literature has concluded that, given the same ethanol production, a mandate always welfare dominates the tax credit. This finding is driven by the fact that the fuel tax is superoptimal in our model (i.e., it exceeds the marginal external cost of gasoline consumption). The superoptimality of the fuel tax in our model reflects the exclusion of vehicle-miles-traveled externalities such as traffic accidents or congestion. The implication of our results is that the biofuel mandate is likely to be inferior to a blender's tax credit (or a tax exemption) in countries that have superoptimal fuel tax, such as the United Kingdom (Parry and Small 2005).

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Figure 1. The Primary Distortion Effects in the Fuel Market

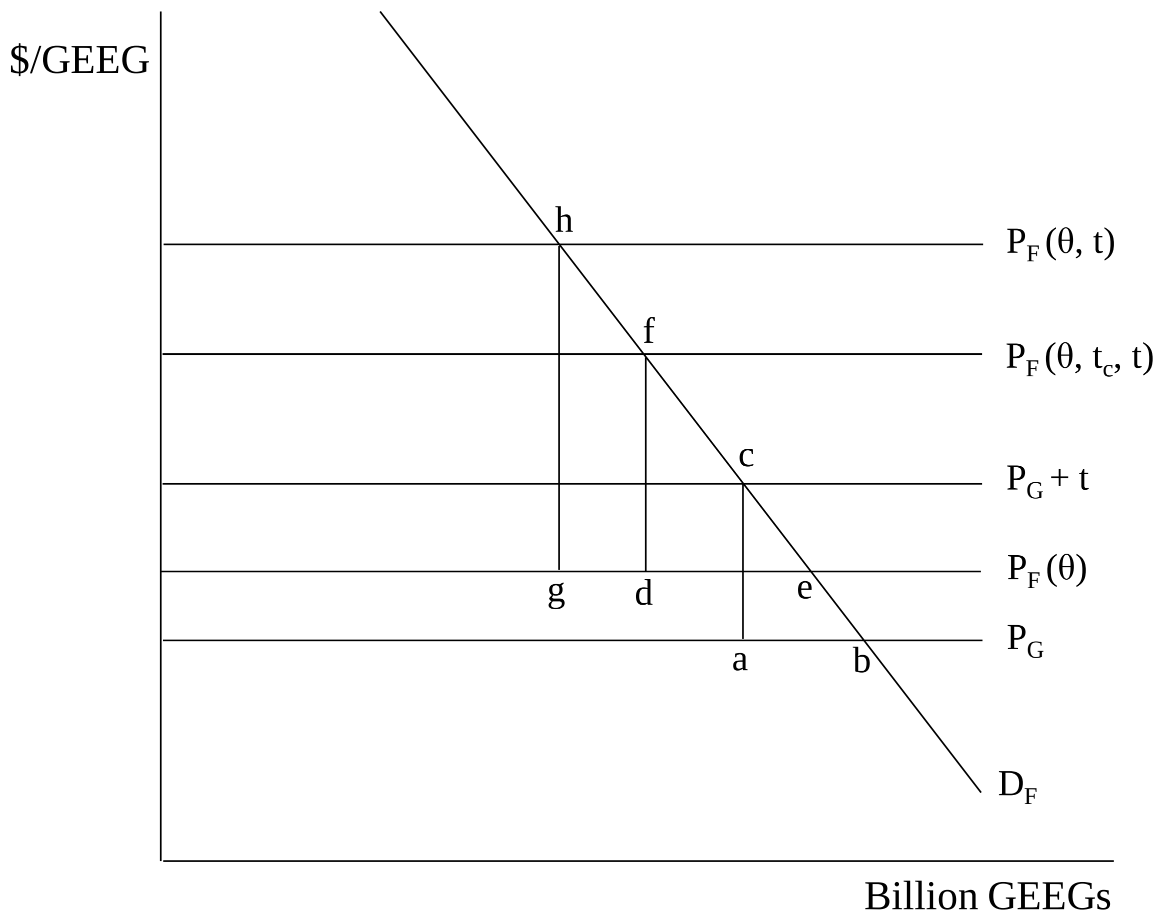
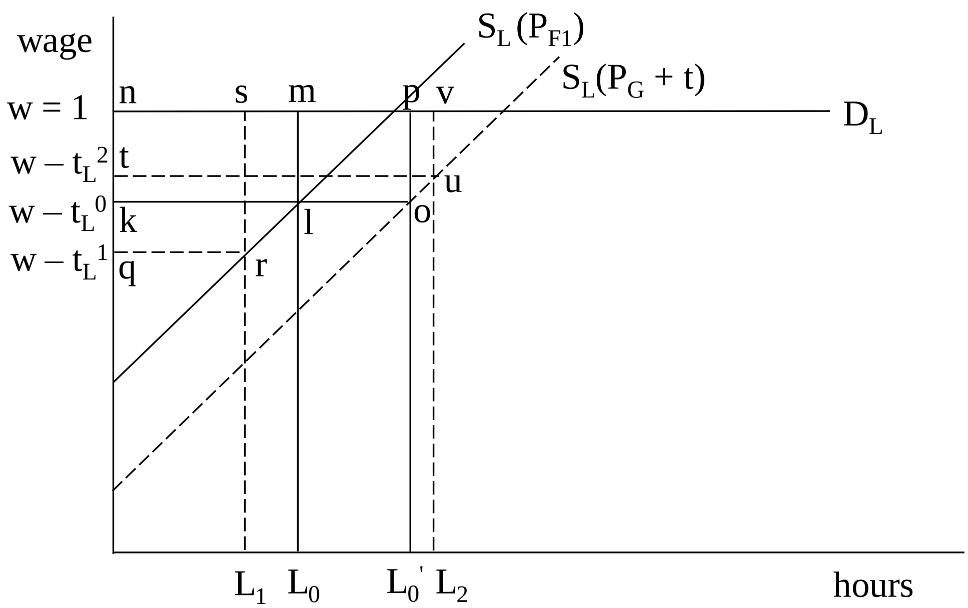
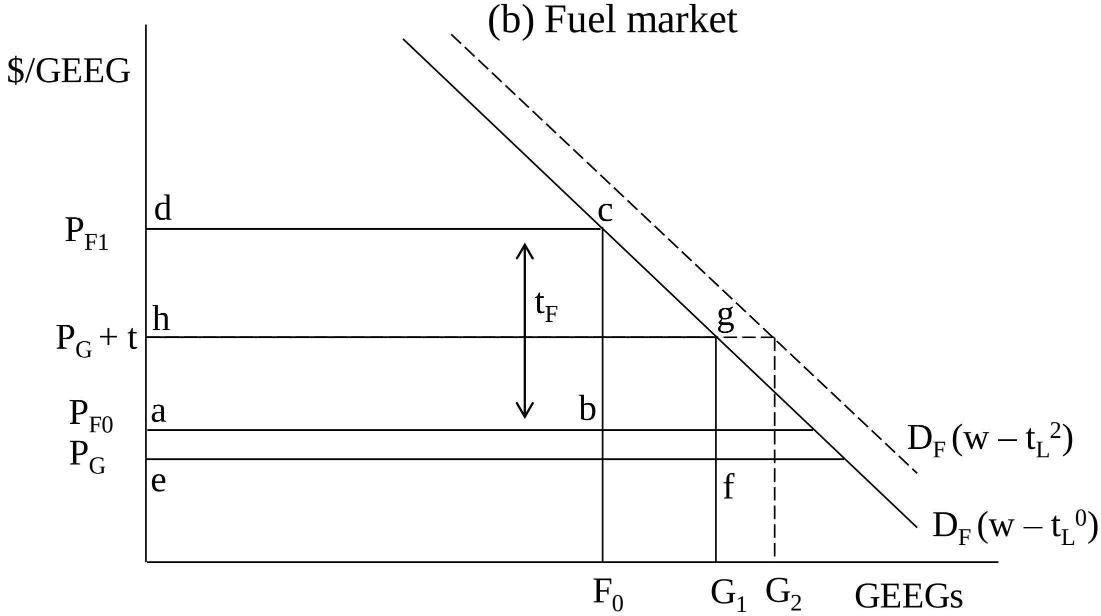


Figure 2. Fiscal Interaction Effects of Removing a Blend Mandate

(a) Labor market



(b) Fuel market



Appendix 1: Derivation of the Marginal Welfare Effects of the Tax Credit

The optimal tax credit solves:

$$\max_{t_c} V\left(R,\pi_C,\omega,P_C\right)=\max_{F,C,x,L}\varphi\left(u\left(F,C,x\right),\bar{L}-L\right)-\sigma\left(R\right)+\lambda\left(\omega L+\Gamma+\pi_C-P_F F-P_C C-P_x x\right)$$

subject to:

$$R=F+\left(\xi-1\right)\gamma e \tag{A1.1}$$

$$\pi_C=\pi_C\left(P_C\right) \tag{A1.2}$$

$$\omega=w\left(1-t_L\right) \tag{A1.3}$$

$$P_C=e_C\left[\gamma P_G-\left(1-\gamma\right)t+t_c\right]-\frac{e_C w}{e_L} \tag{A1.4}$$

$$\Gamma=t_L wL+t\left[F-e\left(\gamma-1\right)\right]-t_c e \tag{A1.5}$$

To simplify further computations, we normalize the wage rate to unity, that is, w =1. Totally differentiating the indirect utility function with respect to t_c, we obtain:

$$\frac{dV}{dt_c}=\frac{\partial V}{\partial R}\frac{dR}{dt_c}+\frac{\partial V}{\partial \pi_C}\frac{d\pi_C}{dt_c}+\frac{\partial V}{\partial \omega}\frac{d\omega}{dt_c}+\frac{\partial V}{\partial P_C}\frac{dP_C}{dt_c}=0 \tag{A1.6}$$

where the partial derivatives come from the objective function,

$$\frac{\partial V}{\partial R}=-\sigma';\frac{\partial V}{\partial \pi_C}=\lambda;\frac{\partial V}{\partial \omega}=\lambda L;\frac{\partial V}{\partial P_C}=-\lambda C \tag{A1.7}$$

and the total derivatives are obtained from constraints (A1.1–4)

$$\frac{dR}{dt_c}=\frac{dF}{dt_c}+\left(\xi-1\right)\gamma\frac{de}{dt_c};\frac{d\pi_C}{dt_c}=\pi_C{}'\frac{dP_C}{dt_c}=C^S e_C;\frac{d\omega}{dt_c}=-\frac{dt_L}{dt_c};\frac{dP_C}{dt_c}=e_C \tag{A1.8}$$

where use has been made of Hotelling's lemma, that is, $d\pi_C/dP_C=\pi_C{}'=C^S$.

Associated with a change in the tax credit is a change in the labor tax such that the real government transfer Γ is constant. To see how the labor tax changes in response to a marginal change in the tax credit, we totally differentiate constraint (A1.5) with respect to t_c to obtain

$$L\frac{dt_L}{dt_c}+t_L\frac{dL}{dt_c}+t\frac{dF}{dt_c}-t\left(\gamma-1\right)\frac{de}{dt_c}-e-t_c\frac{de}{dt_c}=0 \tag{A1.9}$$

Because we are interested in the effects of the tax credit on the labor market, we need to determine dL/dt_c. To do that, we totally differentiate the labor supply function (the mirror image of the consumer's demand for leisure) with respect to t_c, to obtain[27]

$$\frac{dL}{dt_c} = -\frac{\partial L}{\partial \omega}\frac{dt_L}{dt_c} + e_C\frac{\partial L}{\partial P_C} + e_C C^S \frac{\partial L}{\partial \pi_C} \qquad \text{(A1.10)}$$

Substituting the total derivative (A1.10) into (A1.9) and collecting the terms, we arrive at

$$\frac{dt_L}{dt_c} = \frac{t_L e_C \dfrac{\partial L}{\partial P_C} + t_L e_C C^S \dfrac{\partial L}{\partial \pi_C} + t\dfrac{dF}{dt_c} - \left[t_c + t(\gamma - 1)\right]\dfrac{de}{dt_c} - e}{t_L\dfrac{\partial L}{\partial \omega} - L} \qquad \text{(A1.11)}$$

An increase in the labor tax distorts the labor market. The distortion is measured by the marginal excess burden of taxation M defined as the ratio of the increase in the "wedge" distortion (numerator) and the increase in labor tax revenue for a marginal change in the labor tax (denominator). Mathematically,[28]

$$M \equiv \frac{-t_L\dfrac{\partial L}{\partial t_L}}{L + t_L\dfrac{\partial L}{\partial t_L}} \qquad \text{(A1.12)}$$

By rearranging equation (A1.12), the effect of a change in the nominal labor tax on the labor supply can be expressed as

$$\frac{\partial L}{\partial t_L} = -\frac{ML}{(1+M)t_L} \qquad \text{(A1.13)}$$

Alternatively, this effect can be written as

[27] Although the labor supply L depends on ω, Γ, π_C, P_F, P_C, and P_x, a change in the tax credit only affects the labor supply through ω, π_C, P_C.

[28] Note that because L is measured in hours spent working, each term in equation (A1.12) should be multiplied by the wage rate w to convert the numerator and denominator into dollars terms. The term w cancels out, however, resulting in equation (A1.12).

$$\frac{\partial L}{\partial t_L} = \frac{\partial L}{\partial \omega}\frac{\partial \omega}{\partial t_L} \quad \text{(A1.14)}$$

Combining equations (A1.13) and (A1.14) and using the fact that $d\omega / dt_L = -w$ (this follows from equation (A1.3)) yields

$$\frac{\partial L}{\partial \omega} = \frac{ML}{\left(1+M\right)t_L} \quad \text{(A1.15)}$$

The derivative (A1.15) describes the response of labor supply to a marginal change in the real wage rate. Substitution of this derivative into equation (A1.11) and rearrangement produce

$$\frac{dt_L}{dt_c} = -\left(M+1\right)\frac{t_L e_C \frac{\partial L}{\partial P_C} + t_L e_C C^S \frac{\partial L}{\partial \pi_C} + t\frac{dF}{dt_c} - \left[t_c + t\left(\gamma - 1\right)\right]\frac{de}{dt_c} - e}{L} \quad \text{(A1.16)}$$

The final optimality condition is obtained by substituting the derivatives (A1.7), (A1.8), and (A1.16) into equation (A1.6) and collecting the terms:

$$\begin{aligned} -\frac{1}{\lambda}\frac{dV}{dt_c} = &-\underbrace{\left[\left(t-t_c\right)\frac{de}{dt_c} + t\frac{dG}{dt_c}\right]}_{\text{Primary distortion effect}} \\ &\underbrace{-\left(M+1\right)t_L e_C\left(\frac{\partial L}{\partial P_C} + C^S\frac{\partial L}{\partial \pi_C}\right)}_{\text{Tax-interaction effect}} \\ &\underbrace{+M\left[e-\left(t-t_c\right)\frac{de}{dt_c} - t\frac{dG}{dt_c}\right]}_{\text{Revenue-recycling effect}} \\ &\underbrace{+\frac{\sigma'}{\lambda}\left(\frac{dG}{dt_c} + \xi\gamma\frac{de}{dt_c}\right)}_{\text{Externality effect}} \end{aligned} \quad \text{(A1.17)}$$

Appendix 2: Derivation of the Marginal Welfare Effects of the Blend Mandate

The optimal mandate solves:

$$\max_{\theta} V\left(R,\pi_C,\omega,P_C,P_F\right)=\max_{F,C,x,L}\varphi\Big(u\left(F,C,x\right),\bar{L}-L\Big)-\sigma\left(R\right)+\lambda\left(\omega L+\Gamma+\pi_C-P_F F-P_C C-P_x x\right)$$

subject to:

$$R=F+\left(\xi-1\right)\gamma e \tag{A2.1}$$

$$\pi_C=\pi_C\left(P_C\right) \tag{A2.2}$$

$$\omega=w\left(1-t_L\right) \tag{A2.3}$$

$$P_C=e_C\gamma P_E-\frac{we_C}{e_L} \tag{A2.4}$$

$$P_F=\theta\left(P_E+\frac{t}{\gamma}-\frac{t_c}{\gamma}\right)+\left(1-\theta\right)\left(P_G+t\right) \tag{A2.5}$$

$$\Gamma=t_L wL+t\left[F-e\left(\gamma-1\right)\right]-t_c e \tag{A2.6}$$

$$e=e_C\left(C^S-C\right) \tag{A2.7}$$

$$\gamma e=\theta F \tag{A2.8}$$

Note that under the binding blend mandate, the quantities of ethanol and fuel are linked one-to-one as indicated by equation (A2.8).[29] After substituting equations (A2.7) and (A2.8) into equations (A2.1), (A2.6), we obtain:

$$R=F+\gamma\left(\xi-1\right)e \tag{A2.1'}$$

$$\Gamma=t_L wL+tF\left[1-\theta\left(1-\frac{1}{\gamma}\right)\right]-t_c e \tag{A2.6'}$$

We normalize the wage rate to unity, w =1. Totally differentiating the indirect utility function with respect to θ yields:

$$\frac{dV}{d\theta}=\frac{\partial V}{\partial R}\frac{dR}{d\theta}+\frac{\partial V}{\partial \pi_C}\frac{d\pi_C}{d\theta}+\frac{\partial V}{\partial \omega}\frac{d\omega}{d\theta}+\frac{\partial V}{\partial P_C}\frac{dP_C}{d\theta}+\frac{\partial V}{\partial P_F}\frac{dP_F}{d\theta} \tag{A2.9}$$

where the partial derivatives come from the objective function,

[29] Under the tax credit and exogenous gasoline price (which we assume), the quantities of ethanol and fuel are delinked, however.

$$\frac{\partial V}{\partial R}=-\sigma';\frac{\partial V}{\partial \pi_c}=\lambda;\frac{\partial V}{\partial \omega}=\lambda L;\frac{\partial V}{\partial P_C}=-\lambda C;\frac{\partial V}{\partial P_F}=-\lambda F \tag{A2.10}$$

and the total derivatives are obtained from constraints (A2.1') and (A2.2–4)

$$\frac{dR}{d\theta}=\frac{dF}{d\theta}+\gamma(\xi-1)\frac{de}{d\theta};\frac{d\pi_C}{d\theta}=C^S\frac{dP_C}{d\theta};\frac{d\omega}{d\theta}=-\frac{dt_L}{d\theta};\frac{dP_C}{d\theta}=e_C\gamma\frac{dP_E}{d\theta} \tag{A2.11}$$

Totally differentiating equation (A2.6') with respect to θ, we obtain

$$-L\frac{dt_L}{d\theta}=t_L\frac{dL}{d\theta}+t\left[1-\theta\left(1-\frac{1}{\gamma}\right)\right]\frac{dF}{d\theta}-\left(1-\frac{1}{\gamma}\right)tF-t_c\frac{de}{d\theta} \tag{A2.12}$$

where the effect of a change in the blend mandate on the labor supply in the economy can be decomposed, similarly to equation (A1.10) in Appendix, as follows:

$$\frac{dL}{d\theta}=-\frac{\partial L}{\partial \omega}\frac{dt_L}{d\theta}+\frac{\partial L}{\partial P_C}\frac{dP_C}{d\theta}+C^S\frac{\partial L}{\partial \pi_C}\frac{dP_C}{d\theta}+\frac{\partial L}{\partial P_F}\frac{dP_F}{d\theta} \tag{A2.13}$$

Substituting equation (A2.13) into (A2.12), invoking equation (A1.15), and rearranging, we get

$$\frac{dt_L}{d\theta}=-(1+M)\frac{t_L\left(\frac{\partial L}{\partial P_C}+C^S\frac{\partial L}{\partial \pi_C}\right)\frac{dP_C}{d\theta}+t_L\frac{\partial L}{\partial P_F}\frac{dP_F}{d\theta}+t\left[1-\theta\left(1-\frac{1}{\gamma}\right)\right]\frac{dF}{d\theta}-\left(1-\frac{1}{\gamma}\right)tF-t_c\frac{de}{d\theta}}{L} \tag{A2.14}$$

Finally, the optimality condition for a blend mandate is derived by substituting the derivatives (A2.10), (A2.11), and (A2.14) into equation (A2.9) and collecting the terms

$$\begin{aligned}-\frac{1}{\lambda}\frac{dV}{d\theta}=&\underbrace{\left[F\frac{dP_F}{d\theta}-e\gamma\frac{dP_E}{d\theta}+t\left(1-\frac{1}{\gamma}\right)\left(F+\theta\frac{dF}{d\theta}\right)-t\frac{dF}{d\theta}+t_c\frac{de}{d\theta}\right]}_{\text{Primary distortion effect}}\\ &\underbrace{-(1+M)t_L\left[\left(\frac{\partial L}{\partial P_C}+C^S\frac{\partial L}{\partial \pi_C}\right)\frac{dP_C}{d\theta}+\frac{\partial L}{\partial P_F}\frac{dP_F}{d\theta}\right]}_{\text{Tax interaction effect}}\\ &\underbrace{+M\left\{t\left(1-\frac{1}{\gamma}\right)\left(F+\theta\frac{dF}{d\theta}\right)-t\frac{dF}{d\theta}+t_c\frac{de}{d\theta}\right\}}_{\text{R evenue recycling effect}}\\ &\underbrace{+\frac{\sigma'}{\lambda}\left(\frac{dF}{d\theta}+\gamma(\xi-1)\frac{de}{d\theta}\right)}_{\text{Externality effect}}\end{aligned} \tag{A2.15}$$

Appendix 3: Derivation of the Marginal Welfare Effects of the Tax Credit with a Binding Blend Mandate

The tax credit solves:

$$\max_{t_c} V\left(R,\pi_C,\omega,P_C,P_F\right)=\max_{F,C,x,L}\varphi\Big(u\left(F,C,x\right),\bar{L}-L\Big)-\sigma\left(R\right)+\lambda\left(\omega L+\Gamma+\pi_C-P_FF-P_CC-P_xx\right)$$

subject to:

$$R=F+\left(\xi-1\right)\gamma e \tag{A3.1}$$

$$\pi_C=\pi_C\left(P_C\right) \tag{A3.2}$$

$$\omega=w\left(1-t_L\right) \tag{A3.3}$$

$$P_C=e_C\gamma P_E-\frac{we_C}{e_L} \tag{A3.4}$$

$$P_F=\theta\left(P_E+\frac{t}{\gamma}-\frac{t_c}{\gamma}\right)+\left(1-\theta\right)\left(P_G+t\right) \tag{A3.5}$$

$$\Gamma=t_LwL+t\left[F-e\left(\gamma-1\right)\right]-t_ce \tag{A3.6}$$

$$e=e_C\left(C^S-C\right) \tag{A3.7}$$

$$\gamma e=\theta F \tag{A3.8}$$

After substituting equations (A3.7) and (A3.8) into equations (A3.1), (A3.6), we obtain:

$$R=F+\gamma\left(\xi-1\right)e \tag{A3.1'}$$

$$\Gamma=t_LwL+tF\left[1-\theta\left(1-\frac{1}{\gamma}\right)\right]-t_ce \tag{A3.6'}$$

We normalize the wage rate such that w =1. Totally differentiating the indirect utility function with respect to t_c yields:

$$\frac{dV}{dt_c}=\frac{\partial V}{\partial R}\frac{dR}{dt_c}+\frac{\partial V}{\partial\pi_C}\frac{d\pi_C}{dt_c}+\frac{\partial V}{\partial\omega}\frac{d\omega}{dt_c}+\frac{\partial V}{\partial P_C}\frac{dP_C}{dt_c}+\frac{\partial V}{\partial P_F}\frac{dP_F}{dt_c} \tag{A3.9}$$

where the partial derivatives come from the objective function,

$$\frac{\partial V}{\partial R}=-\sigma';\frac{\partial V}{\partial\pi_c}=\lambda;\frac{\partial V}{\partial\omega}=\lambda L;\frac{\partial V}{\partial P_C}=-\lambda C;\frac{\partial V}{\partial P_F}=-\lambda F \tag{A3.10}$$

and the total derivatives are obtained from constraints (A3.1') and (A3.2–4)

$$\frac{dR}{dt_c} = \frac{dF}{dt_c} + \gamma(\xi - 1)\frac{de}{dt_c}; \frac{d\pi_C}{dt_c} = C^S \frac{dP_C}{dt_c}; \frac{d\omega}{dt_c} = -\frac{dt_L}{dt_c}; \frac{dP_C}{dt_c} = e_C \gamma \frac{dP_E}{dt_c} \tag{A3.11}$$

Totally differentiating equation (A3.6') with respect to t_c, we obtain

$$-L\frac{dt_L}{dt_c} = t_L \frac{dL}{dt_c} + t\left[1 - \theta\left(1 - \frac{1}{\gamma}\right)\right]\frac{dF}{dt_c} - e - t_c \frac{de}{dt_c} \tag{A3.12}$$

where the effect of a change in the tax credit on the labor supply in the economy is:

$$\frac{dL}{dt_c} = -\frac{\partial L}{\partial \omega}\frac{dt_L}{dt_c} + \frac{\partial L}{\partial P_C}\frac{dP_C}{dt_c} + C^S \frac{\partial L}{\partial \pi_C}\frac{dP_C}{dt_c} + \frac{\partial L}{\partial P_F}\frac{dP_F}{dt_c} \tag{A3.13}$$

Substituting equation (A3.13) into (A3.12), invoking equation (A1.15), and rearranging, obtains

$$\frac{dt_L}{dt_c} = -(1+M)\frac{t_L\left(\frac{\partial L}{\partial P_C} + C^S \frac{\partial L}{\partial \pi_C}\right)\frac{dP_C}{dt_c} + t_L \frac{\partial L}{\partial P_F}\frac{dP_F}{dt_c} + t\left[1 - \theta\left(1 - \frac{1}{\gamma}\right)\right]\frac{dF}{dt_c} - e - t_c \frac{de}{dt_c}}{L} \tag{A3.14}$$

Finally, the optimality condition for a blend mandate is derived by substituting the derivatives (A3.10), (A3.11), and (A3.14) into equation (A3.9) and collecting the terms

$$\begin{aligned}
-\frac{1}{\lambda}\frac{dV}{dt_c} = &\underbrace{\left\{F\frac{dP_F}{dt_c} - e\gamma\frac{dP_E}{dt_c} + e + t_c\frac{de}{dt_c} - t\left[1 - \theta\left(1 - \frac{1}{\gamma}\right)\right]\frac{dF}{dt_c}\right\}}_{\text{Primary distortion effect}} \\
&\underbrace{-(1+M)t_L\left[\left(\frac{\partial L}{\partial P_C} + C^S\frac{\partial L}{\partial \pi_C}\right)\frac{dP_C}{dt_c} + \frac{\partial L}{\partial P_F}\frac{dP_F}{dt_c}\right]}_{\text{Tax interaction effect}} \\
&\underbrace{+M\left\{e + t_c\frac{de}{dt_c} - t\left[1 - \theta\left(1 - \frac{1}{\gamma}\right)\right]\frac{dF}{dt_c}\right\}}_{\text{Revenue recycling effect}} \\
&\underbrace{+\frac{\sigma'}{\lambda}\left(\frac{dF}{dt_c} + \gamma(\xi - 1)\frac{de}{dt_c}\right)}_{\text{Externality effect}}
\end{aligned} \tag{A3.15}$$

Appendix 4: Derivations for the Numerical Model

The utility-maximizing demand functions can be found in two stages. We first focus on the inner nest of the utility function. Here, minimization of total expenditures on fuel, corn, and the numeraire good, subject to $X = 1$, yields the proportions of individual consumption goods in one unit of the composite good X.[30] These proportions are constant with respect to the level of X and are denoted by $b_F = F/X$, $b_C = C/X$, and $b_x = x/X$, respectively. Thus, the first-stage problem is:[31]

$$\min_{F,C,x} P_F F + P_C C + P_x x$$

subject to:

$$\sigma_X \left(\alpha_F F^{\frac{\delta_x - 1}{\delta_x}} + \alpha_C C^{\frac{\delta_x - 1}{\delta_x}} + (1 - \alpha_F - \alpha_C) x^{\frac{\delta_x - 1}{\delta_x}} \right)^{\frac{\delta_x}{\delta_x - 1}} = 1$$

resulting in the following demand functions (proportions) for $X = 1$:

$$b_F = \left(\alpha_F + \alpha_C \left(\frac{\alpha_F}{\alpha_C} \frac{P_C}{P_F} \right)^{1-\delta_x} + (1 - \alpha_F - \alpha_C) \left(\frac{\alpha_F}{(1 - \alpha_F - \alpha_C)} \frac{P_x}{P_F} \right)^{1-\delta_x} \right)^{\frac{\delta_x}{1-\delta_x}} \frac{1}{\sigma_X}$$

$$b_C = \left(\alpha_C + \alpha_F \left(\frac{\alpha_C}{\alpha_F} \frac{P_F}{P_C} \right)^{1-\delta_x} + (1 - \alpha_F - \alpha_C) \left(\frac{\alpha_C}{(1 - \alpha_F - \alpha_C)} \frac{P_x}{P_C} \right)^{1-\delta_x} \right)^{\frac{\delta_x}{1-\delta_x}} \frac{1}{\sigma_X}$$

$$b_x = \left((1 - \alpha_F - \alpha_C) + \alpha_F \left(\frac{(1 - \alpha_F - \alpha_C)}{\alpha_F} \frac{P_F}{P_x} \right)^{1-\delta_x} + \alpha_C \left(\frac{(1 - \alpha_F - \alpha_C)}{\alpha_C} \frac{P_C}{P_x} \right)^{1-\delta_x} \right)^{\frac{\delta_x}{1-\delta_x}} \frac{1}{\sigma_X}$$

The optimal demands from the first stage provide the price index P_X (price of the aggregate consumption good X), defined as

$$P_X = b_F P_F + b_C P_C + b_x P_x$$

[30] That is, how much of fuel, corn, and the numeraire good is needed to produce one unit of the composite good at a minimum cost.

[31] Note that for $X = 1$, $b_F = F$, $b_C = C$, and $b_x = x$.

The second-stage is utility maximization (outer nest) between leisure and the composite consumption good[32]

$$\max_{N,X} U = \left(\alpha_N N^{\frac{\delta-1}{\delta}} + (1-\alpha_N) X^{\frac{\delta-1}{\delta}} \right)^{\frac{\delta}{\delta-1}} - \sigma(R)$$

subject to:

$$P_X X + w(1-t_L)N = w(1-t_L)\bar{L} + P_X \Gamma + \pi_C$$

resulting in demand for leisure and the composite good:

$$N = \frac{w(1-t_L)\bar{L} + P_X \Gamma + \pi_C}{P_X^{\,1-\delta} \left(\frac{w(1-t_L)(1-\alpha_N)}{\alpha_N} \right)^{\delta} + w(1-t_L)} \text{ and } X = \left(\frac{w(1-t_L)(1-\alpha_N)}{\alpha_N P_X} \right)^{\delta} N$$

[32] Recall that the consumer sees the level of the externality R as exogenous and thus does not take it into consideration when choosing his optimal consumption bundle.

Appendix 5: Determination of the Time-Endowment Ratio

We follow Ballard (2000) to determine the time-endowment ratio Φ (i.e., the representative consumer's endowment of time divided by the amount of labor that is supplied in the baseline) that is consistent with uncompensated price and income labor-supply elasticities found in the literature. Because the utility function used in our paper differs from that in Ballard (2000), below we rederive the calibration procedure.

The representative consumer maximizes his utility, subject to the budget constraint

$$\max U = \left(\alpha_N N^{\frac{\delta-1}{\delta}} + (1-\alpha_N) X^{\frac{\delta-1}{\delta}} \right)^{\frac{\delta}{\delta-1}}$$

subject to:

$$P_X X + \omega N = \omega \overline{L} + REV + \pi_C$$

where $\omega = w(1-t_L)$

The resulting demands for leisure N and the composite consumption good X are

$$N = \frac{\alpha_N{}^{\delta}\left(\omega\overline{L} + REV + \pi_C\right)}{\omega\left(P_X{}^{1-\delta}\omega^{\delta-1}\left(1-\alpha_N\right)^{\delta} + \alpha_N{}^{\delta}\right)} \quad \text{and} \quad X = \left[\frac{\omega\left(1-\alpha_N\right)}{P_X \alpha_N}\right]^{\delta} N$$

The uncompensated leisure-demand elasticity η_N is

$$\eta_N = \frac{\partial N}{\partial \omega}\frac{\omega}{N} = \frac{\alpha_N{}^{\delta}\overline{L}\left[\omega\left(P_X{}^{1-\delta}\omega^{\delta-1}\left(1-\alpha_N\right)^{\delta} + \alpha_N{}^{\delta}\right)\right] - \left[\alpha_N{}^{\delta}\left(\omega\overline{L} + REV + \pi_C\right)\right]\left[\left(P_X{}^{1-\delta}\omega^{\delta-1}\left(1-\alpha_N\right)^{\delta} + \alpha_N{}^{\delta}\right) + (\delta-1)P_X{}^{1-\delta}\omega^{\delta-1}\left(1-\alpha_N\right)^{\delta}\right]}{N\omega\left(P_X{}^{1-\delta}\omega^{\delta-1}\left(1-\alpha_N\right)^{\delta} + \alpha_N{}^{\delta}\right)^2}$$

Denote $\Delta = P_X{}^{1-\delta}\omega^{\delta-1}\left(1-\alpha_N\right)^{\delta} + \alpha_N{}^{\delta}$, then

$$\eta_N = \frac{\alpha_N{}^{\delta}\overline{L}}{\Delta N} - \frac{\alpha_N{}^{\delta}\left(\omega\overline{L} + REV + \pi_C\right)\left[\Delta\delta - (\delta-1)\alpha_N{}^{\delta}\right]}{N\omega\Delta^2} \tag{A5.1}$$

Rearranging the leisure demand function, we obtain

$$\frac{\alpha_N{}^{\delta}}{\Delta} = \frac{N\omega}{\omega\overline{L} + REV + \pi_C} \tag{A5.2}$$

And substituting into equation (5.1), we arrive at

$$\eta_N = \frac{\omega\bar{L}}{\omega\bar{L} + REV + \pi_C} - \delta - (1-\delta)\frac{\alpha_N{}^{\delta}}{\Delta} \tag{A5.3}$$

The relationship between uncompensated and compensated labor supply elasticity is (see Ballard, 2000)

$$\eta_N = -\frac{\eta_L}{\Phi - 1} \tag{A5.4}$$

Solving equations (A5.3) and (A5.4) for δ and α_N, we obtain

$$\delta = \frac{1}{1 + (REV + \pi_C)/\omega L} + \frac{\eta_L}{\Phi - 1}\left(\frac{\Phi + (REV + \pi_C)/\omega L}{1 + (REV + \pi_C)/\omega L}\right) \text{ and } \alpha_N = \left\{\left[\frac{\omega L + REV + \pi_C}{(\Phi - 1)P_X{}^{1-\delta}\omega^{\delta}L}\right]^{\frac{1}{\delta}} + 1\right\}^{-1}$$

The indirect utility function corresponding to the consumer's utility maximization problem above is

$$V = (\omega\bar{L} + REV + \pi_C)\omega^{-1}\left[P_X{}^{1-\delta}\omega^{\delta-1}(1-\alpha_N)^{\delta} + \alpha_N{}^{\delta}\right]^{\frac{1}{\delta-1}} \tag{A5.5}$$

And the expenditure function is given by

$$E^* = V\omega\left[P_X{}^{1-\delta}\omega^{\delta-1}(1-\alpha_N)^{\delta} + \alpha_N{}^{\delta}\right]^{\frac{1}{1-\delta}} \tag{A5.6}$$

By Shepard's Lemma, we have $\partial E^*/\partial\omega = N^* = V\alpha_N{}^{\delta}\left[P_X{}^{1-\delta}\omega^{\delta-1}(1-\alpha_N)^{\delta} + \alpha_N{}^{\delta}\right]^{\frac{\delta}{1-\delta}}$, and the Slutsky derivative is $\partial N^*/\partial\omega = -V\alpha_N{}^{\delta}(1-\alpha_N)^{\delta}\delta\Delta^{\frac{2\delta-1}{1-\delta}}P_X{}^{1-\delta}\omega^{\delta-2}$, from which for the compensated leisure supply elasticity we have

$$\eta_N^* = -\frac{\delta(1-\alpha_N)^{\delta}P_X{}^{1-\delta}\omega^{\delta-1}}{\Delta} \tag{A5.7}$$

The relation between compensated elasticities for labor and leisure supply is given by

$$\eta_L^* = (1 - \Phi)\eta_N^* \tag{A5.8}$$

Because by the Slutsky decomposition the difference between the compensated and uncompensated labor supply elasticities is equal to the absolute value of the total-income elasticity of labor supply (Ballard, 2000), the closing condition for our calibration is

$$\eta_L - \eta_L^* = |\eta_I| \tag{A5.9}$$

which implicitly solves for the time-endowment ratio Φ.

Appendix 6: Supplementary Tables

Table A1. Data Used to Calibrate the Model

Variable/parameter	Symbol	Value	Unit	Source
PARAMETERS				
Carbon emissions of corn ethanol relative to gasoline	ξ	0.80		de Gorter and Just (2010)
Miles per gallon of ethanol relative to gasoline	γ	0.70		de Gorter and Just (2010)
Ethanol produced from one bushel of corn	β	2.80	gallon/bushel	Eidman (2007)
DDGS production coefficient [a]	μ	17/56		Eidman (2007)
Price of DDGS relative to corn price	r	0.86		$r = (P_{DDGS}*56)/(P_C*2000)$
Share of DDGS in one bushel of corn	δ_C	0.26		$\delta_C = r*\mu$
Marginal product of corn in ethanol production	e_C	3.78	gallon/bushel	$\beta/(1-\delta_C)$
Marginal product of labor in ethanol production	e_L	1.25	gallon/hour	$e_C*w/(e_C*P_e-P_C)$
Marginal external cost of CO_2 emissions [b]	MEC	0.06	$/gallon	Parry and Small (2005)
Share parameter of fuel consumption in utility	α_F	2.89E-06		Calibrated using equation for b_F in Appendix 4
Share parameter of corn consumption in utility	α_C	9.63E-10		Calibrated using equation for b_C in Appendix 4
Scale factor on composite consumption good in utility	σ_X	1.06		Calibrated using the constraint in Appendix 4
Labor endowment as proportion of labor	Φ	1.19		Appendix 5
Share parameter of leisure consumption in utility	α_N	0.13		Appendix 5
Returns to scale in corn production	ε^S	0.23		$\varepsilon^{CS}/(\varepsilon^{CS}+1)$
Labor share of income	ρ	0.57		U.S. Bureau of Economic Analysis [c]
Marginal product of labor in numeraire production	k	1.00		$k = w/P_x$
Scale parameter for the corn production function	A	7.50		$A = C^S\text{^}(1-\varepsilon^S)/(\varepsilon^S*P_C/w)\text{^}\varepsilon^S$
Marginal product of labor in gasoline production	B	0.57		$B = w/P_G$
POLICY VARIABLES				
Ethanol tax credit	t_c	0.50	$/gallon	t_c = $0.45/gal. + $0.048/gal. [d]
Blend mandate (energy equivalent)	θ	0.06		$\theta = E/F$
Fuel tax	t	0.49	$/gallon	American Petroleum Institute [e]
Labor tax (ad valorem)	t_L	0.40		Goulder et al. (1999)
After-tax wage	ω	0.60		$\omega = w*(1-t_L)$
PRICES				
Wage	w	1.00	$/hour	Normalized
Price of the numeraire good	P_x	1.00		Normalized
Price of the composite good	P_X	1.00		Normalized to unity in the baseline
Gasoline price	P_G	1.76	$/gallon	Gasoline average rack price in Omaha, Nebraska [f]
Ethanol price (volumetric)	P_e	1.79	$/gallon	Ethanol average rack price in Omaha, Nebraska [f]
Ethanol price (energy)	P_E	2.56	$/GEEG	$P_E = P_e/\gamma$
Fuel price	P_F	2.27	$/GEEG	$P_F = \theta*(P_E + t/\gamma - t_c/\gamma) + (1-\theta)*(P_G + t)$
Corn market price	P_C	3.75	$/bushel	USDA [g]
DDGS price	P_{DDGS}	114.40	$/ton	USDA [h]

Notes:

[a] DDGS = Dried distillers grains with solubles

[b] Corresponds to $25/tonne carbon

[c] http://www.bea.gov/national/index.htm#gdp

[d] $0.45/gallon is the federal component of the tax credit; the $0.048/gallon is the average state tax credit reported by Koplow (2009).

[e] http://www.api.org/statistics/fueltaxes/upload/gasoline-diesel-summary.pdf (average for 2009)

[f] http://www.neo.ne.gov/statshtml/66.html

[g] http://www.ers.usda.gov/data-products/feed-grains-database/feed-grains-yearbook-tables.aspx

[h] http://www.ers.usda.gov/data-products/feed-grains-database/feed-grains-yearbook-tables.aspx#26818

Appendix A1. Data Used to Calibrate the Model (continued)

Variable/parameter	Symbol	Value	Unit	Source
QUANTITIES				
U.S. gross domestic product	GDP	13939.00	billion dollars	U.S. Bureau of Economic Analysis [c]
Time endowment	$\bar{L}$	9434.96	billion hours	$\bar{L} = \Phi L$
Labor supply	L	7945.23	billion hours	ρ*GDP/w
Leisure demand	N	1489.73	billion hours	$N = \bar{L} - L$
Labor used in gasoline production	L_G	217.74	billion hours	$L_G = G/B$
Labor used in ethanol production	L_e	8.83	billion hours	$L_e = e/e_L$
Labor used in corn production	L_C	11.36	billion hours	$L_C = (w/(\varepsilon^S*A*P_C))$^$(1/(\varepsilon^S-1))$
Labor used in numeraire production	L_x	7707.30	billion hours	$L_x = L - L_e - L_c - L_G$
Nominal government revenue	REV	3238.65	billion dollars	$REV = w*t_L*L + t*f - t_c*e$
Real government transfer	Γ	3238.65	billion dollars	REV/P_X
Gasoline supply	G	123.71	billion gallons	G = f - e
Ethanol consumption (volumetric)	e	11.04	billion gallons	EIA [i]
Ethanol consumption (energy)	E	7.73	bullion GEEGs	$E = \gamma*e$
Fuel consumption (volumetric)	f	134.75	billion gallons	EIA [i]
Fuel consumption (energy)	F	131.44	bullion GEEGs	F = G + E
Corn supply	C^S	13.15	billion bushels	USDA [j]
Non-ethanol corn consumption	C	10.23	billion bushels	$C = C^S - C^e$
Corn used for ethanol production	C^e	2.92	billion bushels	$C^e = e/e_C$
Numeraire consumption	x	7707.30		$x = kL_x$
Composite good consumption	X	8040.58		$X = N*(\omega*(1-\alpha_N)/(\alpha_N*P_X))$^$\delta$
Profits in corn production	π_C	37.88	billion dollars	$P_C*C^S - w*L_c$
Externality	R	129.89		$R = G + \xi E$
ELASTICITIES				
Elasticity of corn supply	ε^{CS}	0.30		Cui et al. (2011)
Income elasticity of labor supply	ε^{LI}	-0.10		Ballard (2000)
Uncompensated elasticty of labor supply	ε^{LL}	0.10		Ballard (2000)
Elasticity of substitution between leisure and consumption	δ	1.19		Appendix 5
Elasticity of substitution among consumption goods	δ_X	0.30		Chosen to correspond to elasticities of demand for fuel and corn from the literature.

Notes:

[i] http://www.eia.gov/forecasts/steo/query/

[j] http://www.ers.usda.gov/Data/FeedGrains/FeedYearbook.aspx (Table 4)

Table A2. Description of Market Equilibrium with Alternate Policy Scenarios

	Status Quo	Tax Credit Removed	No Ethanol Policies
Ethanol tax credit ($/gallon)	0.498	0.000	0.000
Blend mandate (%), energy equivalent	5.88	5.88	0.00
Fuel tax ($/gallon)	0.490	0.490	0.490
Fuel price ($/GEEG)	2.268	2.309	2.250
Ethanol price ($/GEEG)	2.557	2.554	N/A
Corn price ($/bushel)	3.745	3.738	2.468
Labor tax rate	0.4000	0.3996	0.3983
Fuel quantity (billion gallons)	134.75	134.04	131.84
Fuel quantity (billion GEEGs)	131.44	130.74	131.84
Gasoline quantity (billion gallons)	123.71	123.06	131.84
Ethanol quantity (billion gallons)	11.038	10.979	0.000
Corn quantity (billion bushels)	10.232	10.239	11.604
Total corn supply (billion bushels)	13.150	13.142	11.604
Labor supply (billion hours)	7945.2	7945.2	7951.6
Price level	1.000	1.001	0.998
Net fuel tax revenue ($ billion)	61	66	65
Total government revenue ($ billion)	3239	3241	3232
Total emissions*	129.89	129.21	131.84

* Emissions units are defined such that 1 gallon gasoline = 1 unit of emissions

N/A: "Not applicable"

Source: calculated

Table A3. Description of Market Equilibria for Table 3 Scenarios

Pre-existing distortion(s)	Fuel tax and labor tax			Fuel tax			Labor tax		
Policy description	Mandate *	Equivalent tax credit	No ethanol policy	Mandate	Equivalent tax credit	No ethanol policy	Mandate	Equivalent tax credit	No ethanol policy
Ethanol tax credit ($/gallon)	0.000	0.703	0.000	0.000	0.850	0.000	0.000	0.583	0.000
Fuel tax ($/gallon)	0.49	0.49	0.49	0.49	0.49	0.49	0.00	0.00	0.00
Fuel price ($/GEEG)	2.31	2.25	2.25	2.32	2.25	2.25	1.81	1.76	1.76
Ethanol price ($/GEEG)	2.55	2.55	N/A	2.76	2.76	N/A	2.59	2.59	N/A
Corn price ($/bushel)	3.74	3.74	2.47	4.29	4.29	2.79	3.84	3.84	2.46
Labor tax rate	0.3996	0.4001	0.3983	0.0	0.0	0.0	0.4045	0.4050	0.4031
Fuel quantity (billion gallons)	134.0	135.0	131.8	144.1	145.4	141.9	143.9	145.0	141.6
Fuel quantity (billion GEEGs)	130.7	131.7	131.8	140.6	141.9	141.9	140.4	141.5	141.6
Gasoline quantity (billion gallons)	123.1	124.1	131.8	132.3	133.6	141.9	132.1	133.2	141.6
Ethanol quantity (billion gallons)	10.98	10.98	0.00	11.81	11.81	0.00	11.79	11.79	0.00
Corn quantity (billion bushels)	10.24	10.24	11.60	10.58	10.58	12.04	10.13	10.13	11.59
Total corn supply (billion bushels)	13.14	13.14	11.60	13.70	13.70	12.04	13.25	13.25	11.59
Labor supply (billion hours)	7945	7945	7952	8558	8559	8560	7945	7945	7952
Price level	1.0007	0.9997	0.9980	1.0016	1.0004	0.9984	0.9924	0.9915	0.9897
Net fuel tax revenue ($ billion)	66	58	65	71	61	70	0	-7	0
Government revenue ($ billion)	3241	3238	3232	70.65	61.26	69.57	3214	3211	3205
Total emissions **	129.2	130.2	131.8	138.9	140.2	141.9	138.7	139.8	141.6
Welfare change from policy removal ($ billion)	7.096	6.607	N/A	6.296	5.693	N/A	7.227	7.269	N/A

* 5.88 percent (energy equivalent)

** Emissions units are defined such that 1 gallon gasoline = 1 unit of emissions

N/A: "Not applicable"

Source: calculated