The Social Costs and Benefits of U.S. Biofuel Policies with Pre-Existing Distortions

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1. Introduction

The primary objectives of U.S. biofuel policies are to enhance energy security (reducing dependence on oil),[1] improve the environment (mitigating global climate change and local air pollutants)[2] and increase the prosperity for agriculture (enhancing farm income and promoting rural development while reducing tax costs of farm subsidy programs).[3] In order to achieve these policy goals, several policies have been implemented but the centerpieces of U.S. policy are federal and state biofuel consumption mandates and consumption subsidies (called 'tax credits'), policies that by themselves do not discriminate against international trade. This is the focus of our paper.

The implications of mandates and tax credits are analyzed under three different second best constraints: a sub-optimal fuel tax; adding a tax credit with a binding mandate; and interaction effects with the fiscal system where mandates and tax credits have differential effects on government tax revenues and the size of the fiscal base. In comparing mandates to tax credits under these three pre-existing distortions, this paper does not analyze the welfare economics of policies that discriminate against trade, namely import barriers, production subsidies and sustainability standards. Under each second best constraint, we simply hold ethanol consumption (and hence ethanol and corn prices) the same.

The emerging literature on biofuels has shown that mandates are superior to tax credits (de Gorter and Just 2007; 2008a; 2009b; Lapan and Moschini). In this paper, we show this superiority is magnified by a sub-optimal fuel tax, as in the United States (Parry and Small), even if fuel prices decline under a mandate. This is because a mandate taxes gasoline consumption to pay for higher ethanol prices and so compensates for the sub-optimal fuel tax. The benefits come in the form of reduced greenhouse gas emissions, externalities associated with miles traveled (local air pollution, traffic congestion and traffic related accidents), and oil dependency. On the other hand, a sub-optimal fuel tax makes an ethanol tax credit even more distortionary because the tax credit lowers the fuel price which is already too low because of the sub-optimal fuel tax.

However, both policies used in combination can have perverse effects on externalities and welfare. By itself, a tax credit subsidizes ethanol consumption but in the presence of a binding mandate, the effects are reversed and the tax credit now subsidizes gasoline consumption. This is an important result not only because many countries use subsidies in combination with biofuel mandates but also because renewable electricity faces similar policy combinations worldwide. Therefore, tax credits contradict the stated policy objectives of reducing dependency on oil and improving the environment, while providing no benefits to corn or ethanol producers.

Finally, there are implications for interactions with the fiscal system; for the same level of ethanol consumption, mandates have different impacts than tax credits on government tax revenues and fuel prices. These fiscal interaction effects can have important welfare implications, depending on how taxpayer revenues are recycled and how the tax base is affected by fuel price changes (see contributions in this volume by Parry, Williams, and Goulder). Although in theory a mandate can cost more in taxpayer monies, empirically we find it saves substantial tax costs for the same quantity of ethanol. This benefit has to be balanced against the cost of a mandate in reducing the tax base through relatively higher fuel prices.

The next section first provides an overview of the welfare economics of biofuel policy in general. Section 3 derives the optimal fuel tax-tax credit combination while Section 4 derives the optimal fuel tax-mandate combination. Section 5 determines the implications of a sub-optimal fuel tax while Section 6 explains how adding a tax credit to a binding mandate subsidizes gasoline consumption. Section 7 summarizes the expected interactions with the fiscal system in terms of net effects on tax revenues and the size of the fiscal base. Section 8 presents simulation results of the social welfare costs and benefits from the pre-existing distortions, highlighting the benefits of a mandate over a tax credit and the enormous costs of adding a tax credit to a mandate. The last section provides some concluding remarks.

2. Background

There is a flourishing literature on the welfare economics of biofuel policies. Some studies emphasize the benefits of ethanol policy in reducing fuel prices and tax costs of farm subsidy programs, and in improving the international terms of trade in corn exports and oil imports (Gardner; Rajagopal et al.; de Gorter and Just 2009a; Schmitz, Moss and Schmitz; Bourgeon and Tréguer; Du, Hayes and Baker; Babcock 2008a). Other studies emphasize the impact on CO_2e emissions and vehicle miles traveled (Vedenov and Wetzstein; Khanna, Ando and Taheripour; de Gorter and Just 2008a; 2009d; Lapan and Moschini). The deadweight costs of the ethanol import tariff are emphasized by Martinez-Gonzalez, Sheldon and Thompson, de Gorter and Just (2008c), and Lasco and Khanna. Some studies argue that ethanol policies fail to pass an overall cost-benefit test (Taylor and Van Doren 2007; Metcalf; Hahn and Cecot), they have an adverse impact on food prices and poverty, especially in developing countries (Runge and Senauer; Mitchell) and create higher greenhouse gas emissions due to indirect land use changes (Searchinger et al.).[4]

Gasoline consumption contributes to 45 percent of total oil consumption in the United States and 31 percent of total CO_2 emissions. CO_2 emissions differ between ethanol and gasoline on a per gallon (gasoline equivalent) basis. Theoretically, there are three alternative ways to calculate CO_2. It must be recognized that all CO_2 emitted upon combustion of ethanol was originally sequestered as the corn was grown. Thus, CO_2 emissions for ethanol are net zero while gasoline emits 17.94 pounds of CO_2 per gallon at combustion.[5] This is the approach also taken by the Nobel Laureate IPCC whose guidelines used in assessing compliance with carbon limits in the Kyoto Protocol, do not count CO_2 emitted from tailpipes and smokestacks when bioenergy is being used.

The second approach is to measure CO_2e emissions using life-cycle accounting; a "well to wheel" measure of GHGs emissions in the production of gasoline, and a "field to fuel tank" measure for ethanol production. Here, gasoline emits 25.57 pounds of CO_2e per gallon while ethanol emits 80 percent of that.[6] The third approach is to add CO_2e emissions due to indirect land use change to the life-cycle accounting measure, in which case ethanol emits more CO_2e than gasoline (see Searchinger et al. and Hertel, Tyner and Birur). The latter two approaches are based on simple CO_2e balance calculations and do not provide any criteria when and where biofuels should be produced. Instead of simply reporting upfront CO_2e emissions from land conversion and annual sequestration (e.g., as in Searchinger et al.), one needs to undertake temporal cost-benefit analysis to determine if ethanol production is beneficial or not (de Gorter and Tsur).[7]

In the empirical section to follow, we take the intermediate case to minimize any controversies and leave the other two options for sensitivity analysis in future research.[8] On a per mile traveled basis, ethanol and gasoline are assumed to have the same value of marginal external costs from traffic congestion, local air pollutants and traffic related accidents.[9]

Another key finding in the literature is that ethanol policy can have a substantial impact on corn prices. However, production costs of U.S. corn-ethanol are very high. The gap between the intercept of the ethanol supply curve and the oil price creates large deadweight costs, far greater than traditional deadweight cost triangles (de Gorter and Just 2008b; 2009b). Furthermore, the claim that ethanol policy reduces tax costs of farm subsidy programs may not be borne out because farm subsidies make ethanol policy more inefficient, and vice-versa. Furthermore, corn subsidies were required in addition to ethanol policy for U.S. ethanol production to occur historically (de Gorter and Just 2009b).

The federal government mandates the use of biofuels in the form of a Renewable Fuel Standard (RFS) of 36 billion gallons per year by 2022, to account for 20 percent of total fuel consumption. Campaign proposals by President Obama would boost this target to 60 billion gallons per year by 2030. The RFS requires 15 billion gallons to be conventional (corn-based) ethanol. But energy legislation also calls for the continuation of a tax credit for biofuels.[10] Federal and state tax credits currently total approximately 52 cents per gallon for corn-ethanol while a parallel program for biodiesel is worth $1.00 per gallon. A production tax credit limited to cellulosic ethanol pays out $1.01 for each gallon produced. These tax credits are worth over $6.5 billion in 2008. This total increases three-fold to $21 billion by 2022 because the increase in mandated production particularly among the more heavily subsidized cellulosic fuels. In total, between 2008 and 2022, taxpayers could pay out over $200 billion to the biofuels industry. If President Obama's proposals for 60 billion gallons per year were to be realized, taxpayer financed subsidies could be over $34 billion per year by the end of the period, for a cumulative subsidy during the 2008-30 period of close to $400 billion.[11]

As noted earlier, subsidies and mandates by themselves do not discriminate against international trade. However, production subsidies, import tariffs (of approximately 57¢/gal.) and sustainability standards do. In addition to creating huge inefficiencies, these import barriers are inconsistent with both energy and environmental goals as lower cost sugar cane based ethanol in

Brazil contributes far more in reducing CO_2e emissions than corn based ethanol. Far less land is required and so much lower indirect land use changes occur because Brazil not only produces twice the amount of ethanol per hectare but also crops displaced by United States now have to be produced elsewhere (e.g., corn yields in Brazil are one-third of that of the United States) and annual net sequestration per hectare is much higher in Brazil (de Gorter and Tsur). Given that ethanol production from Brazil is more economically efficient and climate-friendly than ethanol production in the United States, removal of U.S. production subsidies for corn and ethanol, and of ethanol import tariffs would save billions in CO_2e emissions alone (Lasco and Khanna; de Gorter and Tsur).These inefficiencies due to trade restrictions are independent of the welfare effects of mandate or tax credit analyzed in this paper.

A key finding in the literature that is particularly important for the analysis to follow in this paper is that a mandate is superior to a tax credit. The effects of each policy on key externalities are summarized in Table 1. Although gasoline consumption always declines under either a mandate or a tax credit (hence oil dependence declines), surprisingly it is possible for total fuel consumption to increase under a mandate, depending on the relative elasticity of ethanol supply and gasoline supply (Fischer and Newell; de Gorter and Just 2007; 2009b).[12] This means the change in externalities related to vehicle miles traveled and CO_2e emissions is also ambiguous. It is possible that a mandate increases CO_2e emissions even if ethanol emits less per mile traveled than gasoline. Note however that a reduction in the fuel price is not a sufficient condition for CO_2e emissions to increase. The resulting change in emissions will depend not only on the ratio of emissions from the two fuels, but also on the price responsiveness of producers. If gasoline production is very price inelastic. The increase in ethanol consumption due to the mandate may not be completely offset by the reduction in gasoline consumption, potentially leading to greater emissions (de Gorter and Just 2008a; Lapan and Moschini).

With a tax credit, on the other hand, fuel consumption always increases. A tax credit unambiguously increases miles traveled but CO_2e emissions may either increase or decrease depending on the amount of the increase in ethanol consumption due to the tax credit and on ethanol's contribution to CO_2e emissions. Even though ethanol is considered to emit less CO_2e per mile traveled than gasoline, there is the chance that subsidizing ethanol may increase emissions. This is because subsidizing ethanol lowers the overall price of fuel.[13] Regardless, as the final row in Table 1 indicates, a mandate results in a lower level of total fuel consumption, CO_2e emissions and miles traveled compared to a tax credit for the same quantity of ethanol.[14]

3. The Optimal Fuel Tax-Tax Credit Combination

Denote ξ_E and ξ_G as the CO_2e emissions per mile of fuel consumed from ethanol and gasoline, respectively, with the marginal external costs given by τ_1 dollars per mile.[15] Denote τ_2 as the per mile traveled marginal external costs due to traffic congestion, local air pollutants and traffic related accidents (assumed identical for ethanol and gasoline).

Consider a competitive market with a domestic supply curve for ethanol $E(P_E)$, measured in terms of contribution to vehicle miles traveled, with P_E the price to suppliers of ethanol, and a supply for oil-based gasoline $G(P_G)$, also measured in miles with P_G the market price to suppliers of gasoline. Fuel consists of only two products: ethanol and gasoline. These two are assumed to be perfect substitutes in consumption. Consumers would not be willing to pay more per mile for either fuel. Thus, in a competitive equilibrium, the price per mile of ethanol must equal the price per mile of gasoline: $P_E = P_G$. The domestic demand for fuel (measured in miles) is denoted by $D_F(P_F)$, where P_F is the price per mile of the blended fuel. The market equilibrium price for fuel absent a policy is thus given by P such that:

(1) $$D_F\left(P\right)=E\left(P\right)+G\left(P\right).$$

Now, consider the U.S. policy of charging a tax on all fuels based on volume, and then providing a tax credit for ethanol. Denote the volumetric fuel tax by t_v, measured in dollars per gallon. One gallon of ethanol produces only 70 percent of the miles achieved by a gallon of gasoline. Thus, the tax per mile traveled will be different for gasoline and ethanol. The tax per mile for gasoline is $t=t_v/MPG_G$, where MPG_G is the miles traveled per gallon of gasoline. The corresponding tax per mile traveled for ethanol is thus ϕt where $\phi=MPG_G/MPG_E \approx 1/.7$, or close to 1.4, and where MPG_E is the miles traveled per gallon of ethanol. Let t_c be the tax credit per gallon of ethanol. Thus, the tax credit per mile traveled with ethanol is $t_c = t_{cv}/MPG_E$. Again, the competitive equilibrium will force the consumer price of ethanol and gasoline to be equal,

(2) $$P_G+t=P_E+\phi t-t_c.$$

Thus the consumer will pay P_G+t, and the ethanol price in equilibrium will be given by $P_E=P_G+\left(1-\phi\right)t+t_c$. The equilibrium under a tax and a tax credit will be given by

(3) $$D_F\left(P_G+t\right)=E\left(P_G+\left(1-\phi\right)t+t_c\right)+G\left(P_G\right).$$

Thus, the price of gasoline is an implicit function of the tax and tax credit as defined by (3). Anytime a policymaker adjusts either the tax or tax credit, it will necessarily cause a change in P_G (and thus in the price of ethanol, the quantities of ethanol and gasoline produced and the quantity of fuel demanded) according to the equilibrium condition in (3).

To find the optimal fuel tax-tax credit combination, let $V(P_F,Y,X)$ be the indirect utility function of a representative consumer, yielding the optimal utility as a function of the price of fuel, the level of income, Y, and the level of environmental externalities from CO_2e emissions and miles traveled, X. Under a fuel tax and an ethanol tax credit, assume that government tax revenues are returned lump sum to the representative consumer. Thus income is given by

$$Y = \pi_E\left(P_E\right) + \pi_G\left(P_G\right) + tG\left(P_G\right) + \left(\phi t - t_c\right)E\left(P_E\right), \tag{4}$$

where $\pi_E\left(P_E\right)$ is the profit derived from sale of ethanol as a function of the price of ethanol, $\pi_G\left(P_G\right)$ is profit derived from the sale of gasoline as a function of the price of gasoline, and all other variables are as defined previously. Thus, to solve for the optimal tax and tax credit

$$\max_{t,t_c} V\left(P_F, Y, X\right), \tag{5}$$

where $P_F = P_G + t$ according to (3), Y is as specified in (4), and the money metric externality costs associated with consuming gasoline and ethanol is defined by X:

$$X = \tau_1\left[\xi_E E\left(P_E\right) + \xi_G G\left(P_G\right)\right] + \tau_2\left[E\left(P_E\right) + G\left(P_G\right)\right], \tag{6}$$

We can then solve for the optimal tax on fuel and the tax credit for ethanol (see section 1 in the Appendix), finding $t^* = \tau_1\xi_G + \tau_2$ and $t_c^* = \phi t^* - t_E^* = \phi\left(\tau_1\xi_G + \tau_2\right) - \left(\tau_1\xi_E + \tau_2\right)$ where the social marginal damage due to ethanol is $t_E^* = \tau_1\xi_E + \tau_2$. The optimal gasoline tax is the marginal external cost of consuming gasoline. Alternatively, the optimal ethanol tax credit is the difference between the per mile tax cost of consuming ethanol (the tax burden of paying ϕt^*) and the marginal external cost of consuming ethanol t_E^*. Thus, at the first best optimum, the individual is charged the marginal external cost of consumption for each fuel they consume.

The intuition of how we can achieve the first best with a combination of a fuel tax and tax credit for ethanol is given in Figure 1. To simplify the explanation of Figure 1, we assume the price of gasoline P_G is fixed with the gasoline supply curve given by G. Denote the fuel demand curve by D_F and the ethanol supply curve by E. With neither a fuel tax nor an ethanol tax credit, the market price of gasoline defines the initial market (and consumer) prices for fuel P_{F0} and ethanol P_{E0}.[16] Fuel consumption equals F_0 and ethanol production is E_0. Define the gasoline demand curve by D_{G0} (the fuel demand curve D_F shifted left by the initial quantity of ethanol E_0). This generates gasoline consumption G_0.

To further simplify the analysis, assume CO_2e emissions from gasoline are the only externality given by $\tau_1\xi_G$ (ethanol is assumed to be net zero in CO_2e emissions, the case where $\xi_E = 0$, and externalities due to miles traveled is assumed zero, $\tau_2 = 0$). This means initial externality costs of fuel consumption are given by area *defc*.

Imposing the optimal fuel tax $t^* = \tau_1\xi_G$ generates a new price for gasoline P_{F1} (the market price to gasoline suppliers remains at P_G). Fuel consumption declines to F_1. Because consumers demand miles and are only willing to pay $P_G + (1 - \phi)t^*$ for ethanol, the market price to suppliers of ethanol P_{E1} declines (along with ethanol production to E_1) by $(1 - \phi)t^*$.[17] Hence, $(1 - \phi)t^*$ represents a penalty on blenders of fuel as the government requires the payment of a *volumetric* fuel tax on all fuels but consumers are not willing to pay the excess tax for ethanol.

The optimal solution is to implement a consumption subsidy for ethanol given by the tax credit $t_c = \phi\, \tau_1\xi_G$ such that the new market price for ethanol $P_{E2} = P_{E1} + \phi\, \tau_1\xi_G = P_{F1}$ and ethanol production is E_2. Gasoline consumption G_1 is given by $F_1 - E_1$. Equilibrium in Figure 1 therefore depicts the optimal fuel tax-tax credit combination (assuming $\tau_2 = \tau_{1E} = 0$) where the fuel price equals P_{F1}, the ethanol market price equals P_{E2}, the consumption of fuel equals F_1, ethanol production is E_2 and gasoline consumption equals G_2.

The optimal fuel tax-tax credit combination generates a primary welfare gain in reduced CO_2e emissions of areas *dabc* (increased ethanol consumption) and *hijl* (reduced consumption of gasoline). Fuel tax revenues are areas *ahlb* + *naqr* but the tax costs of the tax credit is area *naqr* so the net tax revenues are area *ahlb* (= $\tau_1\xi_G \cdot G_2$). Deadweight costs in reduced fuel consumption are given by area *hfl* while deadweight costs in ethanol production are area *abc.*

4. The Optimal Fuel Tax-Mandate Combination

Under an ethanol consumption mandate, consumers are forced to accept a specific amount of ethanol $\bar{E}$. The resulting market price for fuel will be the price that covers the average marginal cost of production for the blend

$$P_F = \frac{\bar{E}P_E\left(\bar{E}\right) + P_G G\left(P_G\right)}{\bar{E} + G\left(P_G\right)}, \tag{7}$$

where $P_E\left(E\right)$ is the producer price necessary to produce $\bar{E}$ amount of ethanol. The market equilibrium will thus be determined where demand for miles from fuel is equal to the supply,

$$D_F\left(\frac{\bar{E}P_E\left(\bar{E}\right) + P_G G\left(P_G\right)}{\bar{E} + G\left(P_G\right)}\right) = \bar{E} + G\left(P_G\right). \tag{8}$$

If we allow a volumetric fuel tax with the ethanol consumption mandate, the marginal cost of ethanol to producers becomes $P_E\left(\bar{E}\right) + \phi t$. Thus, with a mandate and a tax, the market equilibrium is determined by

$$D_F\left(\frac{\left(P_E\left(\bar{E}\right) + \phi t\right)\bar{E} + \left(P_G + t\right)G\left(P_G\right)}{\bar{E} + G\left(P_G\right)}\right) = \bar{E} + G\left(P_G\right) \cdot \tag{9}$$

This again defines P_G as an implicit function of the fuel tax and the ethanol mandate. Thus, as the policies change, the price of gasoline will change (and the amount of gasoline consumed) to accommodate the policy.

To find the optimal fuel tax-ethanol mandate combination, consider again the indirect utility function $V\left(P_F, Y, X\right)$. The policy maker must solve

$$\max_{\bar{E},t} V\left(P_F, Y, X\right), \tag{10}$$

where

$$P_F = \frac{\left(P_E\left(\bar{E}\right)+\phi t\right)\bar{E}+\left(P_G+t\right)G\left(P_G\right)}{\bar{E}+G\left(P_G\right)} \tag{11}$$

$$Y = \pi_E\left(P_E\right)+\pi_G\left(P_G\right)+tG\left(P_G\right)+\phi tE\left(P_E\right) \tag{12}$$

and X is as given in (6), and where P_G is a function of the fuel tax and mandate defined implicitly by (9). The optimal fuel tax under the mandate (defined as t^M) can be stated in terms of the first best fuel tax-tax credit combination (derived in the Appendix, section 4)

$$t^M = \frac{t^*G\left(P_G\left(t^*,t_c^*\right)\right)+\left(\phi t^*-t_c^*\right)\bar{E}}{G\left(P_G\left(t^*,t_c^*\right)\right)+\phi\bar{E}}, \tag{13}$$

$$\bar{E} = E\left(P_G\left(t^*,t_c^*\right)+\left(1-\phi\right)t^*+t_c^*\right). \tag{14}$$

Equations (13) and (14) imply the same level of ethanol and gasoline use that was obtained in the first best solution (using a tax and tax credit). However, the optimal fuel tax in this case is lower,

$$t^M = \frac{t^*G\left(P_G\left(t^*,t_c^*\right)\right)+\left(\phi t^*-t_c^*\right)\bar{E}}{G\left(P_G\left(t^*,t_c^*\right)\right)+\phi\bar{E}} < \frac{t^*G\left(P_G\left(t^*,t_c^*\right)\right)+\phi t^*\bar{E}}{G\left(P_G\left(t^*,t_c^*\right)\right)+\phi\bar{E}} = t^*, \tag{14}$$

by the amount $t_c^*\bar{E}\Big/\left(G\left(P_G\left(t^*,t_c^*\right)\right)+\phi\bar{E}\right)$. As displayed in column 1 of Table 2, the optimal mandate under the optimal tax will always equal the amount of ethanol consumed under the optimal fuel tax-tax credit combination, though the optimal fuel tax will be lower. The reason for a lower optimal fuel tax is rather straightforward: the mandate is a tax on the gasoline market to pay for the higher ethanol price. Hence, a lower fuel tax is required to offset the marginal external cost of fuel consumption. The ethanol price is exactly the same as the optimal fuel tax-tax credit combination so one can achieve the first best optimum, resulting in exactly the same indirect utility (shown in section 4 of the Appendix).[18]

The optimal fuel tax-mandate combination is depicted in Figure 2. As in Figure 1, we simplify by assuming CO_2e emissions for gasoline only ($\xi_E = 0$) and ignore the external costs due to miles traveled ($\tau_2 = 0$). The optimal ethanol mandate is $\bar{E}$ with an ethanol market price P_{E1} (generating a pre-fuel tax price of fuel equal to P_{FE1}). The optimal fuel tax with the optimal mandate is denoted by t^M. Total fuel consumption declines to F^* (gasoline consumption is $G^* = F^* - \bar{E}$). Tax revenues from ethanol sales equal area *naji* while tax revenues from gasoline are area *agfe*. Note that it is necessarily the case that area *efkb* equals area *naji*.

5. How a Sub-optimal Fuel Tax Magnifies the Superiority of a Mandate

Now that we have derived the optimal fuel tax-tax credit and fuel tax-mandate combinations, it is important to consider policy constraints imposed by politics. For example, assume it is not politically feasible to raise the gasoline tax to its optimal level in the United States (Parry and Small).[19] We derive two key results in this section: a sub-optimal fuel tax requires a lower tax credit and (under most conditions) a higher mandate. In other words, the superiority of a mandate is widened.

Why the tax credit has to be lowered

If we were to find the optimal ethanol tax credit when the fuel tax is held at 0, we find $t_c < -t_E{}^*$ (shown in section 3 of the Appendix). Thus the optimal ethanol tax credit in this case is in fact a tax that must exceed the marginal external cost of ethanol. In this case, the instrument on ethanol is the only policy available to address the externalities associated with either fuel. The tax reducing external effects from the consumption of ethanol is more effective than a subsidy creating secondary reductions in externalities by substituting ethanol for gasoline.

As the fuel tax exogenously decreases from the optimum, the optimal response ethanol tax credit (the tax credit that maximizes welfare given a fuel tax) decreases and eventually becomes negative once the tax is below the marginal external cost of ethanol (see section 3 in the Appendix). The optimal ethanol tax credit t_c is only positive if (a) CO_2e emissions decline (recall that the effect of a tax credit on CO_2e emissions is ambiguous) and (b) the social benefits of this decline in CO_2e emissions is greater than the social costs of the unambiguous increase in miles traveled with a tax credit. This will occur whenever the fuel tax exceeds the marginal external costs of consuming ethanol. A sub-optimal fuel tax will lead to an optimal tax credit t_c that is below the first best tax credit t_c*.

Alternatively, consider a sub-optimal tax credit. If we find the optimal fuel tax holding the ethanol tax credit at 0, the resulting optimal fuel tax satisfies $t^* > t > t_E{}^*/\phi$ (see section 2 in the Appendix). Thus the optimal fuel tax will be between the marginal external cost of gasoline and the marginal external cost of ethanol (here the adjustment ϕ is due to the fact that the tax is on a volume basis). This will always result in a fuel tax that is less than the fuel tax under the jointly optimal fuel tax and ethanol tax credit, but more than the net tax on ethanol under the jointly optimal fuel tax and ethanol tax credit. In general, exogenously reducing the ethanol tax credit will always decrease the optimal fuel tax, if $t^* > t_E{}^* < \phi$.

Why the mandate has to be increased

With a sub-optimal fuel tax, the optimal ethanol mandate will be positive so long as the marginal external cost plus the marginal internal cost of ethanol is larger than the same value for gasoline within the competitive equilibrium. The level of the optimal consumption mandate $\overline{E}^*$ depends heavily on the elasticity of supply for gasoline and ethanol. In general, the optimal mandate, $\overline{E}(t)$ will result in a price of fuel that satisfies (see section 5 in the Appendix)

$$P_G\left(t,\overline{E}(t)\right)+t<P_F\left(t,\overline{E}(t)\right)<P_G\left(t,\overline{E}(t)\right)+t^*. \tag{15}$$

If we consider lowering the tax from the optimal fuel tax-mandate combination, the direction of the change in the optimal response mandate (the mandate that maximizes welfare given a fuel tax) will be positive if we are at the optimal fuel tax-mandate combination (see the derivation in section 5 of the Appendix)

$$\left(P_G-P_E+(1-\phi)t^M\right)>\left(\frac{\eta_G}{\eta_F}P_F-P_G\right)\frac{D_F}{\overline{E}\eta_G}. \tag{16}$$

where η_G is the supply elasticity for gasoline and η_F is the demand elasticity for fuel. Both the left hand and right hand side of (16) must be negative. Thus, decreasing the optimal response mandate is more likely to be higher than under the first best scenario if ethanol consumption under the first best is relatively small in relation to total fuel consumption, or if both the supply elasticity for gasoline and the demand elasticity for fuel are low. This would appear to typify the current market for fuel, gasoline and ethanol. The conditions in (16) are very similar to that required for an increase in the ethanol mandate to increase the price of fuel (see de Gorter and Just 2008a). Intuitively, if ethanol is a large portion of fuel consumption, increasing the mandate will necessitate a higher percentage decline in gasoline consumption. This larger percentage decline in gasoline consumption creates a much larger percentage decrease in the price of gasoline—potentially leading to a decline in total fuel price that will exacerbate the externalities from consumption of both fuels. However, externalities may increase even if the price of fuel increases with the mandate. Hence the conditions in (16) are slightly more restrictive than those found by de Gorter and Just (2008a).

The intuition for why a mandate needs to be increased with a sub-optimal fuel tax is depicted in Figure 3. As in Figures 1 and 2, we simplify by assuming CO_2e emissions for gasoline only ($\xi_E = 0$) and ignore the external costs due to miles traveled ($\tau_2 = 0$). Consider first the outcome with an optimal fuel tax only ($t^* = \tau_1 \xi_G$). Fuel consumption declines to F_1 with a fuel price of P_{F1} and again, because of the *volumetric* fuel tax, ethanol prices decline to P_{E1}. Gasoline consumption is given by G_1 ($= F_1 - E_1$).

Now consider no fuel tax and the optimal mandate becomes $\bar{E}^*$ and the corresponding fuel price is P_{F2} ($< P_{F1}$). Total fuel consumption is now F_2 and gasoline consumption is G_2. Notice that the level of ethanol production is now higher than $\bar{E}$ in Figure 2, the case of the optimal fuel tax-mandate combination. Ethanol prices P_{E^*} are also now higher. That is because a mandate is a tax on gasoline and a subsidy on ethanol production. It pays to overproduce ethanol with no fuel tax because a mandate compensates for the sub-optimal fuel tax (unlike with a tax credit shown earlier – the lower the fuel tax, the lower the optimal tax credit). However, the optimal fuel tax cannot be achieved indirectly with a mandate alone because of the overproduction of the higher cost ethanol.

As Table 2 displays, under a suboptimal fuel tax, the optimal mandate will increase, while the optimal tax credit will decrease. The increase in the optimal mandate implies greater ethanol consumption than under the first best scenario. Alternatively, the lower tax credit implies less ethanol consumption than under the first best policy.

Compared to a tax credit with a suboptimal fuel tax, a mandate is always superior so long as $t_E^* < \phi t^*$, the condition for the optimal tax credit in the first best scenario to be positive (see the derivation in section 6 of the Appendix). The greater the elasticity of gasoline supply, the greater the advantage of the ethanol mandate over the tax credit in mitigating the suboptimal gasoline tax. Similarly an inelastic demand curve will reduce the gasoline price response of a tax credit also leading to a larger advantage of the mandate over the tax credit (see also section 6 of the Appendix).

Without a tax credit, the optimal fuel tax is such that $t^* > t > t_E^*/\phi$ (see section 2 in the Appendix). Thus, in this case, the optimal tax must fall between the optimal tax on ethanol and the optimal tax on gasoline. The optimal fuel tax with a mandate t^M draws closer to t^* as the supply elasticity of gasoline increases relative to the supply elasticity of ethanol.

6. What if a Tax Credit is added alongside a Binding Mandate?

If the tax credit determines ethanol market prices, then the mandate is dormant. However, the reverse is not true. If a mandate is binding, then the tax credit is subsidizing gasoline consumption instead (on its own, a tax credit subsidizes ethanol consumption only). The reason for this perverse effect of the tax credit subsidizing gasoline consumption instead with a binding mandate can be explained as follows. With a binding mandate, the tax credit fails to provide any incentive to increase production of ethanol. Rather, the only way to take advantage of the subsidy is to reduce the price of the fuel (a blend of gasoline and ethanol) to compete for sales. But, if the price of fuel declines resulting in more fuel, this added fuel must be in the form of gasoline, given the binding mandate for ethanol (see de Gorter and Just 2007, 2008b, 2009a and Lapan and Moschini 2009 for details).[20]

This incurs the costs to society of losing the primary welfare gain of reduced externalities with a mandate. As the tax credit approaches the value of the ethanol price premium due to the mandate, the benefits of the mandate are dissipated. If the tax credit is equal to the ethanol price premium due to the mandate and oil prices are endogenous, then the tax credit reverses the primary welfare gain of reduced externalities of the mandate and more – it cannibalizes part of the fuel tax as well. For a formal derivation, see de Gorter and Just 2008a and Lapan and Moschini. And if the mandate alone increases CO_2e emissions and miles traveled, then the tax credit in this situation just make things worse. So using tax credits with mandates in place contradicts the new energy bill's stated objectives of reducing dependency on oil, improving the environment and enhancing rural prosperity. This result is independent of the CO_2e emissions measures associated with indirect land use and life-cycle accounting that is currently in the forefront of the public debate over biofuels.

To make matters worse, production subsidies for corn and ethanol may subsidize gasoline consumption when there is a binding mandate. The reasoning is similar to that of adding a tax credit to a mandate as discussed earlier. Unlike with a tax credit, however, a subsidy for corn and/or ethanol results in a lower ethanol wholesale price. With production subsidies for corn and ethanol, even though the market price of ethanol declines, ethanol production (and consumption) remains constant because it is determined by the mandate.[21]

This result is also important because renewable electricity faces similar policy combinations with consumption mandates (called 'renewable portfolio standards'), tax credits (called 'tax exemptions'), production subsidies (called 'producer tax credits') and subsidies for biomass production (e.g., for switch grass used in co-firing coal plants) (Fischer and Newell). It is also important to note that even if the mandate is not binding, it otherwise could be and so represents the true opportunity cost of tax credits and production subsidies that subsidize oil consumption (Hahn and Cecot).

7. Interactions with the fiscal system

So far the analysis ignores interactions between biofuel policies and the broader fiscal system. There is an important literature in environmental economics where rankings of alternative environmental policy instruments can be heavily dependent on their impact on government budget revenues and the size of the tax base (see Goulder, Parry and Burtraw 1997; Goulder et al. 1999; and also contributions in this volume by Parry, Williams and Goulder). So too the possible rankings of a biofuel mandate *versus* a tax credit can be reversed if fiscal interaction effects are taken into account.

Table 3 summarizes the fiscal interaction effects when comparing a mandate to a tax credit under several different scenarios. The first column summarizes our results earlier that, in terms of social welfare when fiscal interaction effects are ignored, social welfare is the same with the optimal fuel tax-biofuel policy combinations but that the mandate dominates in the other two cases.

The first row of Table 3 confirms our earlier results that the two optimal policy combinations are identical in every respect, including fiscal interaction effects. As shown in section 4 of the Appendix, the two policies generate identical levels of net tax revenue (income from fuel tax minus the expenditure on the tax credit). As well, all consumer and producer prices, consumption levels and production levels are identical. So there are no differences between a mandate and a tax credit due to fiscal interactions if these biofuel policies are evaluated with the individual social optimum fuel tax combination.

Even though a mandate does not involve taxpayer expenditures (unlike a tax credit), in theory a mandate can still result in lower net government budget revenues because of reduced tax revenues with the reduced fuel consumption. This possibility is shown in Figure 4 where it is assumed that the tax credit equals the fuel tax and the supply curve for gasoline is flat. In this scenario, if fuel demand is more elastic than ethanol supply, a mandate results in lower tax revenues (area *c* + *d* is greater than area *a* + *b*). But empirically the fuel demand is more inelastic than ethanol supply. Furthermore, the tax credit exceeds the fuel tax, making it less likely a mandate involves more tax revenues compared to a tax credit for the same ethanol quantity. Lastly, removing the assumption of a perfectly elastic gasoline supply further widens the superiority of a mandate in saving tax costs.[22]

However, the benefits in tax payer savings depend upon how the revenues are used and on how fuel prices are affected (the latter impacting the size of the tax base). As shown in the last column of Table 3, fuel prices are lower with a tax credit compared to a mandate with the same ethanol quantity in the case of a sub-optimal fuel tax. This reduces the tax base and can offset the benefits of lower tax costs. In the case of the fuel market, Parry (this volume) argues it is more likely that the benefits of reduced tax costs dominate.

8. Empirical Simulations

We calibrate a simple stylized model of the U.S. gasoline and ethanol market for the years 2007, 2015 and 2022 to determine the potential significance of the social deadweight costs due to ethanol mandates and tax credits. The assumed values of key parameters are summarized in Table 4. Life-cycle emissions are taken from the California Air Resources Board recent ruling on California's 'low carbon fuel standard' where ethanol is assumed to emit 80 percent of that from gasoline, based on our discussion earlier. The assumed values for the price of CO_2e, oil dependence, traffic congestion, local air pollution and accidents are taken from Parry (this volume). The efficiency gain per dollar of revenue recycled is taken from Parry (see his Figure 5 in this volume). The fuel tax, fuel demand elasticity, response from improved fuel economy and initial miles per gallon are taken from Parry (this volume).

The supply curve for ethanol is defined as the horizontal difference between the supply of corn and the demand for non-ethanol corn. Thus, the elasticity of ethanol supply is given by $\eta_E^S = \eta_C^S S_C / S_C^E - \eta_{NE}^D S_C^{NE} / S_C^E$, where η_C^S is the supply elasticity for corn, η_{NE}^D is the demand elasticity for non-ethanol corn (domestic and export sales), S_C is the production of corn, S_C^E is the corn used as an input to ethanol production, and S_C^{NE} is corn used for non-ethanol purposes. Because ethanol's share of total corn production is expected to decline and bottom out in 2015 (Babcock 2008b), we estimate different ethanol supply elasticities for each year. The elasticities assumed in the U.S. corn market are as follows: 0.2, -0.2 and -1.0 for supply, non-ethanol domestic demand and export demand, respectively.[23] Using observed or forecast quantities for the various years and the assumed parameter values; the estimated supply elasticity for ethanol are 4, 2 and 3 for 2007, 2015 and 2022, respectively.

The import supply elasticity for gasoline is derived from the negative of the formula used above for the ethanol supply curve, with assumed values of elasticities of domestic supply of gasoline, OPEC supply and excess demand for gasoline in the rest of the world taken from Leiby. The OPEC supply elasticity of 2.375 is the midpoint of the range given in Leiby.

The values for sensitivity analysis (price of CO_2e emissions, efficiency gain per dollar of recycling, response from improved fuel economy and initial miles per gallon) are taken from Parry (this volume). The market price for gasoline is \$2.00 per gallon in 2007 and is estimated to be \$2.50 per gallon in 2015 and 2022. The estimated market prices for ethanol, P_E, is equal to $\lambda(P_G + t) - t + t_c$ where λ is the ratio of miles per gallon of ethanol relative to gasoline and with an assumed value of 0.70, P_G is the price of gasoline, t denotes the volumetric fuel tax and t_c is the tax credit for ethanol (de Gorter and Just 2008b). The weighted average biofuel tax credit is

$0.570, $0.658 and $0.796 per gallon for 2007, 2015 and 2022, respectively.

The likelihood of the mandate binding depends on the level of the tax credit itself. If the tax credit is high enough to bind, the true social opportunity cost is still a mandate that could otherwise generate the same level of ethanol consumption. In the empirical analysis to follow, we use the level of ethanol generated by the tax credit in each year to analyze the tradeoffs between a tax credit, a mandate, or no policy at all. In other words, a mandate is set to reproduce ethanol production and prices that otherwise would occur with the observed tax credit.

The results of these simulations on changes in key market parameters are presented in Table 5 while welfare changes are given in Table 6. A negative value in Table 6 represents a social gain. The first set of results in Table 6 shows the effects of a tax credit alone. The only social benefits of a tax credit are in improved terms of trade in oil imports and reduced oil dependence. Theoretically CO_2e emissions can decline but are found empirically to increase. The efficiency gain per $ of recycling is assumed to be 30 cents (see Figure 5 in Parry, this volume). Others argue it may be zero (e.g., Kaplow) but Parry (this volume) cites literature that 30 cents on the $ is a more accurate estimate for parameters pertaining to the transportation fuel sector. Some argue instead that one should simply use the marginal costs of funds (Williams this volume?). This would imply a higher cost of a tax credit as inefficiencies could range from 35 cents per $ (mean of Browning) or even 70 cents to the $ (Feldstein). Overall, tax credits are estimated to have generated a $300 mil. improvement in social welfare in 2007 but net social losses of $1.1 and $1.5 bil. are predicted for 2015 and 2022, respectively.

The second set of results in Table 6 shows the effects of a mandate alone. Social benefits are substantial. Although not necessary in theory, gasoline market prices and total fuel consumption decline as do miles traveled and CO_2e emissions increase. The estimated market parameters are such that a mandate generates benefits ranging from \$2.5 bil. in 2007 to \$9.5 bil. in 2022.

The last set of results in Table 6 shows the effect of implementing a mandate instead of a tax credit to achieve the same level of ethanol consumption. This simulates the reverse of adding a tax credit to a binding mandate. Therefore, there are social benefits in all categories, with welfare gains of \$2.2, \$5.5 and \$11 bil. in 2007, 2015 and 2022, respectively. Note that the social costs of adding a tax credit to a mandate are greater than the benefits of a mandate alone (e.g., \$11 bil. *versus* \$9.5 bil. in 2022). This is because the tax credit cannibalizes all of the social benefits of a mandate and part of the fuel tax.

The last two rows of Table 6 provide some sensitivity analysis. The forward looking case for vehicle miles traveled allows for a higher response in miles traveled to fuel price changes because of fuel economy regulations (Parry this volume). This increases the costs of a tax credit and benefits of a mandate somewhat. Some (Williams this volume?) argue fuel economy regulations make miles traveled completely sensitive to fuel price changes (i.e., the response parameter β should equal one). Row [11] in Table 6 presents the effects of assuming the price of CO_2 is \$80 per ton as in Stern (2007).

Overall, the results in Table 6 show how the change in terms of trade in oil imports and fiscal interaction effects are significantly larger than the other potential sources of deadweight costs we have analyzed. Even though gasoline prices do not change much, the sheer volume of oil imports generates social benefits that are relatively large. Likewise for fiscal interaction effects although the range of Best/worst given at the bottom of Table 6 includes the possibility that there are no benefits of a mandate in saving taxpayer monies (revenues are not recycled).

Part of the reason for the lower values of cost and benefits associated with oil dependence and CO_2e emissions is allowing for leakages. Although oil consumption declines in the transportation sector, the latter accounts for only 45 percent of total domestic oil consumption so part of the gains are offset by increased consumption of oil in other parts of the domestic economy. The same occurs for CO_2e emissions except we also allow for international leakages (world oil price declines so CO_2e emissions increase in the rest of the world). Furthermore, we assume ethanol production only reduces oil consumption 20 percent because of life-cycle accounting. For these three reasons, the values for oil dependence and CO_2e emissions are dampened significantly.

Finally, it should be emphasized that the estimates of deadweight cost triangles are for fuel demand and domestic oil production only. We ignore the deadweight costs in the domestic ethanol and corn sectors because these distortions are caused by policies that discriminate against trade. Mandates and tax credits by themselves do not discriminate against trade. We hold ethanol production constant in each of our simulations. To estimate the social costs of not having any domestic ethanol production requires analysis as in Lasco and Khanna and de Gorter and Tsur.

9. Concluding Remarks

There is an emerging literature on the welfare economics of biofuel policies that shows a mandate is superior to a consumption subsidy. This paper builds on this literature by assessing three important pre-existing constraints: a sub-optimal fuel tax, a binding ethanol mandate, and wage tax. In each case, an ethanol mandate is found to be even more superior to an ethanol consumption subsidy. In both the theoretical and empirical analysis, we abstract from the welfare effects of policies that discriminate against international trade and so ignore deadweight costs in the U.S. ethanol production and corn sectors. Our focus instead has been in comparing a mandate to a consumption subsidy, holding ethanol consumption fixed in each case.

We present numerical estimates for the first time comparing the effects of a mandate *versus* a consumption subsidy and also the relative importance of the three second best constraints. Our empirical findings show the welfare superiority of a mandate over a consumption subsidy can be quite large with each of the pre-existing distortions.

It is particularly important to highlight the effect of adding a consumption subsidy to a mandate; the benefits of a mandate are wiped out and more because subsidies cannibalize the positive effects of a mandate and fuel tax, thereby contradicting the objectives of renewable energy policy. Therefore, hybrid instruments that combine policies can cause severe adverse policy interaction effects. Not only do most countries use these two policies in concert, these same combinations of policies have also been adopted worldwide for renewable electricity. With the growing momentum for expanded renewable energy mandates and subsidies of various forms, the choice of policy instrument made by policy makers is therefore crucial.

Although the effects of each policy and their interactions are shown to be complex, once understood, a set of relatively clear policy implications emerge. This clear picture on biofuel policies is atypical in the debate comparing alternative policy instruments in the environmental economics literature where the choice of environmental policy instrument (e.g., a carbon tax *versus* cap and trade) is normally deemed as inherently difficult because of competing criteria (see Goulder and Parry for a discussion). See also contributions in this volume by Weisbach and Kaplow on the functional equivalence between a price *versus* quantity based environmental policy. The current debate on appropriate environmental policy for global climate change is often about whether the use of a carrot or a stick, or both is appropriate. Stern (2009, p. 28) argues, for example, that we need both: “No doubt, a combination of tax policies and quotas should be used.” This appears not to hold in the case of a biofuel mandate *versus* a subsidy. Clearly, renewable energy policies are proving to be unique as the stick of a mandate is better than the carrot of a subsidy, and governments should *never* use both.

These conclusions are extremely relevant to the current policy thrust behind recent energy and farm legislation, the stimulus bill, and the proposed climate change bill to develop new clean renewable energy sources by expanding the smorgasbord of subsidies and mandates. The increased resolve of the U.S. government to promote alternative energy sources and combat climate change has also led to a bevy of new policy proposals including ‘cap and trade’, carbon ‘offsets’, ‘green’ tariffs and producer ‘rebates’. These will add to the several layers of incentives and regulations of current policies, themselves combined without being coordinated, and not well understood to date. This means there will be even more complex economic interactions between biofuel, environmental and energy policies — a priority for future research.

Endnotes

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[1] Rising oil prices, dwindling oil supplies, instability in both oil prices and sources of supply (political instability in Middle East and other developing country exporters), and the desire to diversify both energy use and energy sources are the primary concerns under “energy security”.

[2] Negative externalities associated with traffic congestion and traffic related accidents will be shown to be more important than other environmental effects.

[3] Biofuel policy and farm income/rural development are a double edged sword: the tax on livestock and poultry sectors may reduce economic growth in rural areas net of the economic growth due to biofuel production.

[4] For a survey on the welfare economics of biofuel policies, see de Gorter and Just 2010.

[5] For a detailed argument, see de Gorter and Just 2009c.

[6] The 20 percent reduction is based on the Farrell et al. study that used a meta-analysis to calculate a point estimate for CO_2e emissions for the production of U.S. corn-ethanol. In response, the United States has tabled a sustainability standard that required ethanol production to reduce CO_2e relative to gasoline by 20 percent.

[7] De Gorter and Tsur analyze ethanol production as an investment project where the investment costs consist of the (mostly upfront) costs of CO_2 emissions from land converted from forests and grasslands into ethanol production plus the present value of the flow of (annual) foregone net sequestration from the converted land (i.e., the forgone sequestration under the original land use minus the actual sequestration under the biofuel crop). The benefit is the present value of the net flow of avoided emissions due to the displacement of gasoline. A genuine cost-benefit test must convert tons of CO_2 emitted at different times into a dollar value at a particular (reference) point of time. This requires the (shadow) price of CO_2 emissions and some form of discounting. How emissions are valued over time plays an important role in estimating the potential benefits of ethanol production in reducing CO_2 emissions.

[8] The life-cycling approach in welfare analysis is also employed by Holland, Hughes and Knittel and Lasco and Khanna.

[9] Ethanol’s contribution to local air quality is also controversial. Using life-cycle analysis, Jacobson calls it a ‘wash” but others argue ethanol is worse, especially corn-ethanol; see Hill et al. and Hahn and Cecot.

[10] In other countries, the consumption subsidy for biofuels is a tax exemption at the fuel pump while in the United States, it takes the form of a blender’s subsidy. In theory, the two methods have identical effects except for specific cases in international trade (de Gorter, Just and Kliauga; Drabik, de Gorter and Just).

[11] Data are from Koplow and excludes his estimates of ‘market price support’ and tax exempt benefits. If these are included, then Koplow estimates total transfers to the U.S. ethanol sector from consumers and taxpayers to exceed $1 *trillion* from 2008 to 2030.

[12] Holland, Hughes and Knittel get the same result in analyzing California’s ‘low carbon fuel standard’, which is basically the same as a blend mandate.

[13] The resulting impact on emissions will depend also on the relative price responsiveness of fuel demand and gasoline supply; with a greater relative price elasticity of demand increasing emissions under an ethanol subsidy (see de Gorter and Just 2008a; Lapan and Moschini).

[14] For full explanation of these results, see the discussion in de Gorter and Just (2008a; 2009b).

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[15] As discussed in the previous section, $\xi_E = 0, 0.8 \cdot \xi_G$ or is > ξ_G. If the latter, then the tax credit in the analysis to follow is negative.

[16] The ethanol price P_{E0} equals the gasoline price as all units are in gasoline equivalents. If the units were in gallons, then the market price of ethanol P_{E0} is less than P_G because consumers demand miles traveled. The per gallon ethanol price in that case would equal P_G / ϕ.

[17] In dollars per gallon, the market price of ethanol P_{E1} would decline by $(1 - 1/\phi)t^*$ because consumers demand miles.

[18] This result holds regardless if fuel consumption increases with the mandate because even though the mandate subsidizes fuel consumers, it still taxes gasoline consumers (and acts as a monopsony against gasoline suppliers).

[19] The analysis here is opposite for the case of Britain which has a super-optimal fuel tax (Parry and Small).

[20] For a simple, short and intuitive explanation, see de Gorter and Just (2008d).

[21] Production of corn declines with an ethanol production subsidy but increases with a corn production subsidy. For the same per unit subsidy, the ethanol price declines more with an ethanol production subsidy than a corn subsidy. In both cases, the consumption of non-ethanol corn increases.

[22] To understand this latter point, consider the case of a vertical gasoline supply curve. Total fuel consumption is the same with a mandate and tax credit. Hence, there are no fuel tax revenues lost so the more inelastic the gasoline supply curve, *ceteris paribus*, the less likely the mandate foregoes fuel tax revenues.

[23] These parameters are well within the range of a vast literature in agricultural economics that report estimates of various supply and demand elasticities.

Figure 1: Optimal tax credit and fuel tax for CO_2 emissions: Case of $\xi_E = \tau_2 = 0$

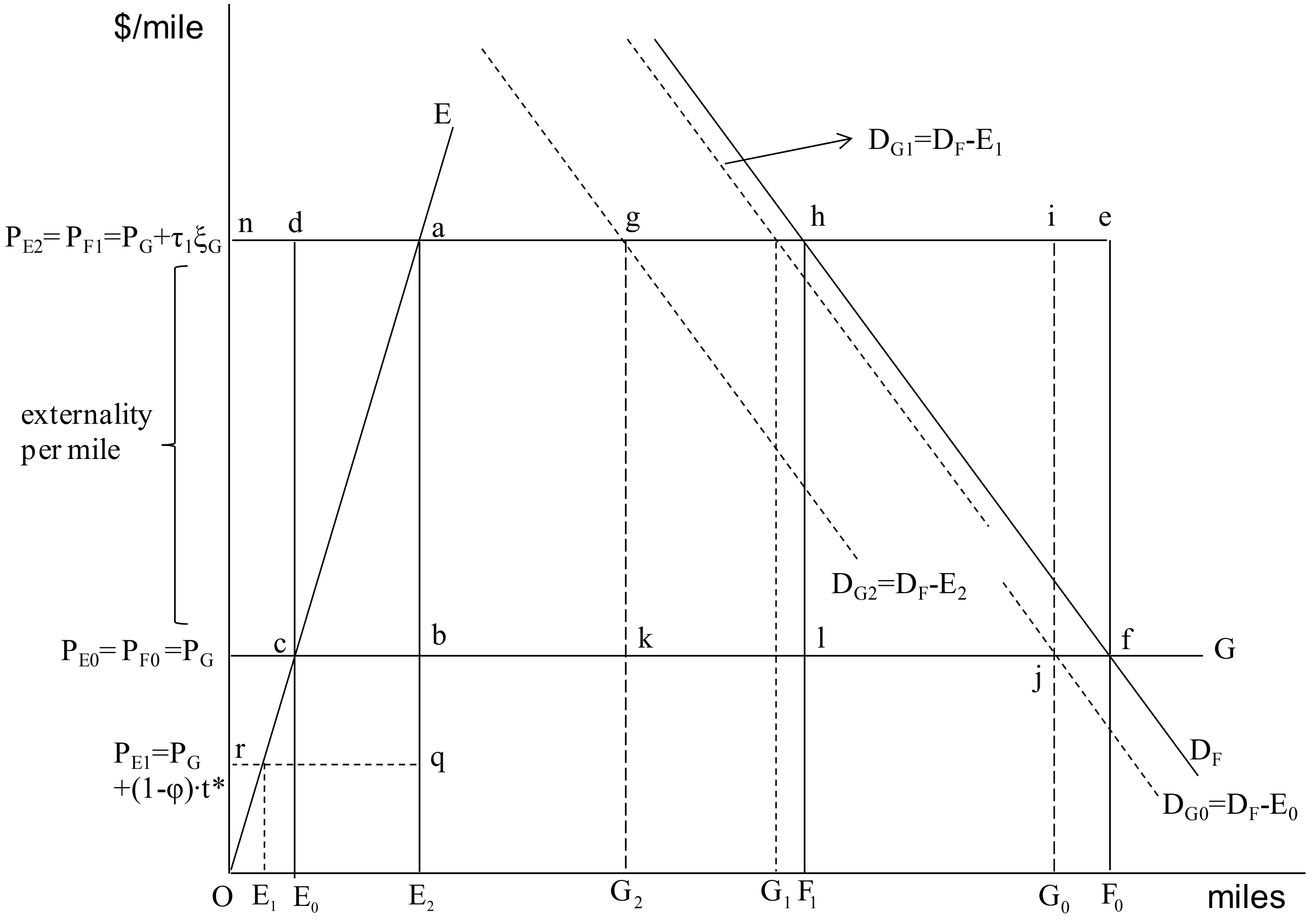

Figure 2: Optimal combination of an ethanol mandate and fuel tax for CO_2 emissions: Case of $\xi_E = \tau_2 = 0$

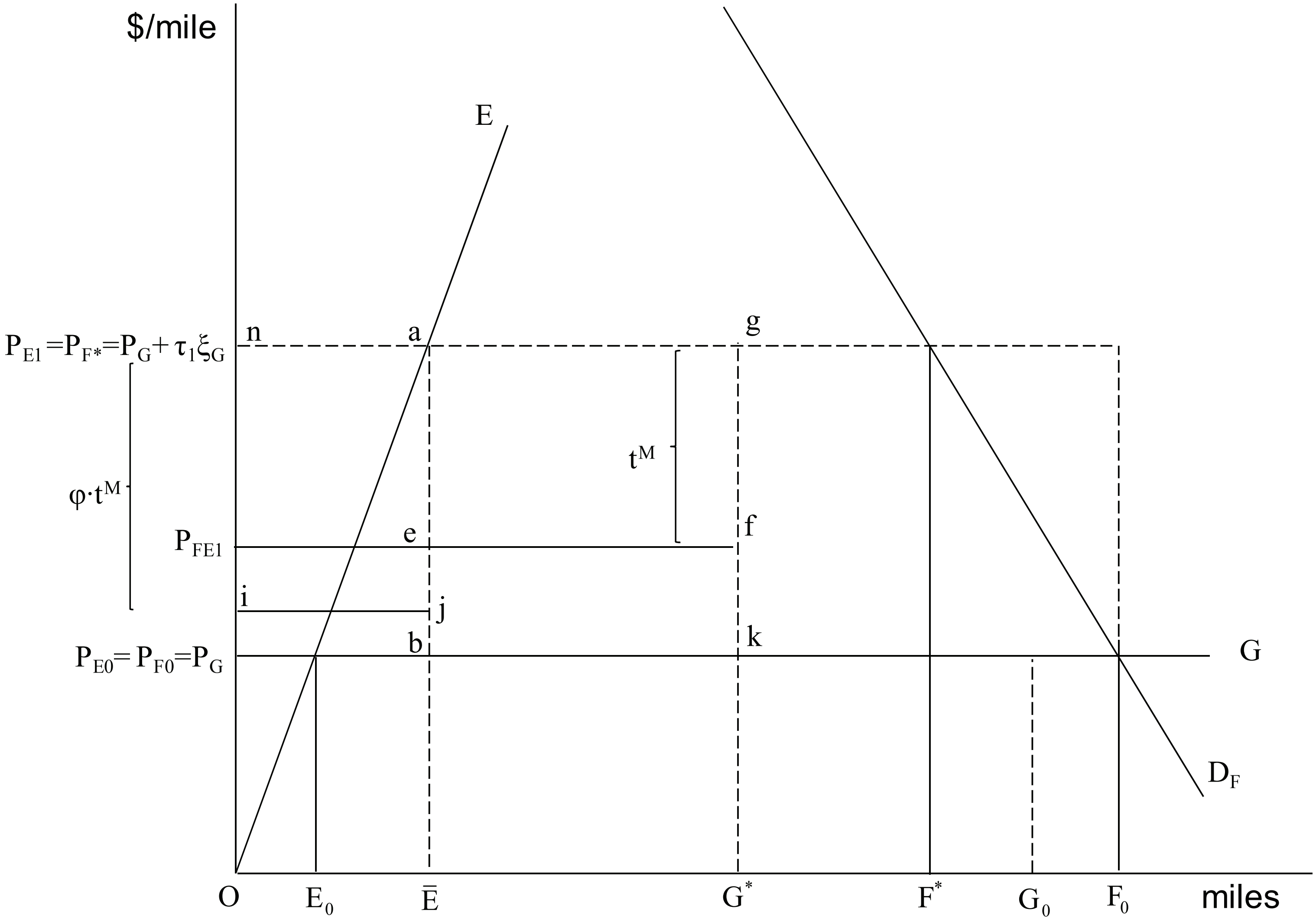

Figure 3: Optimal ethanol mandate compared to optimal fuel tax for CO_2 emissions: Case of $\xi_E = \tau_2 = 0$

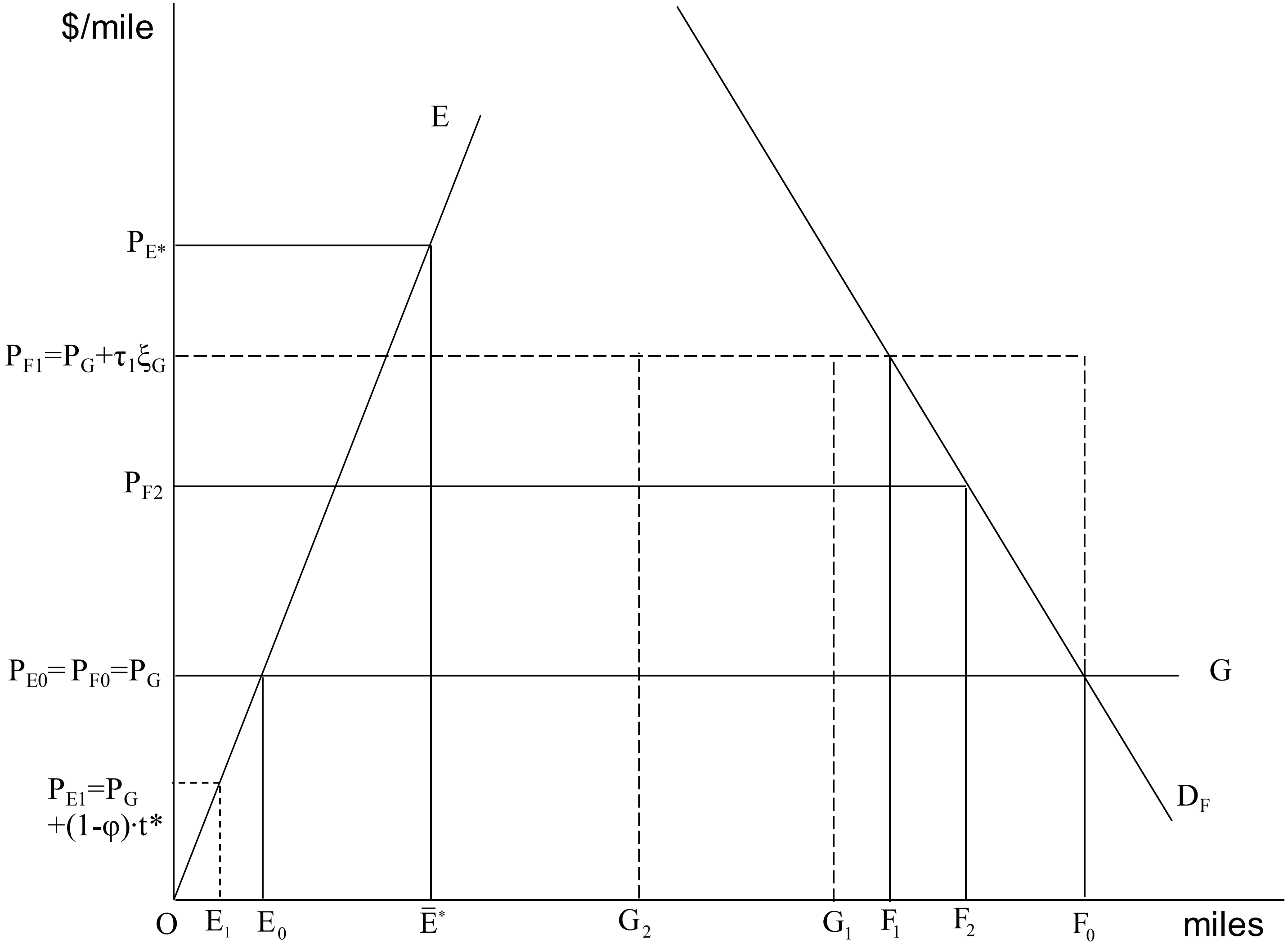

Figure 4: Conditions under which a mandate results in higher taxpayer costs

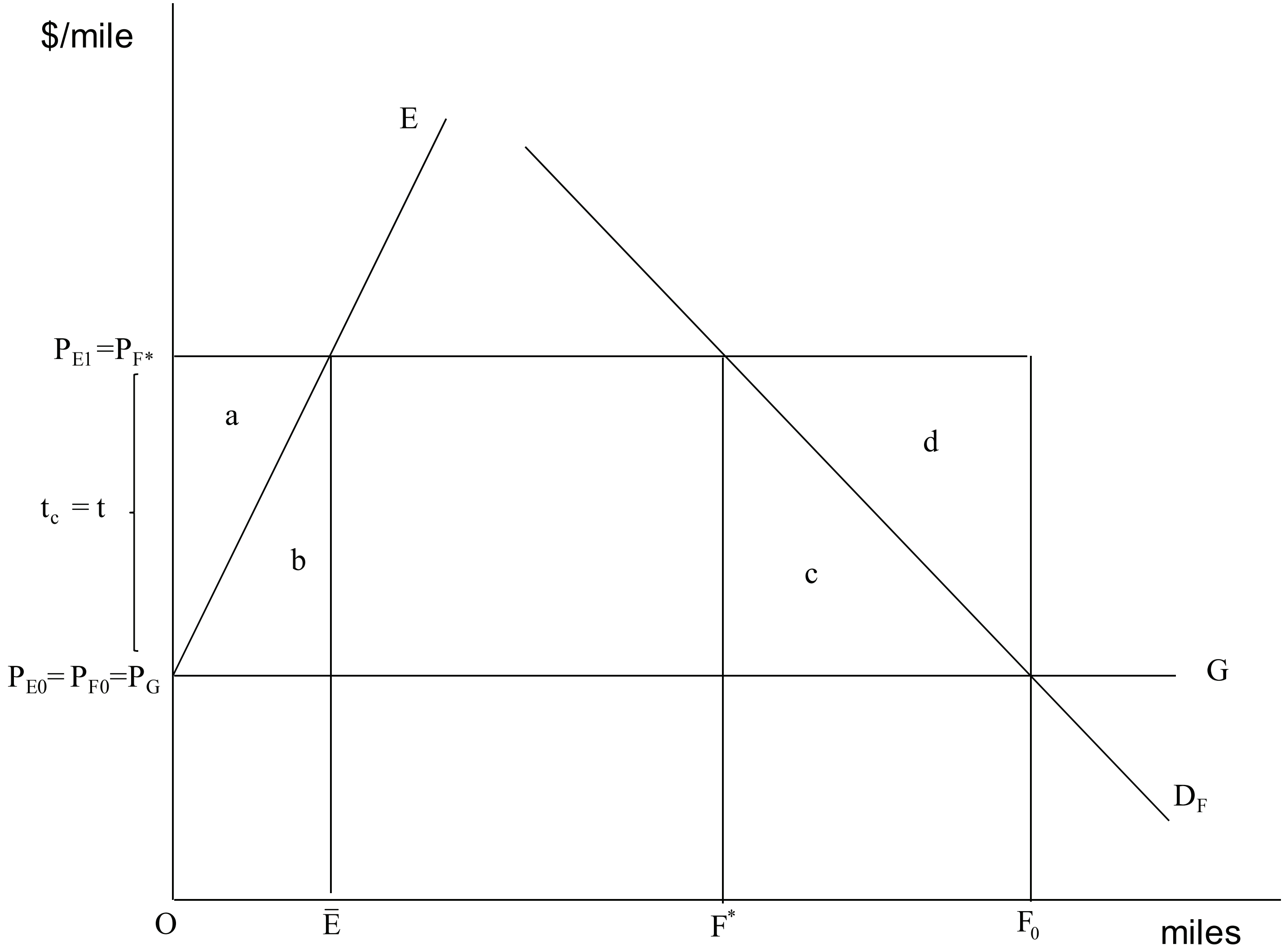

Table 1: Effects of a Mandate vs. a Tax Credit on Externalities

	Oil dependence	**Miles traveled**	**CO_2e emissions**
Mandate	decrease	increase or decrease	increase or decrease
Tax credit	decrease	increase	increase or decrease
Mandate vs. tax credit (same ethanol consumption)	lower with mandate		

Source: de Gorter and Just (2008a) and Lapan and Moschini.

Table 2. Optimal Mandate and Tax Credit

	Optimal Fuel Tax and Ethanol Policy Combination	**Suboptimal Fuel Tax**
Mandate	$\bar{E} = E\left(P_G\left(t^*, t_c^*\right) + \left(1-\phi\right)t^* + t_c^*\right)$ $t < t^*$	$\bar{E} > E\left(P_G\left(t^*, t_c^*\right) + \left(1-\phi\right)t^* + t_c^*\right)$
Tax Credit	$t_c = \phi t^* - t_E^*$ $t = t^*$	$t_c < \phi t^* - t_E^*$

Source: Derived in Appendix

Table 3: Effect of Mandates vs. Tax Credits on Goverment Tax Revenues and Fuel Prices

	Social welfare	**Government tax revenues**	**Fuel prices**
Optimal Fuel Tax/ Ethanol policy combinations	same	same	same
Sub-optimal fuel tax (ethanol cons. same)	higher with mandate*	higher with mandate if (a) ethanol supply more elastic than fuel demand; (b) tax credit higher than fuel tax; and (c) more inelastic gasoline supply curve	lower with tax credit
Sub-optimal fuel tax** (max. social welfare)	higher with mandate*		ambiguous***

* Assuming no interactions with the fiscal system.

** Note that there now is a differential impact on ethanol and hence corn prices and farm subsidy tax costs.

*** Ambiguous only if fuel prices decline with an increase in the mandate; otherwise, fuel prices lower with a tax credit.

Source: calculated.

Table 4: Parameters used in empirical simulations

Benchmark case	
Externalities	
CO_2e emissions life-cycle	
Lbs per gallon gasoline	25.57
Lbs per gallon ethanol	0.8·25.57
Price of CO_2e emissions ($/ton Nordhaus)	10
Oil dependence (¢/gal.)	10
Traffic congestion (¢/mile)	52
Local air pollution (¢/mile)	12
Accidents (¢/mile)	41
Efficiency gain per $ of recyling (¢)	30
Parameters	
Fuel tax (¢/gal.)	41
Fuel demand elasticity	-0.4
Response from improved fuel economy	$\beta = 0.5$
Initial miles per gallon	22.3
Ethanol supply elasticity	4,2,3 (2007; 2015; 2022)
Domestic oil supply elasticity	0.2
OPEC supply elasticity	2.375
Excess demand elasticity for oil in rest of world	-0.86
Sensitivity analysis	
Price of CO_2e emissions ($/ton Stern)	80
Efficiency gain per $ of recyling (¢)	0
Response from improved fuel economy	$\beta = 0.67$
Initial miles per gallon	30.4

Source: Parry (this volume); Leiby; estimated.

Table 5: Market Effects of a Tax Credit *versus* a Mandate

		Tax credit vs. no policy			Mandate vs. no policy			Mandate instead of tax credit*		
	Changes in…	**2007**	**2015**	**2022**	**2007**	**2015**	**2022**	**2007**	**2015**	**2022**
[1]	Gasoline price (¢/gal.)	-0.0081	-0.0126	-0.0269	-0.0093	-0.0155	-0.0323	-0.0012	-0.0029	-0.0054
[2]	Fuel price (¢/gal.)	-0.0081	-0.0126	-0.0269	0.0248	0.0633	0.1119	0.0329	0.0758	0.1388
[3]	Ethanol price (¢/gal.)	0.56	0.65	0.78	0.56	0.65	0.78	0	0	0
[4]	Ethanol consumption (bil. gals)	7.7	10.5	24.7	7.7	10.5	24.7	0	0	0
[5]	Fuel consumption (bil. gals)	0.19	0.26	0.62	-0.58	-1.37	-2.68	-0.76	-1.63	-3.30
[6]	World oil consumption (bil. gals)	-4.0	-5.5	-12.9	-4.6	-6.8	-15.5	-0.6	-1.3	-2.6
[7]	Oil imports (bil. gals)	-4.7	-6.5	-15.5	-5.4	-8.0	-18.5	-0.7	-1.5	-3.1
[8]	Taxpayer costs ($ bil.)	4.7	12.8	25.4	0.3	0.7	1.4	-4.4	-12.1	-24.0

* Ethanol prices and consumption are held equal to that with a tax credit (the inverse of adding a tax credit to a mandate).

Source: calculated.

Table 6: Social Costs and Benefits of a Tax Credit *versus* a Mandate

		Tax credit vs. no policy			Mandate vs. no policy			Mandate instead of tax credit*		
	Changes in…	**2007**	**2015**	**2022**	**2007**	**2015**	**2022**	**2007**	**2015**	**2022**
	Social deadweight costs ($ bil.)									
[1]	International terms of trade	-1.5	-2.3	-5.1	-1.7	-2.9	-6.2	-0.2	-0.5	-1.0
[2]	Oil dependency	-0.40	-0.58	-1.48	-0.47	-0.73	-1.79	-0.07	-0.15	-0.31
[3]	CO_2 emissions ($10/ton Nordhaus)	0.03	0.05	0.11	-0.04	-0.11	-0.21	-0.08	-0.16	-0.33
[4]	Efficiency gain per $ of recycling (30¢)	1.4	3.8	7.6	0.09	0.20	0.41	-1.3	-3.6	-7.2
	Vehicle miles traveled (VMT)									
[5]	Local air pollution	0.02	0.03	0.07	-0.07	-0.16	-0.32	-0.09	-0.20	-0.40
[6]	Traffic congestion	0.10	0.14	0.32	-0.30	-0.71	-1.39	-0.40	-0.85	-1.72
[7]	Traffic accidents	0.08	0.11	0.26	-0.24	-0.56	-1.10	-0.31	-0.67	-1.35
[8]	Deadweight cost triangles**	0.001	0.002	0.012	0.014	0.064	0.241	0.013	0.062	0.229
[9]	*Total****	*-0.3*	*1.1*	*1.5*	*-2.5*	*-4.4*	*-9.5*	*-2.2*	*-5.5*	*-11.0*
[10]	Forward looking VMT (higher fuel economy)	0.11	0.16	0.38	-0.35	-0.83	-1.63	-0.47	-0.99	-2.01
[11]	CO_2 emissions (life-cycle; $80/ton Stern)	0.28	0.39	0.92	-0.33	-0.90	-1.69	-0.61	-1.29	-2.61
	Range of Best/worst****	-1.7/0	-2.7/1.5	-6.1/2.4	-2.8/-2.5	-5.3/-4.4	-11.2/-9.5	-2.8/-0.9	-6.8/-1.9	-13.6/-3.8

* Ethanol prices and consumption are held equal to that with a tax credit (the inverse of adding a tax credit to a mandate).

** Of domestic gasoline supply and fuel demand only.

*** Excludes costs of traffic accidents as that offsets current fuel tax.

**** Includes possibility of no efficiency gain per $ of recycling in Row [4]

Source: calculated.

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Appendix

1. The Optimal Fuel Tax and Ethanol Tax Credit Combination

Finding the optimal fuel tax and ethanol tax credit involves solving

$$\text{(A.1)} \qquad \max_{t,t_c} V\left(P_F, Y, X\right)$$

subject to

$$\text{(A.2)} \qquad P_F = P_G + t\,,$$

$$\text{(A.3)} \qquad P_E = P_G + \left(1-\phi\right)t + t_c\,,$$

$$\text{(A.4)} \qquad Y = \pi_E\left(P_E\right) + \pi_G\left(P_G\right) + tG\left(P_G\right) + \left(\phi t - t_c\right)E\left(P_E\right),$$

$$\text{(A.5)} \qquad X = \tau_1\left[\xi_E E\left(P_E\right) + \xi_G G\left(P_G\right)\right] + \tau_2\left[E\left(P_E\right) + G\left(P_G\right)\right],$$

where P_G is a function of t and t_c implicitly defined by the market equilibrium condition

$$\text{(A.6)} \qquad D_F\left(P_G + t\right) = E\left(P_G + \left(1-\phi\right)t + t_c\right) + G\left(P_G\right).$$

Equations (A.2) through (A.5) can readily be substituted into (A.1). Thus, the first order conditions are given by

$$\begin{aligned} &V_P \cdot \left(\frac{dP_G}{dt} + 1\right) \\ \text{(A.7)} &+ V_Y \cdot \left(\left(\frac{dP_G}{dt} + 1 - \phi\right)\pi_E' + \frac{dP_G}{dt}\pi_G' + G + t\frac{dP_G}{dt}G' + \phi E + \left(\phi t - t_c\right)\left(\frac{dP_G}{dt} + 1 - \phi\right)E'\right) \qquad \text{and} \\ &+ V_X \cdot \left(\tau_1\left[\xi_E\left(\frac{dP_G}{dt} + 1 - \phi\right)E' + \xi_G\frac{dP_G}{dt}G'\right] + \tau_2\left[\left(\frac{dP_G}{dt} + 1 - \phi\right)E' + \frac{dP_G}{dt}G'\right]\right) = 0 \end{aligned}$$

(A.8)
$$V_P \cdot \frac{dP_G}{dt_c} + V_Y \cdot \left(\left(\frac{dP_G}{dt_c} + 1 \right) \pi_E ' + \frac{dP_G}{dt_c} \pi_G ' + t \frac{dP_G}{dt_c} G' - E + \left(\phi t - t_c \right) \left(\frac{dP_G}{dt_c} + 1 \right) E' \right)$$
$$+ V_X \cdot \left(\tau_1 \left[\xi_E \left(\frac{dP_G}{dt_c} + 1 \right) E' + \xi_G \frac{dP_G}{dt_c} G' \right] + \tau_2 \left[\left(\frac{dP_G}{dt_c} + 1 \right) E' + \frac{dP_G}{dt_c} G' \right] \right) = 0$$

Here, a prime denotes a derivative with respect to a sole argument, and a subscript denotes a derivative with respect to the noted argument. By substituting elasticity equivalents

(A.9)
$$E' = \frac{\eta_E E}{P_E} = \frac{\eta_E E}{\left(P_G + (1-\phi) t + t_c \right)},$$

(A.10)
$$G' = \frac{\eta_G G}{P_G},$$

into (A.7) and (A.8), recognizing that $\pi_E ' = E$ and $\pi_G ' = G$, by Hotelling's Lemma we obtain

(A.7′)
$$\left(\begin{array}{l} V_P + V_Y \left[E + G + t \frac{\eta_G G}{P_G} + \left(\phi t - t_c \right) \frac{\eta_E E}{\left(P_G + (1-\phi) t + t_c \right)} \right] \\ + V_X \left[\left(\tau_1 \xi_E + \tau_2 \right) \frac{\eta_E E}{\left(P_G + (1-\phi) t + t_c \right)} + \left(\tau_1 \xi_G + \tau_2 \right) \frac{\eta_G G}{P_G} \right] \end{array} \right) \frac{dP_G}{dt}$$
$$+ V_P + V_Y \left[(1-\phi) E + G + \phi E + \left(\phi t - t_c \right) \frac{(1-\phi) \eta_E E}{\left(P_G + (1-\phi) t + t_c \right)} \right]$$
$$+ V_X \left[\left(\tau_1 \xi_E + \tau_2 \right) \frac{(1-\phi) \eta_E E}{\left(P_G + (1-\phi) t + t_c \right)} \right] = 0$$

(A.8′)
$$\left(\begin{array}{l} V_P + V_Y \left[E + G + t \frac{\eta_G G}{P_G} + \left(\phi t - t_c \right) \frac{\eta_E E}{\left(P_G + (1-\phi) t + t_c \right)} \right] \\ + V_X \left[\left(\tau_1 \xi_E + \tau_2 \right) \frac{\eta_E E}{\left(P_G + (1-\phi) t + t_c \right)} + \left(\tau_1 \xi_G + \tau_2 \right) \frac{\eta_G G}{P_G} \right] \end{array} \right) \frac{dP_G}{dt_c}$$
$$+ V_Y \left(E - E + \left(\phi t - t_c \right) \frac{\eta_E E}{\left(P_G + (1-\phi) t + t_c \right)} \right)$$
$$+ V_X \left[\left(\tau_1 \xi_E + \tau_2 \right) \frac{\eta_E E}{\left(P_G + (1-\phi) t + t_c \right)} \right] = 0.$$

Because marginal external effects are measured in terms of monetary costs, $V_X / V_Y = -1$.

Dividing (A.7′) and (A.8′) by V_Y, recognizing that $V_P / V_Y = -D_F = -E - G$, we can rewrite (A.7′) and (A.8′) as

$$\text{(A.7}''\text{)}\quad \left[t - \left(\tau_1 \xi_G + \tau_2\right)\right] \frac{\eta_G G}{P_G} \frac{dP_G}{dt} + \left[\phi t - t_c - \left(\tau_1 \xi_E + \tau_2\right)\right] \frac{\eta_E E}{\left(P_G + (1-\phi)t + t_c\right)} \left(\frac{dP_G}{dt} + 1 - \phi\right) = 0.$$

$$\text{(A.8}''\text{)}\quad \left[t - \left(\tau_1 \xi_G + \tau_2\right)\right] \frac{\eta_G G}{P_G} \frac{dP_G}{dt_c} + \left[\phi t - t_c - \left(\tau_1 \xi_E + \tau_2\right)\right] \frac{\eta_E E}{\left(P_G + (1-\phi)t + t_c\right)} \left(\frac{dP_G}{dt_c} + 1\right) = 0.$$

Both first order conditions imply the similar relationships with the only difference being the policy instrument with which the price of gasoline is differentiated and the ϕ appearing in the last term of (A.7″). Totally differentiating (A.6), substituting $D_F{}' = \frac{\eta_F D_F}{P_F} = \frac{\eta_F D_F}{P_G + t} < 0$ and collecting terms we obtain

$$\text{(A.11)}\qquad \frac{dP_G}{dt} = -\frac{\left[\frac{\eta_F D_F}{P_G + t} - \frac{(1-\phi)\eta_E E}{\left(P_G + (1-\phi)t + t_c\right)}\right]}{\left[\frac{\eta_F D_F}{P_G + t} - \frac{\eta_E E}{\left(P_G + (1-\phi)t + t_c\right)} - \frac{\eta_G G}{P_G}\right]} < 0$$

and

$$\text{(A.12)}\qquad \frac{dP_G}{dt_c} = \frac{\frac{\eta_E E}{\left(P_G + (1-\phi)t + t_c\right)}}{\left[\frac{\eta_F D_F}{P_G + t} - \frac{\eta_E E}{\left(P_G + (1-\phi)t + t_c\right)} - \frac{\eta_G G}{P_G}\right]} < -1.$$

The numerators of the expressions in the inequalities (A.11) and (A.12) will not generally be equal implying that it is extremely unlikely that (A.7″) and (A.8″) could be satisfied unless the terms of (A.7″) and (A.8″) in square brackets are equal to zero.[1] Thus the optimal tax and tax credit combination, $t^* = \tau_1 \xi_G + \tau_2$ and $t_c{}^* = \phi t^* - t_E{}^* \; = \phi\left(\tau_1 \xi_G + \tau_2\right) - \left(\tau_1 \xi_E + \tau_2\right)$.

2. *Finding the Optimal Tax without a Tax Credit*

Finding the optimal tax with no tax credit involves solving

$$\text{(A.13)} \qquad \max_t V\left(P_F, Y, X\right)$$

subject to (A.2) through (A.5) with $t_c = 0$, with P_G now an implicit function of *t* defined by (A.6) again with $t_c = 0$. The resulting first order condition is (compare with A.7″)

$$\text{(A.7‴)} \quad \left[t - t^*\right]\frac{\eta_G G}{P_G}\frac{dP_G}{dt} + \left[\phi t - t_E{}^*\right]\frac{\eta_E E}{\left(P_G + (1-\phi)t + t_c\right)}\left(\frac{dP_G}{dt} + 1 + \phi\right) = 0,$$

where t^* is the optimal tax (which is equal to the marginal external cost of consuming gasoline) and $t_E{}^*$ is the marginal external cost of consuming ethanol. Totally differentiating (A.6) we find dP_G/dt to have the same formula as given in (A.9) except that now $t_c = 0$. From (A.9) we find

$$\text{(A.14)} \qquad 1 + \phi + \frac{dP_G}{dt} = \frac{\left[\phi\frac{\eta_F D_F}{P_G + t} - (\phi + 1)\frac{\eta_G G}{P_G}\right]}{\left[\frac{\eta_F D_F}{P_G + t} - \frac{\eta_E E}{\left(P_G + (1-\phi)t\right)} - \frac{\eta_G G}{P_G}\right]} > 0.$$

Also recall that $dP_G/dt < 0$. The optimal tax in this case must be between t^* and t_E/ϕ. To see this, first suppose that $t^* > t_E{}^*/\phi$. Evaluating the left hand side of (A.7‴) at $t = t_E{}^*/\phi$ makes the

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[1] For another solution to exist, would require the tax and tax credit to satisfy $\frac{\eta_F D_F}{(2-\phi)\eta_E E} = \frac{P_G + t}{\left(P_G + (1-\phi)t + t_c\right)}$ as well as (A.7″) and (A.8″). With two unknowns and three equations, this can only happen on a set of measure zero.

first term positive and the second term zero, thus the function is increasing in the tax. If we evaluate at $t = t^*$, the first term is positive while the second is negative, thus the function is decreasing in the tax. Given that second order conditions hold globally and that the function is continuous, it must be that $t^* > t > \frac{t_E^*}{\phi}$. Hence in this case (which is representative of the apparent external costs) the optimal tax without a tax credit is less than the optimal tax under the jointly optimal tax credit. Alternatively, if $t^* < t_E^*/\phi$, the same logic implies $t^* < t < \frac{t_E^*}{\phi}$, and thus a higher tax than under the optimal tax and tax credit combination.

3. Optimal Tax Credit without a Sub-optimal Fuel Tax

Finding the optimal tax credit with a fixed fuel tax involves solving

$$\max_{t_c} V\left(P_F, Y, X\right) \tag{A.15}$$

subject to (A.2) through (A.5), with P_G now an implicit function of t_c defined by (A.6). The resulting first order condition is (compare with A.8″)

$$\frac{dV}{dt_c} = -\left[t - t^*\right]\frac{\eta_G G}{P_G}\frac{dP_G}{dt_c} - \left[\phi t - t_c - t_E^*\right]\frac{\eta_E E}{\left(P_G + (1-\phi)t + t_c\right)}\left(\frac{dP_G}{dt_c} + 1\right) = 0 \tag{A.8‴}$$

where t^* and t_E^* are as defined previously—the marginal external cost of consuming gasoline and ethanol respectively. Note that in deriving the left hand side of (A.8‴) we are careful to preserve the sign from the original derivative. By totally differentiating (A.6) with t set equal to zero we can find the value of dP_g/dt_c that is appropriate for this policy. This differentiation results in exactly the condition in (A.10) only with t set exogenously. Consider first the case where $t = 0$. From (A.10), we know that $dP_G/dt_c + 1 < 0$. This and (A.8‴) implies that

$\left(-t_c - t_E^*\right)$ must be positive. Thus $t_c < -t_E^*$. Hence the optimal tax credit without a tax is in fact negative and exceeds the marginal external cost of ethanol.

In general, consider starting with the optimal tax and tax credit combination, and then lowering *t* to see the impact on the first order condition in (A.8‴). If we start with the optimal combination (see section 1 of the Appendix for a derivation), equation (A.8‴) must equal zero. By lowering *t*, $\left[t - t^*\right]$ becomes negative, making the first term of (A.8‴) negative. Also, lowering *t* will make $\left[\phi t - t_c - t_E^*\right]$ negative, thus making the second term negative. Hence, the derivative of welfare with respect to the tax credit is negative. This implies that decreasing the tax will result in a lower optimal tax credit.

4. *Finding the Optimal Combination of a Tax and a Mandate*

To find the optimal tax and mandate, we must solve

(A.16) $$\max_{\bar{E},t} V\left(P_F, Y, X\right),$$

where

(A.17) $$P_F = \frac{\left(P_E\left(\bar{E}\right) + \phi t\right)\bar{E} + \left(P_G + t\right)G\left(P_G\right)}{\bar{E} + G\left(P_G\right)}$$

(A.18) $$Y = \pi_E\left(P_E\left(\bar{E}\right)\right) + \pi_G\left(P_G\right) + t\left[G\left(P_G\right) + \phi\bar{E}\right]$$

(A.19) $$X = \tau_1\left[\xi_E\bar{E} + \xi_G G\left(P_G\right)\right] + \tau_2\left[\bar{E} + G\left(P_G\right)\right],$$

and where P_G is a function of the tax and mandate defined implicitly by

(A.20) $$D_F\left(\frac{\left(P_E\left(\bar{E}\right) + \phi t\right)\bar{E} + \left(P_G + t\right)G\left(P_G\right)}{\bar{E} + G\left(P_G\right)}\right) = \bar{E} + G\left(P_G\right).$$

Equations (A.17) through (A.19) can be substituted into (A.12). Note that under the optimal tax and tax credit, the indirect utility function is

$$V\left(P_G\left(t^*,t_c^*\right)+t^*,Y,X\right), \tag{A.21}$$

where (see (A.4) and (A.5))

$$\begin{aligned} Y = {} & \pi_E\left(P_G\left(t^*,t_c^*\right)+\left(1-\phi\right)t^*+t_c^*\right)+\pi_G\left(P_G\left(t^*,t_c^*\right)\right) \\ & +t^*G\left(P_G\left(t^*,t_c^*\right)\right)+\left(\phi t^*-t_c^*\right)E\left(P_G\left(t^*,t_c^*\right)+\left(1-\phi\right)t^*+t_c^*\right), \end{aligned} \tag{A.22}$$

$$\begin{aligned} X = {} & \tau_1\left[\xi_E E\left(P_G\left(t^*,t_c^*\right)+\left(1-\phi\right)t^*+t_c^*\right)+\xi_G G\left(P_G\left(t^*,t_c^*\right)\right)\right] \\ & +\tau_2\left[E\left(P_G\left(t^*,t_c^*\right)+\left(1-\phi\right)t^*+t_c^*\right)+G\left(P_G\left(t^*,t_c^*\right)\right)\right]. \end{aligned} \tag{A.23}$$

Note again that because the optimal tax and tax credit is equivalent to charging a separate tax on ethanol and gasoline that this achieves the first best optimum. We can show that an equivalent level of indirect utility is obtained by setting the consumption mandate

$$\bar{E} = E\left(P_G\left(t^*,t_c^*\right)+\left(1-\phi\right)t^*+t_c^*\right), \tag{A.24}$$

with producer price for ethanol equal to $P_E = P_G\left(t^*,t_c^*\right)+\left(1-\phi\right)t^*+t_c^*$, and setting the tax so that the price of fuel is equal to $P_F = P_G\left(t^*,t_c^*\right)+t^*$. Note that this is the same price of fuel under the optimal tax and tax credit combination, thus the same amount of fuel must be demanded and consumed. Further, because the identical amount of fuel is consumed, and the identical amount of ethanol, this must result in an identical amount of gasoline, $G\left(P_G\left(t^*,t_c^*\right)\right)$. The necessary tax solves that

$$P_F = \frac{\left(P_G\left(t^*,t_c^*\right)+\left(1-\phi\right)t^*+t_c^*+\phi t\right)\bar{E}+\left(P_G\left(t^*,t_c^*\right)+t\right)G}{\bar{E}+G} = P_G\left(t^*,t_c^*\right)+t^*, \tag{A.25}$$

or,

$$t^M = \frac{t^* G\left(P_G\left(t^*, t_c^*\right)\right) + \left(\phi t^* - t_c^*\right)\bar{E}}{G\left(P_G\left(t^*, t_c^*\right)\right) + \phi\bar{E}}. \tag{A.26}$$

This policy combination results in the indirect utility

$$V\left(P_G\left(t^*, t_c^*\right) + t^*, Y, X\right), \tag{A.27}$$

where (see equations (A.18) and (A.19))

$$\begin{aligned} Y &= \pi_E\left(P_G\left(t^*, t_c^*\right) + (1-\phi)t^* + t_c^*\right) + \pi_G\left(P_G\left(t^*, t_c^*\right)\right) \\ &\qquad + t^M\left[G\left(P_G\left(t^*, t_c^*\right)\right) + \phi E\left(P_G\left(t^*, t_c^*\right) + (1-\phi)t^* + t_c^*\right)\right] \\ &= \pi_E\left(P_G\left(t^*, t_c^*\right) + (1-\phi)t^* + t_c^*\right) + \pi_G\left(P_G\left(t^*, t_c^*\right)\right) \\ &\qquad + t^* G\left(P_G\left(t^*, t_c^*\right)\right) + \left(\phi t^* - t_c^*\right) E\left(P_G\left(t^*, t_c^*\right) + (1-\phi)t^* + t_c^*\right) \end{aligned}, \tag{A.28}$$

$$\begin{aligned} X &= \tau_1\left[\xi_E E\left(P_G\left(t^*, t_c^*\right) + (1-\phi)t^* + t_c^*\right) + \xi_G G\left(P_G\left(t^*, t_c^*\right)\right)\right] \\ &\qquad + \tau_2\left[E\left(P_G\left(t^*, t_c^*\right) + (1-\phi)t^* + t_c^*\right) + G\left(P_G\left(t^*, t_c^*\right)\right)\right]. \end{aligned} \tag{A.29}$$

Here, (A.27), (A.28) and (A.29) result in identical values for P_F, *Y* and *X*, and thus the maximand *V* as in (A.1). Because this is the maximum attainable value of *V*, this combination of tax and mandate must be the optimum values solving (A.21).

5. Finding the Optimal Mandate Holding the Fuel Tax Constant

To find the optimal mandate without a tax, we must solve

$$\max_{\bar{E}} V\left(P_F, Y, X\right), \tag{A.30}$$

where

$$P_F = \frac{\left(P_E\left(\bar{E}\right) + \phi t\right)\bar{E} + \left(P_G + t\right)G\left(P_G\right)}{\bar{E} + G\left(P_G\right)} \tag{A.31}$$

$$Y = \pi_E\left(P_E\left(\bar{E}\right)\right) + \pi_G\left(P_G\right) + t\left[G\left(P_G\right) + \phi\bar{E}\right] \tag{A.32}$$

(A.33) $$X = \tau_1\left[\xi_E \bar{E} + \xi_G G\left(P_G\right)\right] + \tau_2\left[\bar{E} + G\left(P_G\right)\right],$$

and where P_G is a function of the mandate defined implicitly by

(A.34) $$D_F\left(\frac{\left(P_E\left(\bar{E}\right) + \phi t\right)\bar{E} + \left(P_G + t\right)G\left(P_G\right)}{\bar{E} + G\left(P_G\right)}\right) = \bar{E} + G\left(P_G\right)\cdot$$

The first order condition is given by

(A.35)

$$V_P \cdot \left[\frac{\left[\bar{E}P_E{}' + P_E + t + \frac{dP_G}{d\bar{E}}G + \left(P_G + t\right)G'\frac{dP_G}{d\bar{E}}\right]\left(\bar{E} + G\right) - \left[1 + G'\frac{dP_G}{d\bar{E}}\right]\left(\left(P_E + \phi t\right)\bar{E} + \left(P_G + t\right)G\right)}{\left(\bar{E} + G\right)^2}\right]$$

$$+ V_Y \cdot \left[\pi_E{}' P_E{}' + \pi_G{}'\frac{dP_G}{d\bar{E}} + tG'\frac{dP_G}{d\bar{E}} + \phi t\right] + V_X \cdot \left[\left(\tau_1\xi_E + \tau_2\right) + \left(\tau_1\xi_G + \tau_2\right)G'\frac{dP_G}{d\bar{E}}\right] = 0.$$

Dividing by V_Y, and employing elasticity formulas, Hotelling's Lemma, $V_P/V_Y = -D_F = -E - G$, the previous definitions of t^*, $t_E{}^*$ and the identity $V_X/V_Y = -1$ (as discussed in section 1 of the Appendix) we obtain

(A.36) $$-P_F + P_E + \left(1 - \phi\right)t + t_E^* - \left(P_F - P_G - t^*\right)\eta_G \frac{G}{P_G}\frac{dP_G}{d\bar{E}} = 0\,.$$

Note that in deriving the left hand side of (A.36) we are careful to preserve the sign. Thus a value of the left hand side that is positive implies that increasing $\bar{E}$ will increase welfare. If the tax were optimal given the tax credit then $P_F\left(t^*, \bar{E}\left(t^*\right)\right) = P_G\left(t^*, \bar{E}\left(t^*\right)\right) + t^*$, from the previous section. Thus, evaluating (A.36) at this point we find

(A.37) $$-P_F + P_E + \left(1 - \phi\right)t^* + t_E^* = 0\,.$$

If we were to lower *t* from *t** holding all else constant, P_F would decline increasing the first term of (A.36). In (A.36), $(1-\phi)<0$, so reducing t will also increase the third additive term. The terms P_E and t_E* will remain constant (the former because the mandate remains constant). Thus, if the last term also increases, it must be that the (A.36) becomes positive as the tax is lowered below the optimal level, implying a higher optimal ethanol mandate. By totally differentiating (A.34) with respect to P_G and $\bar{E}$, we obtain

(A.38)
$$\frac{dP_G}{d\bar{E}} = -\frac{\left[D_F'\frac{dP_F}{d\bar{E}}-1\right]}{\left[D_F'\frac{dP_F}{dP_G}-G'\right]}$$

which must be negative so long as the equilibrium is stable (in other words as long as the demand for fuel has a more negative slope than the supply of fuel blend, see de Gorter and Just, 2008a). Thus, the optimal ethanol mandate must increase as the tax decreases if $P_F - P_G$ decreases as *t* is lowered from A.36. Totally differentiating (A.34) with respect to P_G and *t* obtains

(A.39)
$$\frac{dP_G}{dt} = -\frac{D_F'\cdot\left(\phi\bar{E}+G\right)}{\left[D_F'\cdot\left(G+\frac{\left(P_G-P_E+(1-\phi)t\right)\bar{E}G'}{\left(\bar{E}+G\right)}\right)-G'\left(\bar{E}+G\right)\right]},$$

or, substituting elasticities

(A.40)
$$\frac{dP_G}{dt} = -\frac{\frac{\eta_F}{P_F}\left(\phi\bar{E}+G\right)}{\left[\frac{\eta_F}{P_F}\left(G+\left(P_G-P_E+(1-\phi)t\right)\bar{E}\eta_G\frac{G}{\left(\bar{E}+G\right)P_G}\right)-\eta_G\frac{G}{P_G}\right]}.$$

Alternatively, differentiating the formula for P_F and substituting elasticities obtains

(A.41)
$$\frac{dP_F}{dt}=\frac{\left(\phi\bar{E}+G\right)+\left[\left(P_G-P_E+\left(1-\phi\right)t\right)\frac{G\bar{E}\eta_G}{\left(\bar{E}+G\right)P_G}+G\right]\frac{dP_G}{dt}}{\left(\bar{E}+G\right)}.$$

Combining (A.40) and (A.41) and simplifying terms obtains

(A.42)

$$\frac{d\left(P_F-P_G\right)}{dt}=\frac{\left(\phi\bar{E}+G\right)}{\left(\bar{E}+G\right)}+\frac{\frac{\eta_F}{P_F}\left(\phi\bar{E}+G-\frac{\eta_F}{P_F}\frac{\left(\phi\bar{E}+G\right)}{\left(\bar{E}+G\right)}\left[G+\left(P_G-P_E+\left(1-\phi\right)t\right)\bar{E}\eta_G\frac{G}{\left(\bar{E}+G\right)P_G}\right]\right)}{\left[\frac{\eta_F}{P_F}\left(G+\left(P_G-P_E+\left(1-\phi\right)t\right)\bar{E}\eta_G\frac{G}{\left(\bar{E}+G\right)P_G}\right)-\eta_G\frac{G}{P_G}\right]}$$

or,

(A.43)
$$\frac{d\left(P_F-P_G\right)}{dt}=\frac{\left(\phi\bar{E}+G\right)}{\left(\bar{E}+G\right)}\left[\frac{\left(-\eta_G\frac{G}{P_G}+\frac{\eta_F}{P_F}\left(\bar{E}+G\right)\right)}{\left[\frac{\eta_F}{P_F}\left(G+\left(P_G-P_E+\left(1-\phi\right)t\right)\bar{E}\eta_G\frac{G}{\left(\bar{E}+G\right)P_G}\right)-\eta_G\frac{G}{P_G}\right]}\right].$$

Note that the first multiplicative term is positive, while the numerator in the square brackets must be negative. The denominator will also be negative if

(A.44)
$$\left(P_G-P_E+\left(1-\phi\right)t\right)>\left(\frac{\eta_G}{\eta_F}P_F-P_G\right)\frac{D_F}{\bar{E}\eta_G},$$

implying that (A.43) is positive. Thus, if (A.44) holds where $t=t^*$, then a suboptimal tax will result in an increased mandate. This condition will hold if the left hand side is not too negative. Note that both sides of (A.44) are negative. Thus, (A.44.) will hold, for example, if the optimal ethanol mandate is low relative to fuel demand, the optimal tax- mandate combination will not create too large a wedge between gasoline and ethanol prices. This condition is very similar to the requirements for the fuel price to increase when the ethanol mandate is increased (see de Gorter and Just 2008a).

6. *Welfare as the Fuel Tax is lowered under the Tax Credit and the Mandate*

Under both the optimal tax-tax credit combination and the optimal tax-mandate combination, the same level of welfare is achieved. Thus, we can determine the impact on welfare of reducing the fuel tax under each biofuel policy by simply differentiating welfare with respect to the tax and evaluating at the optimal policy. Consider first the optimal tax credit given an exogenously set fuel tax. If we begin by evaluating at the optimal tax (first best) the welfare is given by

(A.45)
$$V\left(P_g\left(t^*, t_c{}^*\right) + t^*, Y, X\right)$$

where

(A.46)
$$\begin{aligned} Y = {} & \pi_E\left(P_E\left(t^*, t_c{}^*\right)\right) + \pi_G\left(P_G\left(t^*, t_c{}^*\right)\right) \\ & + t^* G\left(P_G\left(t^*, t_c{}^*\right)\right) + \left(\phi t^* - t_c{}^*\right) E\left(P_E\left(t^*, t_c{}^*\right)\right) \end{aligned}$$

(A.47)
$$\begin{aligned} X = {} & \tau_1\left[\xi_E E\left(P_E\left(t^*, t_c{}^*\right)\right) + \xi_G G\left(P_G\left(t^*, t_c{}^*\right)\right)\right] \\ & + \tau_2\left[E\left(P_E\left(t^*, t_c{}^*\right)\right) + G\left(P_G\left(t^*, t_c{}^*\right)\right)\right] \end{aligned}$$

Differentiating (A.45) with respect to the tax yields

(A.48)
$$\begin{aligned} \frac{dV}{dt} = {} & V_P \cdot \left(\frac{dP_g}{dt} + 1\right) + V_Y \cdot \left(\pi_E{}' \frac{dP_E}{dt} + \pi_G{}' \frac{dP_g}{dt} + G + t^* G' \frac{dP_g}{dt} + \phi E + \left(\phi t^* - t_c{}^*\right) E' \frac{dP_E}{dt}\right) \\ & + V_X \cdot \left(\tau_1\left(\xi_E E' \frac{dP_E}{dt} + \xi_G G' \frac{dP_G}{dt}\right) + \tau_2\left(E' \frac{dP_E}{dt} + G' \frac{dP_G}{dt}\right)\right) \\ = {} & V_P \cdot \left(\frac{dP_g}{dt} + 1\right) + V_Y \cdot \left(\left(E + t_E{}^* \eta_E \frac{E}{P_E}\right) \frac{dP_E}{dt} + \left(G + t^* \eta_G \frac{G}{P_g}\right) \frac{dP_g}{dt} + G + \phi E\right) \\ & + V_X \cdot \left(t_E{}^* \eta_E \frac{E}{P_E} \frac{dP_E}{dt^*} + t^* \eta_G \frac{G}{P_g} \frac{dP_G}{dt^*}\right) \end{aligned}$$

If instead we evaluate the optimal mandate response to a tax with the initial tax given by the optimal tax-mandate combination, we obtain welfare

(A.49)
$$V\left(P_F\left(t^M,\bar{E}\right),Y,X\right)$$

where

(A.50)
$$P_F\left(t^M,\bar{E}\right)=\frac{\left(P_E\left(\bar{E}\right)+\phi t^M\right)\bar{E}+\left(P_G\left(t^M,\bar{E}\right)+t^M\right)G\left(P_G\left(t^M,\bar{E}\right)\right)}{\bar{E}+G\left(P_G\left(t^M,\bar{E}\right)\right)}$$

(A.51)
$$Y=\pi_E\left(P_E\left(\bar{E}\right)\right)+\pi_G\left(P_G\left(t^M,\bar{E}\right)\right)+t^M\left[G\left(P_G\left(t^M,\bar{E}\right)\right)+\phi\bar{E}\right]$$

(A.52)
$$X=\tau_1\left[\xi_E\bar{E}+\xi_G G\left(P_G\left(t^M,\bar{E}\right)\right)\right]+\tau_2\left[\bar{E}+G\left(P_G\left(t^M,\bar{E}\right)\right)\right].$$

Differentiating (A.49) with respect to the tax yields

(A.53)
$$\begin{aligned}\frac{dV}{dt}&=V_P\cdot\left(\frac{\left(\phi\bar{E}+G\right)\left(\bar{E}+G\right)+\frac{dP_G}{dt^M}\left[\left(\bar{E}+G\right)G+\left(P_G-P_E+t^M-\phi t^M\right)G'\bar{E}\right]}{\left(\bar{E}+G\right)^2}\right)\\&\quad+V_Y\cdot\left(\pi_G'\frac{dP_G}{dt^M}+G+\phi\bar{E}+t^M G'\frac{dP_G}{dt^M}\right)+V_X\cdot\left(\tau_1\xi_G+\tau_2\right)G'\frac{dP_G}{dt^M}\\&=V_P\cdot\left(\frac{\left(\phi\bar{E}+G\right)\left(\bar{E}+G\right)+\frac{dP_G}{dt^M}\left[\left(\bar{E}+G\right)G+\left(P_G-P_E+t^M-\phi t^M\right)\frac{\eta_G G}{P_G}\bar{E}\right]}{\left(\bar{E}+G\right)^2}\right)\\&\quad+V_Y\cdot\left(\left(G+t^M\frac{\eta_G G}{P_G}\right)\frac{dP_G}{dt^M}+G+\phi\bar{E}\right)+V_X\cdot t^*\frac{\eta_G G}{P_G}\frac{dP_G}{dt^M}\end{aligned}$$

Thus, in order for the mandate to provide a higher level of welfare, it must be the case that the derivative with respect to the tax under the tax credit is larger (a steeper decline) than under the mandate, or

$$V_P \cdot \left(\frac{\left(\phi\bar{E}+G\right)\left(\bar{E}+G\right)+\frac{dP_G}{dt^M}\left[\left(\bar{E}+G\right)G+\left(P_G-P_E+t^M-\phi t^M\right)\frac{\eta_G G}{P_G}\bar{E}\right]}{\left(\bar{E}+G\right)^2} \right)$$

(A.54)

$$+V_Y \cdot \left(\left(G+t^*\frac{\eta_G G}{P_G} \right)\frac{dP_G}{dt^M}+G+\phi\bar{E} \right)+V_X \cdot t^*\frac{\eta_G G}{P_G}\frac{dP_G}{dt^M}$$

$$<V_P \cdot \left(\frac{dP_g}{dt^*}+1 \right)+V_Y \cdot \left(\left(E+t_E{}^*\eta_E\frac{E}{P_E} \right)\frac{dP_E}{dt^*}+\left(G+t^*\eta_G\frac{G}{P_g} \right)\frac{dP_g}{dt^*}+G+\phi E \right)$$

$$+V_X \cdot \left(t_E{}^*E'\frac{dP_E}{dt^*}+t^*\eta_G\frac{G}{P_g}\frac{dP_G}{dt^*} \right)$$

Dividing both sides of (A.54) by V_Y, employing common identities and canceling like terms allows us to rewrite (A.54) as

(A.55)

$$\left(1-\phi-\frac{dP_E}{dt^*}+\frac{dP_g}{dt^*}-\frac{dP_G}{dt^M}\left(P_G-P_E+\left(1-\phi\right)t^M\right)\frac{\eta_G G}{P_G\left(\bar{E}+G\right)} \right)<0$$

Substituting $P_E = P_G\left(t^*, t_c{}^*\right)+\left(1-\phi\right)t^*+t_c{}^*$ and $dP_E/dt^* = dP_G/dt^*+\left(1-\phi\right)$ into (A.47) obtains

(A.56)

$$-\frac{dP_G}{dt^M}\left(\left(1-\phi\right)\left(t^M-t^*\right)-t_c{}^*\right)\frac{\eta_G G}{P_G\left(\bar{E}+G\right)}<0$$

Note that $dP_G/dt^M<0$, $\eta_G G/\left[P_G\left(\bar{E}+G\right)\right]>0$. Thus, (A.48) will hold only if

(A.57)

$$\left(1-\phi\right)\left(t^M-t^*\right)<t_c{}^*.$$

Substituting in the definition of t^M from (A.26) and the definition of t_c^*, and canceling terms obtains

(A.57)

$$t_E{}^*<t^*\phi,$$

which requires that the marginal external cost of consuming ethanol is below the marginal tax burden of consuming ethanol under the optimal tax-tax credit combination. This is the same requirement that is necessary for a positive tax credit.