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Welfare impacts of alternative biofuel and energy policies

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We employ an open economy general equilibrium model to investigate the effects of government energy policy, with an emphasis on corn-based ethanol, on the U.S. economy. The model specification incorporates world and domestic markets, assumes pollution costs from fuel consumption, and allows endogenous determination of equilibrium quantities and prices for oil, corn and ethanol. The model is calibrated to represent a recent benchmark data set for 2009 and is used to simulate the positive and normative effects of alternative policies. We find that a second best policy of a fuel tax and ethanol subsidy approximates fairly closely the welfare gains associated with the first-best policy of an optimal carbon tax and tariffs on traded goods. The largest economic gains to the U.S. economy from these energy policies arise from the impact of the policies on U.S. terms of trade, particularly in the oil market. We also find that, conditional on the current fuel tax, an optimal ethanol mandate is superior to an optimal ethanol subsidy. In the benchmark case, the optimal ethanol mandate is about 18 billion gallons.

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1. Introduction

Two interrelated and critical issues facing the U.S. and world economies are the dwindling supply of fossil fuels and the increasing emissions of carbon into the atmosphere. The U.S. dependence on imported oil, in particular, has increased sharply in the past quarter century, with a number of significant economic and political consequences. Oil imports worsen the U.S. balance of trade deficit and, together with growing energy consumption from developing countries such as China, lead to higher prices. Some argue that this dependence on oil imports weakens U.S. national security and entails significant military and defense expenditures to ensure continued U.S. access to world oil supplies. Separately, there is the concern with greenhouse gas (GHG) emissions associated with fossil energy use. While some disagreement exists on the potential implications of carbon buildup in the atmosphere, it seems that the major industrialized countries are moving toward a regime in which these emissions will be regulated and (or) priced.

Partly in response to such issues, government support for biofuels has led to rapid growth in U.S. ethanol production. U.S. fuel ethanol production has increased from 1.65 billion gallons in 2000 to 10.76 billion gallons in 2009, making the U.S. the largest world producer of ethanol. This dramatic expansion of ethanol production owes much to critical support policies implemented by the United States. Specifically, U.S. ethanol production currently benefits from a $0.45/gallon subsidy (technically an excise tax credit), an out-of-quota ad valorem import tariff of 2.5% and a $0.54/gallon duty on ethanol imports. In addition, the Energy Policy Act of 2005 specified a renewable fuel standard that “mandates” specific targets for renewable fuel use, the level of which has been considerably expanded by the Renewable Fuel Standard (RFS2) of the Energy Independence and Security Act of 2007. Since then, the ethanol mandates under the RFS2 have been more than met, with ethanol production of 10.76 billion gallons in 2009 exceeding the mandate level by 0.26 billion gallons.[1] According to the RFS2, the renewable fuel requirement rises from 12.95 billion gallons in 2010 to 20.5 billion gallons in 2015, and to 36 billion gallons in 2022; of these latter amounts, up to 15 billion gallons may come from ethanol, while the rest are meant to come from “advanced biofuels,” such as cellulosic biofuel.

Given these ambitious targets and government policy geared to implement them, it is important to have a clear understanding of the welfare implications of policies that impact biofuels production. This topic has been the subject of a few studies that have elucidated some critical economic effects. De Gorter and Just (2009a) analyze the impact of a biofuel blend

[1] The ethanol production of 4.84 billion gallons in 2006 and 6.48 billion gallons in 2007 exceeded the previous RFS mandates of 4.0 billion gallons in 2006 and 4.7 billion gallons in 2007. Ethanol production of 9.23 billion gallons in 2008 also slightly surpassed the RFS2 mandate of 9.0 billion gallons.

mandate on the fuel market. They find that when tax credits are implemented along with the blend mandate, tax credits subsidize fuel consumption instead of biofuels. De Gorter and Just (2009b) also develop a framework to analyze the interaction effects of a biofuel tax credit and a price-contingent farm subsidy. The annual rectangular deadweight costs—which arise because they conclude that ethanol would not be commercially viable without government intervention—dwarf in value the traditional triangular deadweights costs of farm subsidies.

Elobeid and Tokgoz (2008) set up a multimarket international ethanol model to analyze the influence of trade liberalization and the removal of the federal tax credit in the U.S. on ethanol markets. They find that the removal of current tariffs on imported ethanol will lead to a 13.6% decrease in the U.S. domestic ethanol price and a 3.7% increase of ethanol's share in U.S. fuel consumption. With the removal of both tax credits ($0.54/gallon at the time of that study) and tariffs, their study predicts that U.S. ethanol consumption will fall by 2.1% and the price of ethanol will fall by 18.4%.

The foregoing studies do not account explicitly for the impact of climate policies on GHG emissions associated with the fuel energy sector. Khanna, Ando and Taheripour (2008) examine the welfare impact of a carbon tax ($25/tC) on fuel consumption, when the purpose of the tax is to correct the pollution externality from carbon emissions and to account for the other external costs associated with congestions and accidents. At the time of their study, they found that the fuel tax of $0.387/gallon and then-current ethanol subsidy of $0.51/gallon reduces carbon emissions by 5% relative to the no-tax situation (*lassez faire*).[2] Their second best policy of a $0.085 mile tax with a $1.70/gallon ethanol subsidy could reduce gasoline consumption by 16.8%, thereby reducing carbon emissions by 16.5% (71.7 million metric tons).

In considering the effectiveness of ethanol in reducing GHG emissions, one issue that arises is that of "indirect land use" effects. It is argued that diverting feed corn to ethanol production in the United States might bring new marginal land into production elsewhere in order to satisfy the increased demand for agricultural output (Searchinger et al. 2008), an indirect effect of biofuel mandates that could be quite sizable. To assess the global economic and land-use impacts of biofuel mandates, Hertel, Tyner and Birur (2008) use a computable general equilibrium model (CGE), which is built upon the standard Global Trade Analysis Project (GTAP) modeling framework. To jointly meet the biofuel mandate policies of the United States (15 billion gallons of ethanol used by 2015) and the EU (6.25% of total fuel as renewable fuel by

[2] Some studies discuss emissions in terms of metric tons of carbon (tC), other in terms of metric tons of carbon dioxide (tCO_2). One metric ton of carbon is equivalent to 3.67 metric tons of carbon dioxide (conversely, one metric ton of carbon dioxide is equivalent to 0.27 metric tons of carbon). Of course, when reductions are expressed in percentages, units will not matter.

2015), they find that coarse grains acreage in the United States rises by 10%, oilseeds acreage in the EU increases dramatically, by 40%, cropland areas in the United States would increase by 0.8%, and about one-third of these changes occur because of the EU mandate policy. The U.S. and EU mandate policies jointly reduce the forest and pasture land areas of the United States by 3.1% and 4.9%, respectively.

However, the most recent RFS2 pronouncement by the Environmental Protection Agency (EPA) has accounted for international indirect land use changes (ILUC) and made several changes for GHG emissions reduction of ethanol from all feedstocks (EPA 2010). Accounting for ILUC, the EPA finds that corn ethanol still achieves a 21% GHG reduction compared to gasoline. On the other hand, sugarcane ethanol qualifies as an advanced biofuel according to the overall result of the EPA's ILUC modification given that its calculated average of 61% GHG reduction compared to baseline gasoline exceeds the 50% GHG reduction threshold for advanced biofuels. Sugarcane ethanol even meets the 60% GHG reduction standard for cellulosic ethanol.

Lapan and Moschini (2009) note that most of the existing work does not explicitly account for the welfare consequences to the U.S. of policies supporting biofuel production (such as the externality of GHG emission or the benefits to the U.S. that accrue either from improved terms of trade or "improved national security" due to decreased reliance on oil imports). To consider first- and second-best policies within that normative context, Lapan and Moschini (2009) build a simplified general equilibrium (multi-market) model of the United States and the rest-of-the-world economies that links the agricultural and energy sectors to each other and to the world markets. That paper models the process by which corn is converted into ethanol, accounts for byproducts of this process, and allows for the endogeneity of world oil and corn prices, as well as the (different) carbon emissions from gasoline derived from oil and that which is blended with ethanol. The analysis presented is theoretical in nature, aiming at providing analytical insights and results. The authors find that, in their setting, the first best policy would include a tax on carbon emissions, an import tax on oil, and an export tax on corn. If policy is constrained, for example by international obligations, they find that a fuel tax and an ethanol subsidy can be welfare enhancing. They also find that an ethanol mandate is likely to welfare-dominate an ethanol subsidy.

In this paper we construct a tractable computational model that applies and extends the analytical setup of Lapan and Moschini (2009), and we use the model to provide quantitative estimates of the welfare benefits of alternative policies. The model specification allows endogenous determination of equilibrium quantities and prices for oil, corn and ethanol and is calibrated to represent a recent benchmark data set for the year 2009, using the available econometric evidence on elasticity estimates. By varying government policy, we explore how these policies affect equilibrium (domestic and world) prices of corn, oil, ethanol and gasoline. Using standard welfare measures, we compare the net welfare implications of alternative policies and show how different groups are affected by the policies. In addition to characterizing the first best policy, we consider a number of second best interventions involving various combinations of ethanol mandates, ethanol subsidies and a fuel tax. Using the model, we calculate the optimal values for the policy instruments (given the constraint on which instruments are used) and the associated welfare gains. We then explore the robustness of our conclusions by varying the values of various parameters.

Our results consistently show that the largest economic gains to the U.S. from policy intervention come from the impact of policies on the U.S. terms of trade, particularly on the price of oil imports. We also find that first best policy outcomes, which would require oil import tariffs that are not consistent with U.S. international obligations, can be closely approximated by second best tools such as fuel taxes. Furthermore, our results probably underestimate the gains that come from reducing U.S. oil imports because the model does not account for any of the "national security" gains that could arise from reduced U.S. dependence on imported oil.

The rest of this paper is organized as follows. First, we review and extend the analytical model by Lapan and Moschini (2009). Next, we present the equilibrium conditions of the model so that, in conjunction with the assumed parameter values, which are also reported, our results can be readily replicated. This is followed by a definition of our welfare measure and a discussion of how (constrained) optimal policy can be determined. Finally, we report and discuss the results of our simulations, comparing the relative efficacy of alternative policies and investigating the sensitivity of these results to parametric values.

2. The Model

We adapt and extend the model developed in Lapan and Moschini (2009) to make it more suitable for simulating the consequences of alternative policies directed toward reducing U.S. emissions and reducing U.S. reliance on oil imports. The main extension is to recognize that when oil is refined, other products, in addition to gasoline, are produced (e.g., distillate fuel oil, jet fuel, etc.). We aggregate all the non-gasoline output into a single good called petroleum byproducts. The model is a stylized economy with three basic commodities: a numeraire good, corn (food) output and oil. In addition, there is a processing sector that refines oil into gasoline and other petroleum byproducts, and another sector that converts corn into ethanol, which may then be blended with gasoline to create "fuel" used by households. Consumers are assumed to have quasi-linear preferences (which can then be aggregated into a representative consumer) with utility function

(1) $$U = y + \phi\left(D_f\right) + \theta\left(D_c\right) + \eta\left(D_h\right) - \sigma\left(x_g + \lambda x_e\right)$$

where y represents consumption of the numeraire, and (D_f, D_c, D_h) represent consumption of fuel, of food, and of petroleum byproducts, respectively. The last term, $\sigma(\cdot)$, represents environmental damages from carbon emissions due to aggregate combustion of gasoline and ethanol. The parameter λ reflects the relative pollution emissions of ethanol as compared to gasoline (we will return to this parameter later).

The basic elements of the model consist of the following:

(I) U.S. demand for corn as food/feed, represented by $D_c\left(p_c\right)$

(II) U.S. demand for fuel $D_f\left(p_f\right)$

(III) U.S. demand for petroleum byproducts $D_h\left(p_h\right)$

(IV) U.S. corn supply equation $S_c\left(p_c\right)$

(V) U.S. oil supply equation $S_o\left(p_o\right)$

(VI) Foreign oil export supply curve $\bar{S}_o\left(p_o^w\right)$

(VII) Foreign corn import demand curve $\bar{D}_c\left(p_c^w\right)$

(VIII) U.S. oil refining sector, which converts oil into gasoline and petroleum byproducts

(IX) U.S. ethanol production sector, which converts corn into ethanol, and produces a byproduct of dried distillers grains with solubles (DDGS), which becomes part of the food/feed supply

Components (I)-(VII) of the model are self-explanatory. In particular, the (household) demand curves (I-III) come from utility maximization, and thus are the inverse of the marginal utility relations $\phi'(D_f)$, $\theta'(D_c)$, and $\eta'(D_h)$, respectively, and p_f, p_c, p_h are the prices facing households.[3] The domestic supply relations (IV and V) come from competitive profit maximization so that (assuming no externalities associated with their production) they are the inverse of the marginal private (and social) costs; because we assume no taxes on domestic corn or oil producers, (p_c, p_o) represent both supply and demand prices.[4] The foreign relations (VI and VII) represent aggregate excess world oil supply and world corn demand, and distinguishing the world prices (p_o^w, p_c^w) from domestic prices allows for the possibility of U.S. border policies (tariffs or quotas) that would cause U.S. prices to diverge from world prices. Note that if the United States were a small country, world prices (p_o^w, p_c^w) would be exogenous to U.S. economic conditions. However, in reality, the U.S. is a large economic agent in both markets and our simulation will reflect that fact. Finally, components (VIII) and (IX) of the model require a bit more elaboration.

2.1. *Oil Refining Sector*

The refinement of oil yields gasoline x_g and petroleum byproducts x_h. We assume a fixed coefficients production technology so that the process is represented as follows:[5]

(2.1) $$x_g = Min\left[\beta x_o, z_o\right]$$

(2.2) $$x_h = \beta_2 x_g \big/ \beta$$

where x_g is gallons of gasoline output, x_h is gallons of the petroleum byproduct, x_o is barrels of oil input (where domestically produced oil and imported oil are perfect substitutes), and z_o is the amount of a composite input, which aggregates all other inputs used in the oil refining process. Thus, β is the number of gallons of gasoline per barrel of crude oil, and β_2 is the

[3] Since the marginal utility of the numeraire is one, the marginal rate of substitution between each one of the three consumption goods (food, fuel and petroleum byproducts) and the numeraire is the same as the marginal utility of that good. The price of the numeraire is (by definition) normalized to one, so p_f, p_c, p_h represent relative prices.

[4] We do allow for taxes or subsidies on fuel and ethanol, which is equivalent to taxes or subsidies on gasoline and ethanol.

[5] Although in reality there is some substitutability among the various products produced from crude oil, it seems that this substitutability is limited and that the assumption of fixed proportions in output provides a reasonable approximation.

number of gallons of the petroleum byproduct per barrel of oil. This technology and perfect competition imply the following relationship among input and output prices:

(3) $$\beta p_g + \beta_2 p_h = p_o + \beta \omega_g$$

where ω_g represents the unit cost of the composite input z_o, including the rental price of capacity.

2.2. *Ethanol Production Sector*

We also assume a fixed coefficients production process for ethanol production:

(4) $$x_e = Min\left[\alpha x_c, z_e\right]$$

where x_e is ethanol output and z_e the amount of other inputs used per unit of ethanol output. Because the energy content of ethanol is much lower than that of gasoline, and given our working assumption that consumers' demand take that into account (e.g., they ultimately care about the miles traveled with any given amount of fuel, as discussed in de Gorter and Just 2010), it is important to keep track of this fact to handle the blending of ethanol and gasoline (into fuel) in a consistent fashion. Consequently, x_e in equation (4) and in what follows is measured in what we term "gasoline-energy-equivalent gallon" (GEEG) units.[6] Furthermore, we wish to account for the valuable bioproducts of ethanol production by counting only the "net" use of corn in the technological relation in (4). That is, if one bushel of corn used in ethanol production also yields δ_1 units of distillers dried grains with soluble (DDGS), which, being a close corn-substitute in feed use, we assume commands a price of $\delta_2 p_c$, then the *net* amount of corn required to produce a gallons of ethanol is only $\left(1-\delta_1\delta_2\right)$. Hence, the production parameter α in (4) satisfies

(5) $$\alpha = \frac{a\gamma}{1-\delta_1\delta_2}$$

[6] This measure is related to the more common notion of a "gasoline gallon equivalent," which is defined as the amount of alternative fuel it takes to equal the energy content of one gallon of gasoline (essentially this represents the reciprocal of our measure).

where a is the number of gallons of ethanol (in natural units) per bushel of corn; γ captures the lower energy content of ethanol (relative to gasoline); δ_1 represents the units of DDGS per bushel of corn used to produce ethanol; and δ_2 represents the relative price of DDGS.

Given perfect competition in the ethanol sector, this implies the following price relation between the supply price of ethanol and the price of corn:

$$(6) \qquad p_e = \frac{p_c}{\alpha} + \omega_e$$

where ω_e is the cost of all inputs other than corn, including the rental cost of plant capacity, required to produce one unit of ethanol (measured in gasoline energy equivalent units) and p_e is the price of one GEEG of ethanol.

3. Equilibrium

In order to simulate the model, we need to specify the equilibrium conditions that must hold and the set of policy instruments that are considered. For the purpose of our policy analysis, the policy instruments that we allow are border policies, fuel taxes and ethanol subsidies/taxes (or border policies, ethanol mandates and ethanol subsidies).[7] We assume there is trade in crude oil but no trade in the refined products, which is a fair approximation of the *status quo*.[8] Given all that, the equilibrium conditions are as follows:

$$(7) \qquad S_c(p_c) = D_c(p_c) + \bar{D}_c(p_c^w) + x_e/\alpha \qquad \text{(Corn Market Equilibrium)}$$

$$(8) \qquad D_f(p_f) = \beta\left\{S_o(p_o) + \bar{S}_o(p_o^w)\right\} + x_e \qquad \text{(Fuel Market Equilibrium)}$$

$$(9) \qquad D_h(p_h) = \beta_2\left\{S_o(p_o) + \bar{S}_o(p_o^w)\right\} \qquad \text{(Petroleum Byproduct Equilibrium)}$$

[7] If we also allowed, for example, a tax/subsidy on corn production, we would have to distinguish between the supply and demand prices for corn.

[8] Although imports account for over 50% of U.S. crude oil consumption, over the period 2007-2009 net imports of gasoline averaged about 1.7% of total consumption and net trade of "Refinery and Blender Finished Petroleum Product" averaged (in absolute value) under 3% of total consumption (calculated from the "Supply and Disposition Tables" of the U.S. Energy Information, http://tonto.eia.doe.gov/dnav/pet/pet_sum_snd_d_nus_mbbl_m_cur.htm).

(10) $\beta p_g + \beta_2 p_h = p_o + \beta\omega_g$ (Zero Profit Condition Oil Refining)

(11) $p_e = \dfrac{p_c}{\alpha} + \omega_e$ (Zero Profit Condition Ethanol Industry)

(12) $p_o = p_o^w + \tau_o$ (Oil Import Arbitrage Relation)

(13) $p_c^w = p_c + \tau_c$ (Corn Export Arbitrage Relation)

Note that equation (7) embeds the technological relationship $x_c = x_e/\alpha$. In equations (12) and (13), (τ_o, τ_c) are the oil-import-specific and corn-export-specific tariffs, respectively (assumed to be non-prohibitive, so trade still occurs). To close the model, consider first the hypothetical case of *laissez faire* equilibrium, in which $\tau_o = \tau_c = 0$ and there are no other active policy instruments that interfere with the competitive equilibrium. Then we must also have $p_e = p_g = p_f$, and subject to this restriction, conditions (7)-(13) can be solved for the equilibrium prices $(p_c, p_c^w, p_o, p_o^w, p_f, p_h)$ and for the ethanol quantity x_e. For scenarios in which there are active policy instruments, on the other hand, model closure needs to be tailored to the specifics of the policy that applies (e.g., the case of fuel taxes and ethanol subsidies, or that of a binding ethanol "mandate").

3.1. *Equilibrium with Fuel Taxes and Ethanol Subsidies*

Let t be the consumption tax on fuel, per gallon, and b be the volumetric blending subsidy per gallon of ethanol. Then, because gasoline and ethanol are modeled as perfect substitutes for consumers once measured in GEEG units, and because one gallon of ethanol is equivalent to γ GEEGs, arbitrage relations imply[9,]

(14) $p_g = p_f - t$

(15A) $p_e = p_f + \dfrac{b}{\gamma} - \dfrac{t}{\gamma} \quad = p_g + \tilde{b}$

where $\tilde{b} \equiv \left(b^0 - t(1-\gamma)\right)\big/\gamma$ is the effective net subsidy to ethanol, as compared to gasoline, per

[9] The assumption of perfect substitutes seems valid up to at least a 10% utilization rate for ethanol.

GEEG unit.[10] Thus, for the case of taxes and subsidies, equations (7)-(13), (14) and (15A) can be used to calculate the equilibrium, given the policy parameters $\{\tau_{o,}\tau_c,t,b\}$.

3.2. *Equilibrium with Mandates*

With a binding ethanol mandate (denoted by x_e^M) equations (7)-(13) still apply, but with $x_e = x_e^M$ exogenously set. Note that in this case the amount of corn utilized by the ethanol industry is fixed at x_e^M / α, and so, as equation (7) makes clear, the corn price is effectively determined in the corn market. Furthermore, the prices of fuel, gasoline and ethanol will have to be such that arbitrage possibilities are exhausted, i.e., blenders that combine ethanol and gasoline earn zero profit. This zero profit condition, allowing for the existence of exogenous fuel taxes and ethanol subsidies, can be expressed as

(15B) $$\left(p_f - t\right)\cdot D_f(p_f) = p_g\left[D_f(p_f) - x_e^M\right] + \left(p_e - \tilde{b}\right)\cdot x_e^M .$$

Equation (15B) states that the price of fuel is a weighted average of the price of its components (ethanol, gasoline), where the amount of ethanol is exogenously determined. Thus, with a mandate, the equilibrium is calculated using equations (7)-(13) and (15B). As shown in Lapan and Moschini (2009), the impact of an ethanol mandate is that of combining a fuel tax effect with an ethanol subsidy effect.

4. Welfare

In defining welfare, we assume all tax revenue is returned to domestic consumers and that there are no externalities other than those due to carbon emissions. Domestic welfare could be calculated using the indirect utility function along with the profit function for the domestic oil and corn industries and government tax revenue, or by using the direct utility function along with the production costs for domestic oil and corn, and the net imports from world trade in oil and corn. Using the latter approach, and consumer preferences in equation (1), we have

[10] Note that (15A) also accounts for the fact that the tax on fuel t is levied per volume unit. Because it takes $1/\gamma > 1$ gallons of ethanol to make one GEEG of fuel, the effective tax on ethanol is higher than that on gasoline.

$$(16)\quad \begin{aligned} W = &\left\{ I - C(Q_c) - \Omega(S_o) - \omega_e x_e - \omega_g x_g - \left[p_o^w \bar{S}_o - p_c^w \bar{D}_c \right] \right\} \\ &+ \left[\phi(x_g + x_e) + \theta(D_c) + \eta(D_h) \right] - \sigma(x_g + \lambda x_e). \end{aligned}$$

The term in curly brackets in (16) measures consumption of the numeraire good, y, while the term in square brackets on the second line measures consumer utility derived from consumption of fuel, corn and petroleum byproducts, and the last term measures the disutility due to pollution arising from energy consumption. Consumption of the numeraire in (16) is total income I (taken as exogenous and measured in numeraire units) less (i) $C(Q_c)$, the cost of aggregate corn output; (ii) $\Omega(S_o)$, the cost of domestic oil production; (iii) $\{\omega_e x_e + \omega_g x_g\}$, the cost of the other inputs used in ethanol production and oil refining; and (iv) $\left[p_o^w \bar{S}_o - p_c^w \bar{D}_c \right]$, the value of net imports of oil and corn, which are paid for with the numeraire good. Note that the competitive equilibrium conditions $C'(Q_c) = p_c$ and $\Omega'(S_o) = p_o$ yield the inverse supply curves, so specification of the supply curves for the two goods, used in equilibrium conditions (7) and (8), implies the form of the cost relations in (16). Similarly, specification of the demand relations used in (7)-(9) imply the forms of the sub-utility functions in (16), so the only additional specification of functional forms needed for the welfare calculations is that of the externality term, $\sigma(..)$. Thus, for the simulation exercise, welfare comparisons for different policy tools $(\tau_c, \tau_o, t, b; x_e^M)$ can be made by solving the equilibrium conditions from section (3), specifying $\sigma(\cdot)$ and then using (16) to calculate welfare.

To understand how the optimal (or second best) policies are determined, take the total differential of (16) and rearrange terms to yield[11]

$$(17)\quad \begin{aligned} dW = &(\theta' - C')dD_c + \left(\phi' - \lambda\sigma' - \omega_e - (C'/\alpha)\right)dx_e + \left(\left[\phi' + (\beta_2/\beta)\eta' - \sigma'\right] - \omega_g - (\Omega'/\beta)\right)dx_g \\ &+ \left(\Omega' - \left[p_o^w + \bar{S}_o\left(dp_o^w/d\bar{S}_o\right)\right]\right)\bar{S}_o' dp_o^w + \left(\left[p_c^w + \bar{D}_c\left(dp_c^w/d\bar{D}_c\right)\right] - C'\right)\bar{D}_c' dp_c^w. \end{aligned}$$

The first three terms in (17) relate to domestic resource allocation decisions, whereas the last two relate to trade decisions, and for each term, optimality entails equating marginal benefit to marginal cost. Thus, θ' is the value to consumers of additional corn consumption, C' is the

[11] See Lapan and Moschini (2009) for full details.

marginal cost of corn production, and hence optimality requires $\{\theta' = C'\}$. Similarly, the second term—relating to ethanol production—says that the marginal value of fuel to consumers, less the pollution cost, should be equated to the marginal cost of producing ethanol. A similar interpretation applies to the third term, where the term in square brackets is the net *social* value of another unit of refined gasoline and byproducts, and $\left[\omega_g + \left(\Omega'/\beta\right)\right]$ is the extraction and refining cost of producing that gallon. The two terms in the second row relate to trade decisions and are the only places where (world) prices appear explicitly; domestic prices affect domestic welfare only insofar as they affect resource allocation, but changes in world prices affect domestic welfare directly. Thus, the last two terms state that the marginal cost of producing oil domestically should equal the marginal cost of importing oil, and that the marginal cost of producing corn domestically should equal the marginal revenue derived from corn exports.

In a market economy, rational consumers equate the marginal private value of a good to the market price they face, and competitive profit-maximizing firms will equate the marginal private cost to the prices they face. Hence, the rationale for government intervention arises when there is some divergence between private and social costs or benefits. In our model this divergence obviously occurs when fuel is consumed, because of the externality generated by the combustion of that fuel. Furthermore, from the perspective of the domestic economy, a divergence between private and (domestic) social costs also occurs if the country's trade decisions affect world prices. For example, for a competitive firm importing oil, the marginal private cost of the import is its price p_o^w, but from the perspective of the economy as a whole, if additional imports increase world price, the marginal cost of the import is higher than that, namely, $p_o^w + \bar{S}_o(dp_o^w / d\bar{S}_o)$. Similarly, for corn exports, the marginal value perceived by a competitive corn exporter is p_c^w, whereas the marginal revenue for the country as a whole is $p_c^w + \bar{D}_c(dp_c^w / d\bar{D}_c)$. Thus, as shown in Lapan and Moschini (2009), the first best policy entails oil import tariffs, corn export tariffs and a tax on carbon emissions. As for the latter, the "carbon tax" is fully equivalent, in this model, to a fuel tax (i.e., a tax on both gasoline and ethanol) along with an ethanol subsidy (because of the assumed differential pollution of ethanol, captured by the parameter λ).[12] Specifically, it is shown that the "first best" policy instruments are[13]

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[12] The first best net ethanol subsidy, $\tilde{b}$, reflects the differential pollution rates between the two energy sources. The fact that the statutory fuel tax is in gallon terms implies a higher effective tax on ethanol in GEEG units. Thus, even if ethanol caused the same amount of pollution as gasoline, the first best would require a positive gross subsidy b to ethanol to offset the higher fuel tax.

$$
(18) \quad
\begin{aligned}
t^* &= \sigma'(\cdot); \\
\tilde{b}^* &= (1-\lambda)\sigma'(\cdot) \\
\tau_o^* &= \bar{S}_o(\cdot)/\bar{S}_o'(\cdot) \\
\tau_c^* &= \bar{D}_c(\cdot)/\bar{D}_c'(\cdot).
\end{aligned}
$$

In our analysis, such a first best scenario provides an important (and insightful) benchmark for other, perhaps more realistic, policy scenarios. Another useful benchmark is the "*laissez faire*" scenario, i.e., the unfettered competitive equilibrium with $t = b = \tau_o = \tau_c = 0$. In fact, all welfare calculations are reported as differences relative to the *laissez faire*, and comparisons of each policy scenario with the first best provide information as to the efficacy of the various second best policies considered. Note that in all scenarios except the first best we restrict tariffs to be zero (i.e., $\tau_o = \tau_c = 0$) so that, realistically, they presume that the United States is in compliance with its WTO obligations.[14] Once we impose this restriction, we are operating in a "second best" environment and the (constrained) optimal values of these second best instruments depend on the feasible policy space. As noted, we assume the feasible policy instruments are fuel taxes and/or ethanol subsidies (or ethanol mandates and/or ethanol subsidies or fuel taxes).[15] Using these policy restrictions and the behavioral conditions outlined earlier, (17) can be rewritten as

$$
(17A) \quad dW = \left(p_f - p_e - \lambda\sigma'\right)dx_e + \left(p_f - p_g - \sigma'\right)dx_g - \bar{S}_o dp_o + \bar{D}_c dp_c.
$$

Thus, when tariffs are not permitted, in determining the welfare consequences of domestic policy instruments, one must consider their impact on the terms of trade as well as on carbon emissions. As we shall see from the simulations, under many plausible scenarios, it is these "large country" effects that dominate the welfare calculations. When there are no border policies, it can

[13] To calculate the actual values of the instruments, the equilibrium conditions described in Section 3 must be used in conjunction with (18).

[14] Because an import tariff on a given good is equivalent to a domestic production subsidy and a domestic consumption tax of the same amount, banning import tariffs is equivalent to placing a restriction on domestic policies, which explains the second best nature of these policy scenarios.

[15] Thus, for example, we do not allow a tax on domestic corn production.

be shown that (17A) reduces to[16]

(17B) $$dW = \left(p_f - p_e - \lambda\sigma' + \frac{\bar{D}_c}{\alpha Q'} \right) dx_e + \left(p_f - p_g - \sigma' - \frac{\bar{S}_o}{\Delta'(p_o)} \right) dx_g .$$

Here $\Delta(p_o) \equiv \beta(\bar{S}_o(p_o) + S_o(p_o))$ is the supply of unblended gasoline, and $Q(p_c) \equiv \{S_c(p_c) - D_c(p_c) - \bar{D}_c(p_c)\}$ is the residual supply of corn for ethanol. When both fuel taxes and ethanol subsidies can be used, the second best policies are

(19) $$\begin{aligned} t^{sb} &= \sigma' + \frac{\bar{S}_o}{\Delta'} \\ \tilde{b}^{sb} &= (1-\lambda)\sigma' + \frac{\bar{S}_o}{\Delta'} + \frac{\bar{D}_c}{\alpha Q'} \end{aligned}$$

where the superscript "*sb*" denotes second best. The tax t^{sb} can be thought of as the tax levied on gasoline, which incorporates two positive components because increased gasoline use worsens the U.S. terms of trade for oil and increases pollution costs. The difference between the tax and subsidy optimal levels, $\tilde{b}^{sb} - t^{sb} = \bar{D}_c / \alpha Q' - \lambda\sigma'$, represents the effective overall subsidy (or tax) on ethanol; the positive component reflects the fact that increased ethanol use benefits the United States by increasing world corn prices, while the negative component reflects the pollution costs associated with ethanol use.

When the ethanol subsidy is the only choice variable, the government cannot independently control gasoline and ethanol consumption. For this case it can be shown that the optimal ethanol subsidy, as a function of the exogenous fuel tax, t^0, is[17]

[16] The paper by Lapan and Moschini (2009) contains the details, but the logic underlying (17B) is direct. If the government induces increased ethanol use, this increases the price of corn: specifically, $dp_c / dx_e = 1/\alpha Q'$. Similarly, increased gasoline use will drive up the price of oil, harming the country by making imports more expensive.

[17] This formula differs from the corresponding one in Lapan and Moschini (2009) because here we explicitly allow for the presence of petroleum byproducts, a feature that is important for the quantitative results of interest in this study. In the special case where $\beta_2 = 0$ (i.e., no byproducts), of course, the two conditions are identical.

$$(20) \qquad \tilde{b}^{sub} = \frac{\bar{D}_c}{\alpha Q'} - \lambda\sigma' + \rho\left(\sigma' + \frac{\beta\bar{S}_o}{\psi'}\right) + (1-\rho)t^0$$

where

$$\rho = \frac{\beta\Delta'}{\beta\Delta' - D'_f + \beta\Delta'(\beta_2/\beta)^2\left(D'_f/D'_b\right)} \in (0,1).$$

Note that $\tilde{b}^{sub} = \tilde{b}^{sb} + (1-\rho)\left(t^0 - t^{sb}\right)$. Hence, when the fuel tax is not a choice variable and $t^0 < t^{sb}$, then the subsidy will generally be lower than the second best subsidy and this subsidy will be increasing in the exogenous tax rate.

When only the mandate is the choice variable, it can be shown that the first-order condition for an optimal choice of the mandate reduces to[18]

$$(21) \qquad \frac{dW}{dx_e} = \left(p_f - p_e - \lambda\sigma' + \frac{\bar{D}_c}{\alpha Q'}\right) + \left(p_f - p_g - \sigma' - \frac{\bar{S}_o}{\Delta'}\right)\left(\frac{dx_g}{dx_e}\right)^{man} = 0$$

where the superscript "*man*" denotes the mandate scenario, and

$$\left(\frac{dx_g}{dx_e}\right)^{man} = \frac{-\left(1 + \left(\frac{-D'_f}{\alpha^2 Q'}\right)s + (1-s)\delta\left(\frac{-D'_f}{x_f}\right)\right)}{1 + \left(-D'_f\right)\left(\frac{1}{\beta\Delta'} + \frac{(\beta_2/\beta)^2}{-D'_b}\right)(1-s) + \frac{s\delta D'_f}{x_f}}$$

where $s \equiv x_e/(x_e + x_g) \in (0,1)$ denotes the share of ethanol in total fuel, and $\delta \equiv \left(p_e - p_g - \tilde{b}\right) > 0$. In the simulations that follow, we consider each of the cases discussed above.

5. Calibration of the Model

The baseline model is calibrated to fit 2009 data using linear supply and demand curves. In order to calibrate the model, we need to specify the values of the exogenous parameters and the value

[18] Again, the procedure for deriving this result is similar to that in Lapan and Moschini (2009), but the specific result differs because of the presence, in our model, of petroleum byproducts.

of the policy variables in this baseline period. In addition, we also need to specify the domestic and world import demand functions for corn $D_c(p_c)$ and $\bar{D}_c(p_c^w)$, the domestic supply of corn $S_c(p_c)$, the domestic and world export supply functions for oil $S_o(p_o)$ and $\bar{S}_o(p_o^w)$, the demand for fuel $D_f(p_f)$ and the demand for petroleum byproducts $D_h(p_h)$. If these functions come from a two-parameter family of functions, as for the linear functional forms that we will be using, each demand or supply function can be "calibrated" using an estimate of the elasticity (of supply or demand) for that function and the value of the relevant variables in the baseline period.

Table 1A gives the assumed baseline values, and sources, for the primitive parameters (e.g., elasticities) used in the calibration of the model, and Table 1B gives the value of some other calculated parameters, and their method of calculation, which are provided to ease the interpretation of the model. Tables 2A and 2B give the primary sources (or methods of calculation) and the 2009 value used for each baseline variable, including the policy variables. Some parameters are drawn from a comprehensive survey of the literature, while others are calculated from their definitions in terms of more primitive terms. In general, data for corn utilization and price are gathered from the Feed Grain Database of the U.S. Department of Agriculture (USDA) at http://www.ers.usda.gov/Data/FeedGrains/, and data for oil, gasoline and oil refinery byproducts are obtained from the U.S. Energy Information Administration (EIA) website at http://www.eia.doe.gov/. Ethanol quantity data are from the Renewable Fuels Association (RFA) website and ethanol prices are provided by the Nebraska Energy Office (NEO) website at http://www.neo.ne.gov/statshtml/66.html. More specific information on sources of data used is provided in the tables that follow.

5.1. Prices in the Baseline

Because ethanol has a lower energy content than gasoline, its quantity, price, fuel tax and subsidy level used in the simulation are all converted to be expressed per GEEG. Currently, fuel consumption (blended gasoline with ethanol) is subject to the federal tax of $0.184/gallon plus state-level taxes, which are, on average, equal to $0.203/gallon. Hence, for gasoline, $t^0 = \$0.39$. However, because one gallon of ethanol equals only .69 GEEG, the fuel tax on ethanol is t^0/γ, that is, $0.565/GEEG. Ethanol production has a tax credit of $b^0 = \$0.45$/gallon when blended with gasoline, which is equivalent to a net subsidy to ethanol of $\tilde{b}^0 =$ $0.475/GEEG. The U.S. ethanol price of $1.79/gallon is the 2009 average rack price F.O.B. Omaha, Nebraska, and this corresponds to a price of \$2.59/GEEG.[19] Prices of fuel and (unblended) gasoline are calculated from arbitrage conditions, which are assumed to hold in the *status quo*, that is, $p_f = p_e - \tilde{b}^0 + t^0 = \$2.50$ /GEEG, and $p_g = p_e - \tilde{b}^0 = \$2.11$ /GEEG.[20] The crude oil price of \$61.00/barrel is the refiner's composite acquisition cost of crude oil, the weighted average of acquisition costs of domestic and imported oil. The corn price of \$3.74/bushel uses the averaged farm price. The USDA price of the byproduct in ethanol production, DDGS, is \$114.40/t (metric ton), which reflects the wholesale price in Lawrenceburg, IN. We used EIA data to calculate a weighted average retail price, excluding taxes, for petroleum byproducts in the oil refining process; this price index is denoted p_h, and its 2009 value is \$1.76/GEEG.[21] The prices of the "other" inputs used in gasoline and ethanol production, w_g and w_e, are derived from the zero profit condition, $w_g = p_g + \beta_2 p_h / \beta - p_o / \beta = \$1.10$ /GEEG and $w_e = p_e - p_c / \alpha = \$1.11$ /GEEG, respectively. The estimated productivity parameters α, β and β_2 are discussed next.

5.2. Productivity Parameters

One bushel of corn produces approximately 2.80 gallons of ethanol (Eidman 2007); thus $a = 2.80$. The production of ethanol generates bioproducts that are useful as animal feed (and thus can replace corn in that use). The nature of such bioproducts depends on whether ethanol is produced in a dry milling plant or in a wet milling plant. Because dry milling plants are much more common, we construct the model as if all ethanol is produced in dry milling plants.[22] According to industry sources (RFA), such a process generates as a byproduct about 17 lbs of DDGS per bushel of corn; given that there are 56 pounds in a bushel, then $\delta_1 = 0.303$. The

[19] See http://www.neo.ne.gov/statshtml/66.html for the primary data.

[20] This calculation method is necessary for the internal consistency of our model. A question, perhaps, is how close this calculated value is to 2009 observed data. From EIA data, the average retail price of all grades and all formulations of gasoline in 2009 was \$2.406/gallon, which is fairly close to the calculated fuel price. Also, from the same source, the average wholesale (rack) price of gasoline in 2009 was \$1.75/gallon, which is not too close to our computed gasoline price.

[21] Because prices for all the byproducts of the refining process were not available, the price index we constructed only uses the prices of aviation gasoline, kerosene-type jet fuel, kerosene, distillate fuel oil, and residual fuel oil. Together, these products account for 70%, by weight, of all petroleum byproducts in the oil refining process.

[22] According to the RFA, more than 80% of corn used in ethanol production is processed via dry milling plants, with the remaining 20% processed via wet milling plants.

DDGS price relative to the corn price is captured by the parameters $\delta_2 = 0.776$, calculated as described in Table 1A from the data discussed in the foregoing. Given the assumption of perfect substitution between corn and DDGS in feed use, then each processed bushel of corn generates, as a byproduct , the equivalent of $\delta_1\delta_2 = 0.24$ bushels of corn.[23] Hence, the ethanol production coefficient, accounting for byproduct value, is $\alpha = 2.53$ GEEG/bushel.

5.3. Quantities in the Baseline

For the baseline scenario, we use domestic production including stock changes and other adjustments to measure domestic supply, net exports of corn to measure foreign demand and net imports of oil to measure foreign oil supply. In the *status quo* (for 2009), there are 13.15 billion bushels of corn and 1.93 billion barrels of domestic oil produced in the U.S. The quantities of foreign corn demanded (U.S. exports) and oil supplied (U.S. imports) were 1.86 billion bushels and 3.29 billion barrels, respectively. Corn utilization consists of three main uses: domestic food/feed use (exclusive of ethanol use), foreign demand (exports) and ethanol use. The U.S. ethanol production of 10.76 billion gallons (RFA data) corresponds to 7.43 billion GEEG. Given the assumed fixed-proportion technology of ethanol production, the net amount of corn used in ethanol production is calculated to be $Q_c = x_e / \alpha = 2.94$ billion bushels. The corn food/feed use is then obtained from market balance, where $D_c = S_c - \bar{D}_c - Q_c = 8.35$ billion bushels. EIA reports data for the finished motor gasoline product, including blended ethanol, of 134.4 billion gallons, which measures total fuel consumption in volumetric units. Subtracting ethanol production (in volumetric units) from the figure for finished motor gasoline gives unblended gasoline's contribution to total fuel consumption, $x_g = 123.6$ billion GEEG units. Final fuel consumption, measured in GEEG units is the sum of gasoline and ethanol consumption in the same units, $x_f = x_g + x_e = 131.0$ billion GEEG units. The assumed fixed-proportions technology in oil refining gives the calculated yield of gallons of gasoline per barrel of crude oil as $\beta = x_g / x_o = 23.6$ GEEG/barrel.[24] Given β, the yield of petroleum byproducts

[23] EPA now assumes that 1 pound of distillers grains will replace 1.196 pounds of total corn and soybean meal for various beef cattle and dairy cows in 2015. The displacement ratio remains at 1:1 for swine and poultry (EPA 2010).

[24] Alternatively, one could recover the β parameter from refinery yields data reported by EIA, e.g., β = (42 gallon/barrel) × (1 - Annual Average Process Gains) × (Finished Motor Gasoline Yield). Note that this formula accounts for the fact that EIA measures gains as negative numbers. This procedure would yield $\beta = 20.6$ GEEG/barrel. The discrepancy of this value with

(in gallons) from a barrel of crude oil is calculated to be $\beta_2 = 21.1$. [25]

5.4. Carbon Emissions

The carbon emission rate of gasoline, measured as carbon dioxide (CO_2), is 11.29 kg/GEEG (Wang 2007). The estimated net carbon dioxide emissions rate of ethanol has a considerable range, which depends on feedstock sources and the accounting for indirect land use changes. We apply the rate of 8.42 kg/GEEG of CO_2 from the life cycle perspective suggested by Farrel et al. (2006), which is close to the emission rate of corn ethanol without feedstock credits reported in Searchinger et al. (2008). There is, of course, considerable uncertainty (and controversy) about ethanol's actual carbon dioxide emissions. For example, Searchinger et al. (2008) estimate the following specific CO_2 rates: 5.934 kg/GEEG for corn ethanol with feedstock credits, and 19.164 kg/GEEG for corn ethanol without feedstock credits but accounting for land-use changes.[26] These values, in turn, imply that the relative pollution efficiency of ethanol to gasoline (i.e., the parameter λ) is around 0.75 in the benchmark case, with a range of 0.52 to 1.70 .[27] To capture the influence of such uncertainty on the optimal values of the policy instruments, some sensitivity analysis on the impact of ethanol's emissions rate will be carried out.

5.5. Carbon Dioxide Emissions Cost

There are extensive estimates regarding the social cost of carbon dioxide emissions. Tol (2009) surveys 232 published estimates of the marginal damage cost of carbon dioxide. The mean of these estimates is a marginal cost of carbon emissions of \$105/tC (metric ton carbon), which is equivalent to \$28.60/tCO_2, with a standard deviation equivalent to \$243/tC (\$66/tCO_2), where social costs are measured in 1995 dollars. The widely cited "Stern Review" (Stern et al. 2006) has a higher estimate of approximately \$80/tCO_2, due to a lower discount rate applied to future

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the one we use, as explained in the text, is likely due to the additives in blended gasoline.

[25] As explained in Table 1, there are 42 gallons per barrel of crude oil, and because of a yield gain in the refining product, there are approximately 44.7 gallons of refined product per barrel of oil. Subtracting the calculated value of 23.6 gallons of gasoline per barrel of crude oil provides the calculated value of β_2.

[26] Note that, for ease of comparison, we have converted their measures of carbon dioxide emissions rates from grams of CO_2 per megajoule of energy to kilograms per GEEG. The feedstock credits refer to the carbon benefit of devoting land to biofuels (Searchinger et al. 2008).

[27] The value for λ of 0.75 corresponds closely to the recent EPA released value of 0.79 (EPA 2010).

economic damage from climate change. Using a more conventional discount rate, Hope and Newbery (2008) find that the carbon cost from the Stern report could be reduced to the range of \$20-\$25/tCO_2.

The National Highway Traffic Safety Administration (NHTSA) calculates their proposed corporate average fuel economy (CAFE) standard by relying on Tol's (2008) survey, which includes 125 estimates of the social carbon cost published in peer-reviewed journals through the year 2006 (NHTSA 2009). Tol (2008) reports a \$71/tC mean value, and a \$98/tC standard deviation of these estimates of the social carbon cost (expressed in 1995 dollars). Adjusted to reflect increases of emissions at now-higher atmospheric concentrations of GHGs, and expressed in 2007 dollars, Tol's (2008) mean value corresponds to \$33/tCO_2, with a standard deviation of about \$47/tCO_2. NHTSA (2009) also employs a range of estimates for the value of reducing GHG emissions, which consists of a domestic value (\$2/tCO_2) at the lower end, a global value (\$33/tCO_2) equal to the mean value in Tol (2008), and a global value (\$80/tCO_2) one standard deviation above the aforementioned mean value.

The EPA (2008) derives estimates of the social carbon cost using the subset of estimates in Tol's (2008) survey. They report an average value of \$40/tCO_2 for studies using a 3% discount rate, and \$68/tCO_2 for studies using a 2% discount rate. These values are also updated to reflect increases in the marginal damage costs of emissions at growing atmospheric concentrations of CO_2 and expressed in 2006 dollars.

The pollution externality cost used in our paper is meant to account for local and global warming costs. We use a value of \$33/tCO_2, which, as discussed, is consistent with NHTSA (2009). For our sensitivity analysis we explore the implications of different values for this cost, in the range of \$2/tCO_2 – \$100/tCO_2. The lower end of this range is of some interest because it corresponds to the NHTSA estimate of the impact of CO_2 pollution on the domestic economy only. Other externality costs associated with congestion, accidents and non-carbon pollution are not explicitly taken into account.[28] Given the assumed linear cost function of the emissions externality $\sigma(\cdot)$, the marginal effect $\sigma'(\cdot)$ represents the normalized constant marginal emissions damage from gasoline. Given our assumption of \$33/tCO_2 for the cost of carbon dioxide pollution, $\sigma'(\cdot) = 37$ cents/GEEG.

[28] Parry and Small (2005) take the lower and upper limit of pollution damages to be \$0.7/tC and \$100/tC respectively, and the central value to be \$25/tC. They also account for external congestion costs of 3.5¢/mile, and an external accident cost of 3¢/mile.

5.6. Elasticities

The elasticity estimates are obtained from the literature to reflect the best available econometric evidence. As most of the studies suggest that the short-run corn supply elasticity is within the range of [0.2, 0.4], and the long-run supply elasticity is 0.5, we pick a value of $\varepsilon_c = 0.23$ from the USDA (2007).[29] The elasticity of domestic food/feed demand of $\eta_c = -0.2$ is from de Gorter and Just (2009b). The estimates for the elasticity of foreign corn import demand $\left(\overline{\eta}_c\right)$ range from an inelastic value of -0.30 (short-run value) used by Gardiner and Dixit (1986), to a considerably more elastic value of -2.41, reported by the country commodity linked system performed by the Economics Research Service at the USDA. They get implied partial elasticities of foreign behavior with respect to a sustained exogenous shock to the world price of corn only, the implied elasticity of net imports in the third year is -2.41. We use the value of -1.74, obtained from the 2004 FAPRI Missouri documentation, and also carry out sensitivity analysis within the range of [-3.0, -1.0]. Estimates for the elasticities of domestic oil supply $\left(\varepsilon_o\right)$ of 0.2 and foreign export oil supply $\left(\overline{\varepsilon}_o\right)$ of 2.63 are drawn from de Gorter and Just (2009b).[30] A range of [1.0, 5.0] for elasticity of foreign export oil supply is considered for the purpose of sensitivity analysis. The elasticity of fuel demand η_f is assigned a benchmark value of -0.5, with the range [-0.9, -0.2], as suggested by Toman, Griffin and Lempert (2008), which is consistent with Parry and Small (2005) as well (they use an elasticity of gasoline demand of -0.55, with the range [-0.9, -0.3]). As for elasticities of gasoline and ethanol supply, the construction of our model does not need these as primitive parameters, although the implied elasticities of the derived ethanol supply and gasoline supply are easily derived for the purpose of comparison with other models.[31]

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[29] Gardner (2007) uses a short-run elasticity of 0.23 from USDA, and a long-run elasticity of 0.5; de Gorter and Just (2009b) use 0.2 as the elasticity of corn supply.

[30] They define the foreign oil (export) supply as the horizontal difference between the OPEC supply and the excess demand of other oil importers excluding the United States, then derive this elasticity under the assumption that OPEC supply elasticity is 0.71 and the excess demand is -0.86, both of which are in the range of Leiby (2007).

[31] Quantities are given by production technology, and prices are found from long-run equilibrium conditions, as explained in the text. Given these quantities and prices, the implied elasticities (in the baseline case) of the derived ethanol supply and gasoline supply can be calculated as per the formulae reported in Table 1 to yield $\varepsilon_e = 4.73$ and $\varepsilon_g = 1.42$, respectively.

6. Results

Given the assumed parameters discussed in the foregoing section, the remaining parameters of the model are calibrated (i.e., the coefficients of the postulated linear supply and demand curves are computed) to replicate price and quantity data of the baseline (or *status quo*) scenario for the calendar year 2009. We then consider a number of policy environments; only in the first-best situation are border policies (import and export tariffs) allowed. These scenarios are as follows:

(i) *Laissez-faire*, with no border or domestic taxes or subsidies.

(ii) Current fuel tax but no ethanol policy.

(iii) The first best: border policies and domestic policies are used.

(iv) The second best: the fuel tax and ethanol subsidy are chosen optimally.

(v) The ethanol subsidy is chosen optimally; the fuel tax is set at its current level.

(vi) An ethanol mandate is chosen optimally; the fuel tax is set at its current level.

For each scenario, we report in Table 3A the values of the policy instruments and the equilibrium value of the simulated variables. In Table 3B, for the same sets of scenarios, we report the welfare impacts (as changes from the fictitious *laissez faire* equilibrium), broken down into their components so as to illustrate the distributional effect, as well as the impact of each scenario on the total carbon emission.[32] The overall net welfare gains are calculated in the usual manner, by summing the (changes in) producer surpluses, consumer surpluses, government tax revenue and the pollution damages.[33] Perhaps the most striking thing about our results is that all scenarios improve upon the *laissez faire* equilibrium solution. In particular, the *status quo* equilibrium with "ad hoc" levels of the ethanol subsidy and the fuel tax captures over one-half of the maximum gain that can be achieved with first-best policies.

6.1. Status Quo and Status Quo Ante Ethanol

The *status quo* values for prices and quantities reflect the actual (average) values of those variables for 2009. Compared to the simulated *laissez faire* equilibrium, the fuel tax of \$0.39/GEEG and the gross ethanol subsidy of \$0.45/gallon lead to higher (retail) fuel prices, higher ethanol prices, a very modest 3% decline in (world and domestic) oil prices but a significant 18% increase in corn prices. Consequently, the combined policy causes domestic fuel consumption to fall—but just barely—as a 6.7 billion gallon decline in gasoline consumption is offset by a 6.4 billion gallon

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[32]The producer surpluses for ethanol producers and oil refiners are zero because of the assumed constant-returns-to-scale technology and competitive behavior in these sectors

[33] Because ethanol production for 2009 exceeds the mandate level, in calibrating the model we assume that the mandate does not bind, and that it is the fuel tax and ethanol subsidy policies that affect equilibrium values.

increase in ethanol consumption (a 4.4 billion increase in GEEG units). This (small) drop in fuel consumption—and the substitution of some ethanol for gasoline—leads to a 3% (or a 49.9 million tCO_2) decrease in carbon dioxide emissions; at the baseline cost of \$33/tCO_2, this is equivalent to a \$1.6 billion decrease in pollution costs. As Table 3B shows, the principal beneficiaries of this *status quo* policy are the government (higher tax revenue) and corn producers, while oil producers are hurt by the fuel tax and consumers are hurt by higher prices (but they benefit, however modestly, because of the reduced externality incidence). As previously noted, relative to the *laissez faire* there is an \$8 billion increase in net welfare, which amounts to 53% of the maximum gain achievable by optimum policies. U.S. dependence on foreign oil also declines, as oil imports (billion barrels) fall by about 8%.

The column "no ethanol policy" in Table 3B looks at the scenario in which the current fuel tax of \$0.39/GEEG continues to apply, but there is no subsidy or other policy supporting ethanol production. When compared to the *status quo* scenario, this case provides a useful characterization of the marginal impact of current U.S. ethanol policies. Specifically, without such policies the ethanol industry would be almost non-existent, with only 0.58 billion gallons of production (around 5% of the status quo value). The lack of explicit government support is not the only effect working against ethanol production in this scenario: the fuel tax, being levied per volume of fuel, implicitly taxes ethanol at a higher rate (because of the latter's lower efficiency level in GEEG terms). The fuel price is also higher with no ethanol policy than in the *status quo*, which illustrates an aspect of current policies discussed by de Gorter and Just (2009b): the ethanol subsidy has a consumption subsidy effect for final consumers. As for welfare effects, the introduction of the current ethanol support policy is beneficial (the welfare measure of the *status quo* exceeds that of the no ethanol policy scenario by \$6.3 billion). But note that the mechanism by which this happens is not by reducing pollution, which actually is higher under the *status quo* than under the no ethanol policy scenario (by 20 million tCO_2). Instead, ethanol policies are mostly useful because of their terms-of-trade effects. Comparison of these two scenarios in Table 3B also illustrates that the big winners from the ethanol policy are corn producers and fuel consumers.

6.2. The First Best Policies

In the baseline scenario, the marginal emissions damage is \$33/tCO_2 and thus the first best policy entails a tax on carbon dioxide emissions of \$33/tCO_2, in addition to oil import and corn export tariffs. This tax on carbon dioxide emissions is equivalent, in our model, to a gasoline tax of \$.37/GEEG, which is remarkably close to the *status quo* (average) fuel tax of \$0.39. Since in the baseline model ethanol is assumed to pollute less than gasoline, and since the $0.37 tax is assumed levied on gallons of *fuel*, then a gross subsidy to ethanol of $0.18/gallon (or $\tilde{b}^* =$ $0.094/GEEG) is required to support the first best solution. Thus, the first best policies entail a 27.8¢/GEEG tax on ethanol, a 37¢/GEEG tax on gasoline, a $19.2/barrel import tariff on oil, and a $1.10/bushel export tariff on corn. These policies would increase welfare by $15.0 billion compared to the *lassez faire* scenario, and $7.0 billion compared to the *status quo*. Compared to the *laissez faire* scenario, the combined effect of these policies is to increase U.S. oil prices by over 21%, while world oil prices fall by slightly over 9%. Despite the corn export tariff, U.S. corn prices increase by 16.4% (world corn prices rise by over 51%); because of the conversion of corn into ethanol, the negative impact on U.S. corn prices of the corn export tariff is overwhelmed by the positive impact of higher domestic oil prices. Overall fuel consumption falls significantly, and ethanol replaces some gasoline, so carbon dioxide emissions fall by slightly over 10%. U.S. dependence on foreign oil falls sharply, as imports fall by nearly 24%, oil consumption falls and domestic oil production rises. From a welfare perspective, domestic oil producers and corn producers both gain and the government gains significant tax revenue, but consumers lose both because of higher oil (and fuel) prices and because of higher corn prices.

Compared to current policies, the first best policy leads to a significant reduction in oil imports, fuel consumption and pollution, and a significant increase in ethanol production. Corn prices fall as the negative impact of the lower ethanol subsidy and the corn export tariff more than offset the positive impact on corn prices because of the oil import tariff. Thus, while the implementation of first best policies brings a welfare gain of $7.0 billion compared to the *status quo*, there is a significant redistribution of income away from consumers and corn producers to oil producers and the government. Moreover, more than half of the welfare gain is accounted for by the decline in pollution costs.

6.3. Second Best Policies: Fuel Taxes and Ethanol Subsidies

The second best fuel tax and ethanol subsidy are presented in the fourth column of Table 3B. Interestingly, we see that these policies perform almost as well as the first best policies in terms of the welfare gain, and actually result in a (very slightly) larger reduction in carbon dioxide emissions. In addition, oil imports are only 3% larger than under first best policies. The first best oil tariff of $19.2/barrel (at 23.6 gallons per barrel) is similar to a gasoline tax of $0.81/gallon; combined with the $0.37/gallon tax for pollution damages, this means the first best policies are similar to an overall fuel tax of $1.18, which is remarkably close to the second best tax of $1.17, as given in Table 3A.[34] We also see from the table that, relative to the first best, the ethanol subsidy increases significantly. Note that the second best policy can be characterized as a tax on gasoline at the rate of $1.16/gallon and a small net tax on ethanol (the second-best subsidy of $1.16/gallon for ethanol essentially offsets the fuel tax). This results in an increase in ethanol production to 15.2 billion gallons, slightly above the 2015 mandate level of 15 billion gallons. The combined policies also lead to a nearly 17% increase in domestic corn prices. Thus, the fuel tax increases largely offset the elimination of the oil import tariff, and the ethanol subsidy increase partially offsets the impact on the world corn price of the elimination of the corn export tariff.[35] Compared to the *laissez faire*, these policies reduce world oil prices by 8% and increase world corn prices by over 36%; relative to the first best, world oil prices increase by a very modest $0.60/barrel and world corn prices fall by a more substantial $0.47/bushel.

Even though the second best policy captures almost 90% of the gains achievable by the first best policy mix (relative to *laissez faire*), the distributional effects differ. Compared to the first best policy mix, consumers lose more, largely because of higher domestic corn prices; domestic oil producers suffer significant losses as the domestic price of oil falls, but corn producers gain and government tax revenue increases. Overall, the policy largely redistributes income from oil producers to the government. Perhaps the principal surprise is how well this second best policy mix performs compared to the first best policy mix.

It should also be noted that the crucial difference between this second best scenario and the first best scenario discussed earlier is that here, border policies (oil import and corn export tariffs) are precluded. Having restricted the policy space to taxing fuel while supporting ethanol production, which policy instrument is used in the ethanol market does not matter. More precisely, the second best policy mix could be alternatively characterized as comprising an ethanol mandate equal to the second best ethanol production (15.22 billion gallons) along with the appropriate fuel tax (which can be shown to equal $1.03/gallon).

6.4. Optimal (Constrained) Ethanol Policy

Columns 5 and 6 of Table 3A report the results of two scenarios in which ethanol policy instruments are the only levers, with the fuel tax fixed at its current rate of $0.39/gallon. Specifically, in the scenario of column 5 an ethanol subsidy is the only discretionary policy

[34] The reason the gasoline tax it is not equivalent to an oil import tariff, despite the assumed Leontief technology for converting oil to gasoline, is because the gasoline tax is also levied on domestic oil production.

[35] Of course, the fuel tax affects corn prices and the ethanol subsidy has a modest affect on oil prices.

instrument, and in the scenario of column 6, an ethanol mandate is the only instrument. For both cases it is seen that, while there are significant welfare gains relative to the *laissez faire* equilibrium, the gains compared to the *status quo* are not large; thus, in terms of our second best policy instruments, the fuel tax has a potentially larger impact on welfare than does ethanol policy.

As shown in the sixth column of Table 3A, the optimal ethanol subsidy, when the fuel tax is fixed at $0.39/GEEG, is $0.68/gallon, fairly close to the *status quo* subsidy level and, as predicted by the theory, well below the second best subsidy level that applies when fuel taxes are also chosen optimally. However, for the case of the $0.39/gallon fuel tax, the "net" subsidy to ethanol is actually $0.42/GEEG, as opposed to a net tax of only $0.02/GEEG in the second best scenario. Compared to the second best scenario, ethanol production increases by 4.5%, and exceeds the 2015 mandate level of 15 billion gallons. Compared to the second best, the lower fuel tax means that gasoline consumption also increases, so CO_2 emissions are not only higher than in the second best, they are higher than in the *status quo* situation (Table 3B). Overall, then, given the fuel tax, the benefits of adjusting the subsidy away from its *status quo* value are minimal, and the environmental benefits are negative.

As noted in Lapan and Moschini (2009), an ethanol mandate is equivalent to a revenue neutral ethanol subsidy and fuel tax. Since column 6 combines this mandate with the *status quo* fuel tax, and since this combined effective fuel tax is lower than the second best combination of fuel tax and ethanol subsidy, the optimal mandate yields higher welfare than the optimal subsidy policy (column 5). Of course, by construction, the welfare level that is attained here is lower than that associated with the optimal second best policy (column 4). Compared to the optimal subsidy policy, since raising the ethanol mandate simultaneously raises the effective fuel tax, gasoline consumption is lower under the mandate than under the subsidy whereas ethanol production (and hence the price of ethanol) exceeds that under any other policy.[36] This ethanol consumption level exceeds the RFS2 mandate requirement of 15 billion gallons per year of conventional biofuel (corn ethanol) by 2015. The mandate also leads to higher domestic corn prices than under any of the other policies, and world corn prices are higher only in the first best case when a corn export tariff is used. World oil prices are lower than under the *status quo* or the optimal ethanol subsidy, but higher than under the first or second best policies.[37] Carbon dioxide

[36] In the case in which the mandate is the only choice variable, raising it has the additional effect of reducing gasoline consumption and imports; under either first or second best policies, gasoline consumption can be controlled through its own policy instrument.

[37] World corn and oil prices are important because they reflect the terms of trade for the United

emissions are lower than under the optimal ethanol subsidy but higher than under the first or second best policies. These emissions decrease relative to the *status quo* even though total fuel consumption increases by 1.0 GEEG as the replacement of some gasoline by ethanol is sufficient to overcome the increase in overall fuel consumption. Welfare, by definition, is higher than under the *status quo*, and also higher than under the optimal subsidy, but considerably lower than under first or second best policies. In other words, the mandate is superior to an ethanol subsidy but not nearly as effective as an (optimally) chosen fuel tax.

6.5. Summary of Baseline Results

By definition, the inability to use the first best policies, including import and export tariffs, must result in lower welfare. Nevertheless, when we are free to choose optimally the ethanol subsidy and fuel tax, this second best policy combination comes surprisingly close to matching the first best policy in terms of welfare gains and carbon emission reductions. Naturally, the additional restriction to only one free policy instrument—the ethanol subsidy or the ethanol mandate—leads to further welfare declines. In either of these cases, since fuel taxes (or oil import tariffs) are not choice variables, it is desirable to increase ethanol consumption (and price), with the larger increase coming under the mandate because of the fact that raising the mandate increases the effective tax on fuel. Because of this effective tax, the ethanol mandate yields higher welfare and higher ethanol utilization than does the ethanol subsidy, and, as noted, the optimal mandate leads to fulfillment of the RFS2 mandate on conventional biofuel by 2015, as do the second best policies. Still, the clear lesson is that fuel taxes are a more powerful instrument for reducing carbon dioxide emissions and increasing welfare than are ethanol policies.

6.6. Sensitivity Analysis

In order to investigate the robustness of our conclusions, we varied key parameters one at a time, recalibrated the model (when necessary) to the *status quo* 2009 baseline, and then explored the welfare implications of alternative policies. The alternative values for each of the parameters that we considered are summarized in Table 4 and refer to the following parameters: (i) cost of carbon dioxide emission; (ii) relative pollution efficiency of ethanol; (iii) elasticity fuel demand and of petroleum byproduct demand; (iv) elasticity of foreign corn import demand; (v) elasticity of foreign oil export supply.

Needless to say, the optimized value of the relevant policy instruments changed with the change in these basic parameters. Whereas the Appendix, and Tables A1-A6 therein, provide

States and thus are one component of the welfare impact of each policy.

more details, there are several results that are common to all sensitivity analysis experiments:

- For all cases considered, the *status quo* policies dominated *laissez faire* and in all cases, except when foreign oil export supply is very inelastic, delivered at least 40% of the maximal benefits achievable with first best policies.
- The basic result that the fuel tax/ethanol subsidy regime is a close substitute for first best policy holds for all cases.
- The *optimal mandate* policy dominated the optimal subsidy policy in all cases and it resulted in the highest use of ethanol in all cases considered. Nevertheless, in most cases it did not significantly outperform the *status quo* in welfare terms, the one exception being when foreign oil export supply was very inelastic.
- In all cases in which ethanol emitted less pollution than gasoline (per GEEG), the optimal mandate resulted in lower pollution than the optimal ethanol subsidy (even when carbon dioxide was priced at $2/t$CO_2$). The mandate also resulted in lower pollution than *laissez faire* except when the foreign oil export supply elasticity was very low—in this case the potential welfare gains associated with higher ethanol use, through the terms-of-trade effect on oil, were so large that CO_2 emissions increased relative to *laissez faire*.
- In all cases, though, the carbon emissions reductions achieved through either the first best or the second best policy of fuel taxes and ethanol subsidies were very close to each other and far exceeded those achieved under any other considered policy. Not surprisingly, oil imports were always lowest under the first best, when oil tariffs were used, but the second best was a very close second in reducing U.S. dependence on foreign oil.
- The welfare gains achievable with the second best policy of fuel taxes and ethanol subsidies was greater than 81% of the maximum gains achievable in all cases (the average of this fraction of the maximum welfare gain, over all experiments reported in the Appendix, is 89%).
- The case in which optimal policy delivered small gains—and hence did not improve much on other policies, such as the *status quo* or the optimal mandate—was when the world oil export supply elasticity was large (5.0). This illustrates the dominating role played by the oil market on the potential gains from government policy.
- Varying the parameters of the model does not change one of our basic results: the case for ethanol is not largely about pollution, but rather, it is about the policy's impact on the U.S. gains from trade (through its impact on the terms of trade).

7. Conclusion

This paper constructs a tractable computational model, which applies and extends the analytical model of Lapan and Moschini (2009), to analyze the market and welfare impacts of U.S. energy policies. Specifically, using this framework, we formally solve the optimal values for policy instruments under alternative policy scenarios. We then calibrate the model to fit the baseline period of 2009, and use simulation to compare equilibrium quantities, prices and net welfare under the alternative policy settings. Not surprisingly, the simulations support the policy rankings in Lapan and Moschini (2009), and in particular the conclusion that an ethanol mandate dominates an ethanol subsidy policy.

There are several interesting findings. First, the second best instruments of a fuel tax and an ethanol subsidy come close to replicating the outcomes under the first best policy combination of oil import tariffs, corn export tariffs and a carbon tax. For our baseline model, the second best fuel tax of $1.17/GEEG and ethanol subsidy of $1.16/gallon would increase ethanol consumption to 10.5 billion GEEG units (15.2 billion gallons), a 41% increase compared to the current (*status quo*) situation, it would decrease gasoline consumption by almost 10% and it would reduce emissions by 7.4%, as compared to the *status quo*.

In addition, the ethanol mandate, when used optimally in conjunction with the existing fuel tax would achieve the highest ethanol consumption, of approximately 18 billion gallons (12.4 billion GEEG), which exceeds the RFS2 mandate on conventional biofuels (15 billion gallons per year by 2015). However, since the effective tax on fuel is lower than under either the first or second best policy, it would achieve a smaller reduction in carbon emissions and a smaller welfare gain than would either of these policies. Finally, because of the magnitude of U.S. oil imports, the greatest economic gain arising from any policy intervention considered is due to the terms of trade effects through the world oil market. Because we have not included any other putative gain from reducing oil imports (e.g., national security effects arising from a reduced dependence on imports), we probably still significantly underestimate the potential gains associated with policies that reduce oil imports.

Table 1A – Primitive Parameters Used to Calibrate the Model

Parameter	symbol	value	Source/explanation
Domestic supply elasticity of oil	ε_o	0.20	de Gorter and Just (2009b)
Foreign supply elasticity of oil	$\bar{\varepsilon}_o$	2.63	de Gorter and Just (2009b)
Domestic supply elasticity of corn	ε_c	0.23	USDA (2007)
Foreign demand elasticity of corn	$\bar{\eta}_c$	-1.74	FAPRI (2004)
Domestic demand elasticity of corn	η_c	-0.20	de Gorter and Just (2009b)
Demand elasticity of fuel	η_f	-0.50	Toman, Griffin and Lempert (2008)
Demand elasticity of petroleum byproducts	η_h	-0.50	Assumed equal to η_f
Ethanol produced by one bushel of corn (gallons/bushel)	a	2.8	Eidman (2007)
DDGS production coefficient	δ_1	0.303	$\delta_1 = 17/56$
DDGS relative price to corn	δ_2	0.776	$\delta_2 = (114.4 \times 56)/(3.74 \times 2205)$
Gasoline production coefficient (gallon/barrel)	β	23.6	$\beta = x_g / x_o$
Ethanol heat content (BTUs/gallon)	γ_e	76000	NREL (2008)
Gasoline heat content (BTUs/gallon)	γ_g	110000	NREL (2008)
CO_2 emissions rate of gasoline (kg/gallon)	CE_g	11.29	Wang (2007)
CO_2 emissions rate of ethanol (kg/GEEG)	CE_e	8.42	Farrel et al. (2006)
Marginal emissions damage ($/t$CO_2$)	$\tilde{\sigma}'(\cdot)$	33	NHTSA (2009)

Table 1B – Calculated Parameters Used in the Model

Parameter	symbol	value	Source/explanation
Derived supply elasticity of ethanol	ε_e	4.73	$\varepsilon_e = (\varepsilon_c^s S_c - \eta_c D_c - \bar{\eta}_c \bar{D}_c)\alpha p_e / Q_c p_c$
Derived supply elasticity of gasoline	ε_g	1.42	$\varepsilon_g = (\varepsilon_o S_o + \bar{\varepsilon}_o \bar{S}_o)\beta p_g / x_o p_o$
Portion value of DDGS returning to corn market	$\delta_1\delta_2$	0.24	calculated
Ethanol produced by one bushel of corn accounting for DDGS value (GEEG/bushel)	α	2.53	$\alpha = \frac{a\gamma}{1-\delta_1\delta_2}$
Petroleum byproduct production coefficient (GEEG/barrel) [1]	β_2	21.1	$\beta_2 = 42 \times 1.065 - \beta$
Ethanol energy equivalent coefficient (GEEG/gallon)	γ	0.69	$\gamma = \gamma_e / \gamma_g$
Relative pollution efficiency	λ	0.75	$\lambda = CE_e / CE_g$
Normalized marginal emissions damage of gasoline ($/gallon)	$\sigma'(\cdot)$	0.372	$\sigma'(\cdot) = \tilde{\sigma}'(\cdot) CE_g / 1{,}000$

1. A 42-U.S. gallon barrel of crude oil provided around 6.5% average gains from processing crude oil in 2009 (see Refinery Yield Rate Table (EIA) accessible at http://tonto.eia.doe.gov/dnav/pet/pet_pnp_pct_dc_nus_pct_m.htm).

Table 2A – Value of Variables at the Calibrated Point (raw data for year 2009)

Variable	Symbol	Value	Source/explanation
Fuel tax ($/gallon)	t^0	0.39	sum of federal tax 18.4¢/gal and weighted average of state tax 20.6¢/gal (EIA).[1]
Ethanol subsidy ($/gallon)	b^0	0.45	RFS2
Oil price ($/barrel)	p_o	61.0	composite acquisition cost of crude oil (EIA).[2]
Corn price ($/bushel)	p_c	3.74	weighted average farm price of corn (Feed Grains Database, USDA).[3]
Ethanol price ($/gallon)	p_e^v	1.79	ethanol average rack price in Omaha, Nebraska
DDGS price ($/ton)	p_d	114.4	wholesale price in Lawrenceburg, IN (Feed Grains Database, USDA).[4]
Domestic oil supply (billion barrels)	S_o	1.93	production plus adjustments and stock changes (EIA).[5]
Foreign oil supply (billion barrels)	$\bar{S}_o$	3.29	net import (EIA).
Ethanol supply (billion gallons)	x_e^v	10.76	domestic production (RFA).
Fuel demand (billion gallons)	D_f^v	134.4	finished motor gasoline including ethanol (EIA).
Domestic corn supply (billion bushels)	S_c	13.15	domestic production (Feed Grains Database, USDA).[6]
Foreign corn import demand (billion bushels)	$\bar{D}_c$	1.86	net export (Feed Grains Database, USDA).

1. These tax values are taken from the EIA table "Federal and State Motor Fuels Tax" at: http://www.eia.doe.gov/pub/oil_gas/petroleum/data_publications/petroleum_marketing_monthly/current/pdf/enote.pdf.
2. Oil price comes from table "Refiner Acquisition Cost of Crude Oil" (EIA) http://tonto.eia.doe.gov/dnav/pet/pet_pri_rac2_dcu_nus_m.htm.
3. Corn price comes from table "Corn and Sorghum: Average Prices Received by Farmers" (Feed Grains Data, USDA). http://www.ers.usda.gov/Data/FeedGrains/Table.asp?t=09
4. DDGS price comes from table "Byproduct Feeds: Average Wholesale Price, Bulk, Specified Markets" (Feed Grains Data, USDA). http://www.ers.usda.gov/Data/FeedGrains/Table.asp?t=16
5. Oil domestic/foreign supply and fuel/ethanol supply on volumetric basis come from table "Supply and Disposition" (EIA). http://tonto.eia.doe.gov/dnav/pet/pet_sum_snd_d_nus_mbbl_m_cur.htm
6. Corn supply and foreign demand come from table "Corn: Supply and Disappearance" (Feed Grains Data, USDA). http://www.ers.usda.gov/Data/FeedGrains/Table.asp?t=04

Table 2B – Variables at the Calibrated Point (calculated values)

Variable	Symbol	Value	Source/explanation
Net ethanol subsidy ($/GEEG)	$\tilde{b}^o$	0.477	$\tilde{b}^o = b^o/\gamma - (1-\gamma)t^o/\gamma$
Ethanol price ($/GEEG)	p_e	2.59	$p_e = p_e^v / \gamma$
Fuel price ($/GEEG)	p_f	2.50	$p_f = p_e - \tilde{b}^o + t^o$.[1]
Gasoline price ($/GEEG)	p_g	2.11	$p_g = p_e - \tilde{b}^o$
Price of inputs other than corn in ethanol production ($/GEEG)	ω_e	1.11	$\omega_e = p_e - p_c / \alpha$
Price of inputs other than oil in gasoline production ($/GEEG)	ω_g	1.10	$\omega_g = p_g + \beta_2 p_h/\beta - p_o/\beta$
Price of petroleum byproducts ($/GEEG)	p_h	1.76	weighted average retail price excluding taxes (EIA).[2]
Quantity of petroleum byproducts (billion GEEG)	x_h	110.3	$x_h = \beta_2 x_o$
Oil supply (billion barrels)	x_o	5.22	$x_o = S_o + \bar{S}_o$.
Corn used in ethanol production accounting for byproduct value (billion bushel)	Q_c	2.94	$Q_c = x_e / \alpha$
Domestic corn demand as food/feed uses (billion bushels)	D_c	8.35	$D_c = S_c - \bar{D}_c - Q_c$
DDGS supply (billion bushels)	x_d	0.89	$x_d = \delta_1 Q_c$
Ethanol supply (billion GEEGs)	x_e	7.43	$x_e = \gamma x_e^v$
Gasoline supply(billion GEEGs)	x_g	123.6	$x_g = D_f^v - x_e^v$
Fuel demand (billion GEEGs)	D_f	131.0	$D_f = x_g + x_e$

1. Ethanol subsidy, quantity and price are converted into GEEG units in simulation.

2. Price index includes resale prices to end users excluding taxes for aviation gasoline, kerosene-type jet fuel, kerosene, distillate fuel oil, and residual fuel oil, which come from table "Refiner Petroleum Product Prices by Sales Type" (EIA), http://tonto.eia.doe.gov/dnav/pet/pet_pri_refoth_dcu_nus_m.htm.

Table 3A – Market Effects of Alternative Policy Scenarios

	Laissez Faire	No Ethanol Policy	*Status Quo*	First Best	Optimal Tax & Subsidy	Optimal Subsidy	Optimal Mandate
Fuel tax ($/gallon)	0.00	0.39	0.39	0.37	1.17	0.39	0.39
Ethanol Subsidy ($/gallon)[1]	0.00	0.00	0.45	0.18	1.16	0.68	0.00
Oil Tariff ($/barrel)	0.00	0.00	0.00	19.20	0.00	0.00	0.00
Corn Tariff ($/bushel)	0.00	0.00	0.00	1.10	0.00	0.00	0.00
Fuel Price ($/GEEG)	2.36	2.64	2.50	2.85	2.84	2.44	2.47
Gasoline Price ($/GEEG)	2.36	2.25	2.11	2.48	1.67	2.05	1.97
Ethanol Price ($/gallon)	1.63	1.43	1.79	1.78	1.95	1.97	2.04
U.S. Oil Price ($/barrel)	62.9	62.0	61.0	76.2	57.6	60.5	59.9
U.S. Corn Price ($/bushel)	3.17	2.43	3.74	3.69	4.32	4.41	4.67
Petroleum byproduct Price ($/GEEG)	1.57	1.66	1.76	2.07	2.10	1.81	1.87
Gasoline Quantity (billion GEEG)	130.3	127.2	123.6	112.5	111.7	121.8	119.7
Ethanol Quantity (billion gallons)	6.32	0.58	10.76	13.84	15.22	15.92	17.94
Corn Production (billion bushels)	12.69	12.09	13.15	13.11	13.62	13.69	13.90
Corn Demand (billion bushels)	8.61	8.94	8.35	8.38	8.10	8.06	7.94
Corn Export (billion bushels)	2.36	2.99	1.86	0.95	1.36	1.29	1.06
Oil Domestic Supply (billion barrels)	1.95	1.94	1.93	2.03	1.91	1.93	1.93
Oil Import (billion barrels)	3.56	3.43	3.29	2.72	2.81	3.22	3.13

Notes: (1) Although we use GEEG units for ethanol price, subsidy and quantity in our simulation, as discussed in the text, for ease of interpretation the results reported here are converted into natural units.

Table 3B – Welfare Effects of Alternative Policies (Changes Relative to *Laissez Faire*)

	Laissez Faire	No Ethanol Policy	*Status Quo*	First Best	Optimal Tax & Subsidy	Optimal Subsidy	Optimal Mandate
Social Welfare ($ billion)	--	1.7	8.0	15.0	13.4	8.8	9.8
Pollution effect ($ billion)	-49.8	2.3	1.6	5.2	5.2	1.3	1.7
Tax Revenue ($ billion)	0	49.8	47.6	97.9	131.3	42.9	53.7
P.S. Oil Supply ($ billion)	--	-1.7	-3.7	26.4	-10.2	-4.7	-5.9
P.S. Corn Supply ($ billion)	--	-9.2	7.4	6.7	15.1	16.3	19.9
C.S. Corn Demand ($ billion)	--	6.5	-4.9	-4.4	-9.6	-10.3	-12.4
C.S. Fuel Demand ($ billion)	--	-35.7	-18.5	-62.0	-61.3	-9.6	-13.4
C.S. Petroleum byproduct	--	-10.3	-21.6	-54.8	-57.1	-27.2	-33.8
CO_2 Emission (million tCO_2)	1,508	-69.0	-49.9	-157.6	-158.6	-40.3	-52.8

Table 4 – Parameters and Values Used in the Sensitivity Analysis

Parameter	Symbol	Baseline	Range
Cost of CO_2 emission ($/t$CO_2$)	$\sigma'(\cdot)$	33	[2 , 100]
Ethanol CO_2 emission efficiency	λ	0.75	[0.52 , 1.70]
Elasticity of fuel demand	η_f	-0.5	[-0.9 , -0.2]
Elasticity of foreign corn import demand	$\bar{\eta}_c$	-1.74	[-3.0 , -1.0]
Elasticity of foreign oil export supply	$\bar{\varepsilon}_o$	2.63	[1.0 , 5.0]
Elasticity of petroleum byproduct demand	η_h	-0.5	[-0.9 , -0.2]

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Appendix – Sensitivity Analysis

Tables A1 to A6 provide a few more details on the sensitivity analysis carried out. In these tables we concentrate on the main four scenarios discussed in the text: the first best solution with border policies and the carbon tax; the second best solution without border policies but where the fuel tax and the ethanol subsidy are optimally chosen; the case when the only active policy instrument is an ethanol subsidy; and the case in which the active policy instrument is the ethanol mandate. For each case only one parameter at a time is changed from the set of baseline values, and for each of these tables we report the results of the baseline parameters (middle column) along with the lower and upper ends of the parameter ranges postulated (as reported in Table 4).

The elasticity of the foreign oil export supply $\bar{\varepsilon}_0$ plays a predictable, but crucial, role. Naturally, the optimal oil import tariff varies inversely with this elasticity. The second best policy with the optimal fuel tax and ethanol subsidy also varies inversely with this parameter's values. But note that even a fairly elastic supply of foreign oil ($\bar{\varepsilon}_0 = 5$) provides scope for the fuel tax and ethanol subsidy to exceed $0.8/gallon, and the second best solution still achieves over 80% of the gain achievable with the first best policy. Perhaps the most noticeable effect is that, as the export supply elasticity increases, the relative performance of the ethanol-only policy (compared to the first and second best) improves, because the higher foreign supply elasticity means that the gains obtained from taxing foreign oil become less important.

Altering the elasticity of foreign corn import demand $\bar{\eta}_c$ over the range considered has predictable results. Hardly surprising, the first best corn export tariff varies inversely with this elasticity, but the impact on the optimal oil tariff is minimal (and the first best carbon tax is unaffected). The most notable result, perhaps, is that the second best instruments do not perform as well, in a relative sense, when the foreign corn demand is very inelastic. This is not a surprise because, whereas the fuel tax does a good job of approximating an import tariff (given the low domestic oil supply elasticity), the ethanol subsidy—or mandate—is not a very good substitute for the corn export tariff. Thus, when foreign corn demand is inelastic, the second best policies, and ethanol policies alone, are not as effective. Still, ethanol policies are useful, and in the case when fuel taxes are not endogenous, the optimal mandate can exceed 18 billion bushels.

Varying the elasticity of domestic demand for fuel and petroleum byproducts, η_f and η_h, does not have very dramatic results. As one would expect, the oil import tariff, or, in the case of the second best, the fuel tax, is (marginally) higher when fuel demand is inelastic. Also, given the fuel tax, the optimal ethanol subsidy, or ethanol mandate, is higher when domestic fuel demand is inelastic. The basic result that the fuel tax/ethanol subsidy regime is a close substitute for first best policy still holds.

When the cost of CO_2 is reduced to \$2/tCO_2, the first best gasoline tax is only 2¢ per gallon, and the relative attractiveness of ethanol *because* of its lower pollution emissions is negligible. Nevertheless, the first best policies—which do not include a measurable ethanol subsidy—not only deliver significant welfare gains compared to the *status quo*, but they also result in sharp increases in ethanol production and—despite a \$0.99/bushel tax on corn exports—an increase in the U.S. corn price. This outcome is driven by the \$20.20/barrel oil import tariff, which drives up domestic fuel prices and increases the competitiveness of ethanol. In the second best case, the high fuel tax proxies for the oil import tariff and the ethanol subsidy (the net ethanol subsidy is \$0.21/GEEG) partly proxies for a corn export tariff. Because of these two policies, the second best price of corn is considerably higher than in the first best situation (though the world price of corn is lower than in the first best case); and the world price of oil in the second best case is only slightly higher than in the first best case, indicating that the fuel tax is a much better proxy for an oil import tariff than is the ethanol subsidy for a corn export tariff. Finally, given an exogenous fuel tax of \$0.39/GEEG, the optimal subsidy is larger than the *status quo* level, and thus a binding ethanol mandate can improve upon both the *status quo* and an ethanol subsidy. Note that, even without a carbon-pollution rationale for ethanol mandates, the impact of the mandate on world oil and corn prices is such that ethanol production under the mandate exceeds the current mandated level for 2015 by almost 3 billion gallons.

Raising the cost of CO_2 to \$100/tCO_2 has predictable effects on first and second best policies and outcomes. The first best fuel tax increases to \$1.13/gallon—reflecting the costs of emissions—and due to the assumption that ethanol releases less pollution, a gross subsidy of \$0.55/gallon (equivalent to $\tilde{b}^* = \$.29$/GEEG) is part of the first best solution. The higher fuel tax, by itself, would reduce U.S. imports and this, in turn, means that tariffs will be lower than under the case where the pollution tax was minimal. Note that in this case the second best policy, while still a good proxy for first best policies, far outperforms the case in which only ethanol policy is discretionary. Indeed, given the existing fuel tax, the optimal subsidy—and the welfare outcome—is only slightly above the *status quo* level. In this case, the ethanol mandate leads to a considerable improvement over the ethanol subsidy and to considerably more ethanol output than the subsidy. The reason for the dominance of the mandate is because the tax on fuel is very low compared to its second best level (\$0.39 versus \$1.84), and hence the implicit fuel tax embodied in the mandate is more important than the implicit subsidy. One less transparent result, perhaps, is that ethanol production—under either the optimal subsidy or the optimal mandate—is lower when pollution costs are high. That is, while more ethanol on the market crowds out some gasoline, total fuel consumption expands as ethanol production increases, and the efficiency gain of using ethanol is not sufficient to offset the pollution costs of the expanded fuel consumption. Thus, the argument for an ethanol mandate is not really because of ethanol's relative pollution efficiency, but rather because of both the implicit tax on fuel and also the terms-of-trade effect. Clearly, then, in the logic of this model, combining an ethanol subsidy with the mandate is very poor policy.

Variations in the relative efficiency of ethanol in terms of pollution emissions—from $\lambda = .52$ to $\lambda = 1.7$—have predictable results in terms of the ethanol subsidy/tax but don't otherwise overturn other patterns with the exception that, in the case when ethanol pollutes more than gasoline, optimal ethanol mandates lead to more pollution than optimal ethanol subsidies (not a surprising result). Nevertheless, mandates still deliver higher welfare, and the largest use of ethanol still occurs under mandates. Despite the significant subsidies to ethanol, *status quo* policies—even when ethanol is more polluting—still deliver higher welfare than *laissez faire,* and the *status quo* subsidy is remarkably close to the optimal subsidy, given the fuel tax. The story remains that the case for ethanol is not largely about pollution, but rather it is about the policy's impact on the U.S. gains from trade (through the impact on the terms of trade).

Table A1 – Sensitivity Analysis: Elasticity of Foreign Oil Supply

	$\overline{\varepsilon}_o = 1.0$	$\overline{\varepsilon}_o = 2.63$	$\overline{\varepsilon}_o = 5.0$
First best			
Fuel tax ($/gallon)	0.37	0.37	0.37
Ethanol Subsidy ($/gallon)	0.18	0.18	0.18
Oil tariff ($/barrel)	43.07	19.20	10.93
Corn tariff ($/bushel)	0.83	1.10	1.26
Ethanol Quantity (billion gallons)	17.22	13.84	11.95
CO_2 Emission Changes (million tCO_2)[1]	-215.9	-157.6	-123.6
Social Welfare Changes ($ billion)[2]	43.31	15.03	8.15
Tax & Subsidy			
Fuel tax ($/gallon)	2.13	1.17	0.83
Ethanol Subsidy ($/gallon)	2.06	1.16	0.84
Ethanol Quantity (billion gallons)	18.72	15.22	13.42
CO_2 Emission Changes (million tCO_2)[1]	-227.1	-158.6	-122.3
Social Welfare Changes ($ billion)[2]	37.41	13.43	7.20
Subsidy-only			
Fuel tax ($/gallon)	0.39	0.39	0.39
Ethanol Subsidy ($/gallon)	0.92	0.68	0.58
Ethanol Quantity (billion gallons)	20.96	15.92	13.67
CO_2 Emission Changes (million tCO_2)[1]	-10.9	-40.3	-50.9
Social Welfare Changes ($ billion)[2]	16.79	8.77	5.69
Mandate			
Fuel tax ($/gallon)	0.39	0.39	0.39
Ethanol Subsidy ($/gallon)	--	--	--
Ethanol Quantity (billion gallons)	26.96	17.94	14.60
CO_2 Emission Changes (million tCO_2)[1]	-26.6	-52.8	-61.0
Social Welfare Changes ($ billion)[2]	21.25	9.84	6.11

Notes: CO_2 Emission changes and Welfare Changes are relative to *Laissez Faire*.

Table A2 – Sensitivity Analysis: Elasticity of Foreign Corn Demand

	$\bar{\eta}_c = -3.0$	$\bar{\eta}_c = -1.74$	$\bar{\eta}_c = -1.0$
First best			
Fuel tax ($/gallon)	0.37	0.37	0.37
Ethanol Subsidy ($/gallon)	0.18	0.18	0.18
Oil tariff ($/barrel)	19.21	19.20	19.20
Corn tariff ($/bushel)	0.65	1.10	1.90
Ethanol Quantity (billion gallons)	13.79	13.84	13.87
CO_2 Emission Changes (million tCO_2)[1]	-155.9	-157.6	-158.7
Social Welfare Changes ($ billion)[2]	14.82	15.03	15.63
Tax & Subsidy			
Fuel tax ($/gallon)	1.17	1.17	1.17
Ethanol Subsidy ($/gallon)	1.11	1.16	1.21
Ethanol Quantity (billion gallons)	14.83	15.22	15.65
CO_2 Emission Changes (million tCO_2)[1]	-157.7	-158.6	-158.8
Social Welfare Changes ($ billion)[2]	13.48	13.43	13.47
Subsidy-only			
Fuel tax ($/gallon)	0.39	0.39	0.39
Ethanol Subsidy ($/gallon)	0.63	0.68	0.74
Ethanol Quantity (billion gallons)	15.63	15.92	16.29
CO_2 Emission Changes (million tCO_2)[1]	-39.0	-40.3	-40.8
Social Welfare Changes ($ billion)[2]	8.80	8.77	8.83
Mandate			
Fuel tax ($/gallon)	0.39	0.39	0.39
Ethanol Subsidy ($/gallon)	--	--	--
Ethanol Quantity (billion gallons)	17.64	17.94	18.38
CO_2 Emission Changes (million tCO_2)[1]	-49.8	-52.8	-55.3
Social Welfare Changes ($ billion)[2]	9.77	9.84	10.02

Notes: CO_2 Emission changes and Welfare Changes are relative to *Laissez Faire.*

Table A3 – Sensitivity Analysis: Elasticity of Fuel Demand

	$\eta_f = -0.9$	$\eta_f = -0.5$	$\eta_f = -0.2$
First best			
Fuel tax ($/gallon)	0.37	0.37	0.37
Ethanol Subsidy ($/gallon)	0.18	0.18	0.18
Oil tariff ($/barrel)	18.69	19.20	19.93
Corn tariff ($/bushel)	1.22	1.10	0.94
Ethanol Quantity (billion gallons)	12.41	13.84	15.85
CO_2 Emission Changes (million tCO_2)	-201.2	-157.6	-98.0
Social Welfare Changes ($ billion)	16.96	15.03	12.46
Tax & Subsidy			
Fuel tax ($/gallon)	1.15	1.17	1.20
Ethanol Subsidy ($/gallon)	1.15	1.16	1.16
Ethanol Quantity (billion gallons)	13.95	15.22	17.05
CO_2 Emission Changes (million tCO_2)	-201.0	-158.6	-99.9
Social Welfare Changes ($ billion)	15.32	13.43	10.90
Subsidy-only			
Fuel tax ($/gallon)	0.39	0.39	0.39
Ethanol Subsidy ($/gallon)	0.61	0.68	0.78
Ethanol Quantity (billion gallons)	14.61	15.92	17.59
CO_2 Emission Changes (million tCO_2)	-52.3	-40.3	-30.6
Social Welfare Changes ($ billion)	9.41	8.77	8.20
Mandate			
Fuel tax ($/gallon)	0.39	0.39	0.39
Ethanol Subsidy ($/gallon)	-	-	-
Ethanol Quantity (billion gallons)	17.28	17.94	18.67
CO_2 Emission Changes (million tCO_2)	-63.6	-52.8	-40.6
Social Welfare Changes ($ billion)	10.64	9.84	8.90

Notes: CO_2 Emission changes and Welfare Changes are relative to *Laissez Faire*.

Table A4 – Sensitivity Analysis: Elasticity of Petroleum byproduct Demand

	$\eta_h = -0.9$	$\eta_h = -0.5$	$\eta_h = -0.2$
First best			
Fuel tax ($/gallon)	0.37	0.37	0.37
Ethanol Subsidy ($/gallon)	0.18	0.18	0.18
Oil tariff ($/barrel)	18.67	19.20	20.22
Corn tariff ($/bushel)	1.04	1.10	1.23
Ethanol Quantity (billion gallons)	14.66	13.84	12.26
CO_2 Emission Changes (million tCO_2)	-187.2	-157.6	-103.4
Social Welfare Changes ($ billion)	17.68	15.03	10.39
Tax & Subsidy			
Fuel tax ($/gallon)	1.15	1.17	1.22
Ethanol Subsidy ($/gallon)	1.12	1.16	1.22
Ethanol Quantity (billion gallons)	16.02	15.22	13.69
CO_2 Emission Changes (million tCO_2)	-189.4	-158.6	-101.7
Social Welfare Changes ($ billion)	16.20	13.43	8.55
Subsidy-only			
Fuel tax ($/gallon)	0.39	0.39	0.39
Ethanol Subsidy ($/gallon)	0.71	0.68	0.60
Ethanol Quantity (billion gallons)	16.97	15.92	14.00
CO_2 Emission Changes (million tCO_2)	-55.0	-40.3	-18.2
Social Welfare Changes ($ billion)	10.94	8.77	5.22
Mandate			
Fuel tax ($/gallon)	0.39	0.39	0.39
Ethanol Subsidy ($/gallon)	-	-	-
Ethanol Quantity (billion gallons)	19.37	17.94	15.26
CO_2 Emission Changes (million tCO_2)	-74.1	-52.8	-22.2
Social Welfare Changes ($ billion)	12.34	9.84	5.78

Notes: CO_2 Emission changes and Welfare Changes are relative to *Laissez Faire*.

Table A5 – Sensitivity Analysis: Cost of CO_2 pollution ($/$tCO_2$)

	$\tilde{\sigma}'(\bullet)=2$	$\tilde{\sigma}'(\bullet)=33$	$\tilde{\sigma}'(\bullet)=100$
First best			
Fuel tax ($/gallon)	0.02	0.37	1.13
Ethanol Subsidy ($/gallon)	0.01	0.18	0.55
Oil tariff ($/barrel)	20.20	19.20	17.06
Corn tariff ($/bushel)	0.99	1.10	1.34
Ethanol Quantity (billion gallons)	15.19	13.84	10.91
CO_2 Emission Changes (million tCO_2)[1]	-108.8	-157.6	-263.1
Social Welfare Changes ($ billion)[2]	10.90	15.03	29.12
Tax & Subsidy			
Fuel tax ($/gallon)	0.87	1.17	1.84
Ethanol Subsidy ($/gallon)	1.01	1.16	1.47
Ethanol Quantity (billion gallons)	16.47	15.22	12.54
CO_2 Emission Changes (million tCO_2)	-110.3	-158.6	-263.0
Social Welfare Changes ($ billion)	9.27	13.43	27.56
Subsidy-only			
Fuel tax ($/gallon)	0.39	0.39	0.39
Ethanol Subsidy ($/gallon)	0.72	0.68	0.59
Ethanol Quantity (billion gallons)	16.89	15.92	13.83
CO_2 Emission Changes (million tCO_2)	-38.4	-40.3	-44.2
Social Welfare Changes ($ billion)	7.55	8.77	11.60
Mandate			
Fuel tax ($/gallon)	0.39	0.39	0.39
Ethanol Subsidy ($/gallon)	--	--	--
Ethanol Quantity (billion gallons)	17.942	17.941	17.939
CO_2 Emission Changes (million tCO_2)	-52.8	-52.8	-52.8
Social Welfare Changes ($ billion)	8.21	9.84	13.38

Notes: CO_2 Emission changes and Welfare Changes are relative to *Laissez Faire*.

Table A6 – Sensitivity Analysis: Ethanol Pollution Efficiency Parameter

	$\lambda = 0.52$	$\lambda = 0.75$	$\lambda = 1.70$
First best			
Fuel tax ($/gallon)	0.37	0.37	0.37
Ethanol Subsidy ($/gallon)	0.24	0.18	-0.07
Oil tariff ($/barrel)	19.12	19.20	19.58
Corn tariff ($/bushel)	1.02	1.10	1.47
Ethanol Quantity (billion gallons)	14.91	13.84	9.32
CO_2 Emission Changes (million tCO_2)[1]	-170.2	-157.6	-146.0
Social Welfare Changes ($ billion)[2]	15.50	15.03	13.74
Tax & Subsidy			
Fuel tax ($/gallon)	1.17	1.17	1.19
Ethanol Subsidy ($/gallon)	1.20	1.16	0.98
Ethanol Quantity (billion gallons)	16.20	15.22	11.11
CO_2 Emission Changes (million tCO_2)[1]	-173.6	-158.6	-132.7
Social Welfare Changes ($ billion)[2]	13.98	13.43	11.75
Subsidy-only			
Fuel tax ($/gallon)	0.39	0.39	0.39
Ethanol Subsidy ($/gallon)	0.72	0.68	0.50
Ethanol Quantity (billion gallons)	16.89	15.92	11.82
CO_2 Emission Changes (million tCO_2)[1]	-57.1	-40.3	-7.0
Social Welfare Changes ($ billion)[2]	9.35	8.77	6.91
Mandate			
Fuel tax ($/gallon)	0.39	0.39	0.39
Ethanol Subsidy ($/gallon)	--	--	--
Ethanol Quantity (billion gallons)	18.97	17.94	13.49
CO_2 Emission Changes (million tCO_2)[1]	-75.1	-52.8	-0.5
Social Welfare Changes ($ billion)[2]	10.55	9.84	7.53

Notes: CO_2 Emission changes and Welfare Changes are relative to *Laissez Faire*.