Welfare Impacts of Alternative Biofuel and Energy Policies

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An open-economy equilibrium model is derived to investigate the effects of energy policy on the U.S. economy, with emphasis on corn-based ethanol. A second best policy of a fuel tax and ethanol subsidy is found to approximate 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 their impact on U.S. terms of trade, particularly in the oil market. Conditional on the current fuel tax, an optimal ethanol mandate is superior to an optimal ethanol subsidy.

Key words: biofuel policies, carbon tax, ethanol subsidy, gasoline tax, greenhouse gas emissions, mandates, renewable fuel standard, second best.

JEL *Classification*: Q2, H2, F1.

Two interrelated critical issues facing the United States 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 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. 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 over greenhouse gas (GHG) emissions associated with fossil fuel energy use. While some disagreement exists on the potential implications of carbon buildup in the atmosphere, it seems that 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, which increased from 1.65 billion gallons in 2000 to 10.76 billion gallons in 2009, making the United States the largest world producer of ethanol. 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 (RFS1) that “mandated” specific targets for renewable fuel use, the level of which has been considerably expanded by the Energy Independence and Security Act of 2007 and its RFS2. Since then, the ethanol mandates under RFS2 have been more than met, and renewable fuel requirements have risen from 12.95 billion gallons in 2010 to 20.5 billion gallons in 2015 to 36 billion gallons in 2022. Of these requirements, up to 15 billion gallons may come from ethanol, while the rest are meant to come from “advanced biofuels,” such as cellulosic biofuel.

The purpose of this article is to provide an economic analysis of the welfare implications of U.S. policies that impact biofuel production. Facets of this topic have been the subject of a few studies. de Gorter and Just (2009a) analyze the impact of a biofuel blend mandate on the fuel market. They find that when tax credits are implemented along with the blend mandate, tax credits subsidize fuel

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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 deadweight 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 United States on ethanol markets. They find that the removal of current tariffs on imported ethanol would 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 and that the removal of both tax credit and tariffs would cause U.S. ethanol consumption to fall by 2.1% and the price of ethanol to 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 per metric tonne of carbon [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 the then-current ethanol subsidy of $0.51/gallon reduces carbon emissions by 5% relative to the no-tax, *laissez faire* situation. 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 tC).[1]

In assessing the effectiveness of ethanol in reducing GHG emissions, an issue that has commanded considerable attention is that of "indirect land use" effects: The diversion of feed corn to ethanol production in the United States increases aggregate demand for agricultural output and might bring new marginal land into production (Searchinger et al. 2008). To assess the global economic and land use impacts of biofuel mandates, Hertel, Tyner, and Birur (2010) use a computable general equilibrium model built upon the standard Global Trade Analysis Project modeling framework. To jointly meet the biofuel mandate policies of the United States (15 billion gallons of ethanol by 2015) and the EU (6.25% of total fuel as renewable by 2015), they find that coarse grains acreage in the United States rises by 10%, oilseed acreage in the EU increases dramatically by 40%, cropland areas in the United States 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 pastureland areas of the United States by 3.1% and 4.9%, respectively. The most recent RFS2 pronouncement by the EPA accounts for international indirect land use changes (ILUCs) and makes several changes for GHG emission reduction of ethanol from all feedstocks (U.S. Environmental Protection Agency [EPA] 2010). Accounting for ILUCs, the EPA finds that corn ethanol still achieves a 21% GHG reduction compared with gasoline. The EPA also finds, using its ILUC modification, that sugarcane ethanol qualifies as an advanced biofuel because it achieves an average 61% GHG reduction compared with baseline gasoline, which exceeds the 50% GHG reduction threshold for advanced biofuels

Lapan and Moschini (2009) note that most existing work does not explicitly account for the welfare consequences to the United States of policies supporting biofuel production (such as the externality of GHG emissions or the benefits to the United States that accrue either from improved terms of trade or from "improved national security" due to decreased reliance on oil imports). To consider first and second best policies within that normative context, Lapan and Moschini build a simplified general equilibrium (multimarket) 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; they model the process by which corn is converted into ethanol, account for by-products of this process, and allow for the endogeneity of world oil and corn prices, as well as the (different) carbon emissions from gasoline derived from oil and from blends with ethanol. The analysis by Lapan and Moschini (2009) is theoretical in nature, aiming at providing analytical insights and results. They find that 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

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

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 article 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 some government policies, we explore how these policies affect equilibrium (domestic and world) prices of corn, oil, ethanol, and gasoline. Throughout the analysis, we maintain the assumption that due to a prohibitive tariff, there are no U.S. imports of ethanol. This approach is consistent with a number of other articles that have studied the impact of biofuel mandates (e.g., the theoretical model of de Gorter and Just 2009a; de Gorter and Just 2009b; Khanna, Ando, and Taheripour 2008). Whereas some models have considered the possibility of U.S. ethanol imports (e.g., Elobeid and Tokgoz 2008), all of the foregoing studies have treated world oil prices as exogenous. As discussed in the conclusion, the welfare consequences of eliminating this (prohibitive) ethanol tariff would be significantly affected by the endogeneity of world oil prices.

Using standard welfare measures, we compare the net welfare implications of alternative policies and show how different groups are affected by them. 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 United States from policy intervention come from the impact of policies on 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 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. GHG emissions and reducing U.S. reliance on oil imports. The extension recognizes that when oil is refined, other products, in addition to gasoline, are produced (distillate fuel oil, jet fuel, etc.). We aggregate all the nongasoline output into a single good called *petroleum by-products*. 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 by-products, 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 the following utility function:

$$U = y + \varphi(D_f) + \theta(D_c) + \eta(D_h) - \sigma(x_g + \lambda x_e) \quad (1)$$

where y represents consumption of the numeraire, and D_f, D_c, and D_h represent consumption of fuel, of food, and of petroleum by-products, 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 compared with gasoline (we will return to this parameter later).

The basic elements of the model consist of the following:

1. U.S. demand for corn as food/feed, represented by $D_c(p_c)$
2. U.S. demand for fuel $D_f(p_f)$
3. U.S. demand for petroleum by-products $D_h(p_h)$

4. U.S. corn supply equation $S_c(p_c)$
5. U.S. oil supply equation $S_o(p_o)$
6. Foreign oil export supply curve $\bar{S}_o(p_o^w)$
7. Foreign corn import demand curve $\bar{D}_c(p_c^w)$
8. U.S. oil refining sector, which converts oil into gasoline and petroleum by-products
9. U.S. ethanol production sector, which converts corn into ethanol and produces a by-product of dried distillers grains with solubles (DDGS), which becomes part of the food/feed supply

Components 1–7 are self-explanatory. In particular, the (household) demand curves (1.–3.) come from utility maximization and thus are the inverse of the marginal utility relations $\varphi'(D_f)$, $\theta'(D_c)$, and $\eta'(D_h)$, respectively, and p_f, p_c, p_h are the prices facing households.[2] The domestic supply relations (4. and 5.) 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 and p_o represent both supply and demand prices.[3] Foreign relations (6. and 7.) 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 United States is a large economic agent in both markets, and our simulation will reflect that fact. Throughout the analysis, we assume that U.S. tariffs on ethanol imports are prohibitive, so the U.S. ethanol price is decoupled from the world price. Finally, components 8 and 9 require a bit more elaboration.

Oil Refining Sector

The refinement of oil yields gasoline x_g and petroleum by-products x_h. We assume a fixed coefficients production technology so that the process is represented as follows[4]:

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

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

where x_g is gallons of gasoline output, x_h is gallons of the petroleum by-product, 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 number of gallons of the petroleum by-product per barrel of oil. This technology and perfect competition imply the following relationship among input and output prices:

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

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

Ethanol Production Sector

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

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

where x_e is ethanol output and z_e is 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 by 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 gallons" (GEEGs).[5] Furthermore, we wish to account for the valuable bioproducts of ethanol production by counting only the "net" use of corn in the technological

[2] Since the marginal utility of the numeraire is one, the marginal rate of substitution between each of the three consumption goods (food, fuel, and petroleum by-products) 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, and p_h represent relative prices.

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

[4] 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.

[5] 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).

relation in equation (4). That is, if one bushel of corn used in ethanol production also yields δ_1 units of 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 $(1 - \delta_1\delta_2)$. Hence, the production parameter α in equation (4) satisfies

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

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]:

$$p_e = \frac{p_c}{\alpha} + \omega_e \tag{6}$$

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 GEEGs) and p_e is the price of one GEEG of ethanol.

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 that 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[9]:

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

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

$$D_h(p_h) = \beta_2\{S_o(p_o) + \bar{S}_o(p_o^w)\} \quad \text{(Petroleum By-product Equilibrium)} \tag{9}$$

$$\beta p_g + \beta_2 p_h = p_o + \beta\omega_g \quad \text{(Zero Profit Condition Oil Refining)} \tag{10}$$

$$p_e = \frac{p_c}{\alpha} + \omega_e \quad \text{(Zero Profit Condition Ethanol Industry)} \tag{11}$$

$$p_o = p_o^w + \tau_o \quad \text{(Oil Import Arbitrage Relation)} \tag{12}$$

$$p_c^w = p_c + \tau_c \quad \text{(Corn Export Arbitrage Relation)} \tag{13}$$

Note that equation (7) embeds the technological relationship $x_c = x_e/\alpha$. In equations (12) and (13), τ_o and τ_c are the specific tariffs for oil imports and corn exports, respectively (assumed to be nonprohibitive, so that 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, equations (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").

Equilibrium with Fuel Taxes and Ethanol Subsidies

Let t be the consumption tax on fuel, per gallon, and b be the volumetric blending subsidy

[6] If the United States imported ethanol, we would need to specify the net world export supply of ethanol to close the model.

[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 Administration, http://tonto.eia.doe.gov/dnav/pet/pet_sum_snd_d_nus_mbbl_m_cur.htm).

[9] If there were world trade in ethanol, with perhaps some nonprohibitive import tariff, then an additional arbitrage condition would be needed to relate world and domestic ethanol prices.

per gallon of ethanol. Then, because gasoline and ethanol are modeled as perfect substitutes for consumers once measured in GEEGs, and because one gallon of ethanol is equivalent to γ GEEGs, arbitrage relations imply[10]

$$p_g = p_f - t \tag{14}$$

$$p_e = p_f + \frac{b}{\gamma} - \frac{t}{\gamma} = p_g + \tilde{b} \tag{15A}$$

where $\tilde{b} \equiv (b - t(1-\gamma))/\gamma$ is the effective net subsidy to ethanol, compared with gasoline, per GEEG.[11] Thus, for the case of taxes and subsidies, equations (7)–(15A) can be used to calculate the equilibrium, given the policy parameters $\{\tau_o, \tau_c, t, b\}$.

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

$$\begin{aligned}(p_f - t)\cdot D_f(p_f) &= p_g[D_f(p_f) - x_e^M] \\ &\quad + (p_e - \tilde{b})\cdot x_e^M.\end{aligned} \tag{15B}$$

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 by Lapan and Moschini (2009), the impact of an ethanol mandate is that of combining a fuel tax with an ethanol subsidy in a revenue-neutral fashion.

Welfare

In defining welfare, we assume that 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

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

The term in curly brackets in equation (16) measures consumption of the numeraire good, y, while the term in square brackets on the third line measures consumer utility derived from consumption of fuel, corn, and petroleum by-products, and the last term measures the disutility due to pollution arising from energy consumption.[12] Consumption of the numeraire in equation (16) is total income I (taken as exogenous and measured in numeraire units) less (*a*) $C(Q_c)$, the cost of aggregate corn output; (*b*) $\Omega(S_o)$, the cost of domestic oil production; (*c*) $\{\omega_e x_e + \omega_g x_g\}$, the cost of the other inputs used in ethanol production and oil refining; and (*d*) $[p_o^w \bar{S}_o - p_c^w \bar{D}_c]$, 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 equation (16). Similarly, specification of the demand relations used in equations (7)–(9) imply the forms of the subutility functions in equation (16), so the only additional specification of functional forms needed for the welfare calculations is that of the externality term, $\sigma(..)$. Thus,

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

[11] Note that equation (5) 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.

[12] This formulation does not explicitly impute pollution to the use of distillates. However, because gasoline and distillates are derived from a barrel of oil in fixed proportions in the model, then a tax on any one of them—properly adjusted—will have the same effect.

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 relevant equilibrium conditions, specifying $\sigma(\cdot)$ and then using equation (16) to calculate welfare.

To understand how the optimal (or second best) policies are determined, take the total differential of equation (16) and rearrange terms (Lapan and Moschini, 2009) to yield

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

The first three terms in equation (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 marginal cost of corn production, and hence optimality requires that marginal benefit equals marginal cost $\{\theta' = C'\}$. 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 by-products, and $[\omega_g + (\Omega'/\beta)]$ is the extraction and refining cost of producing that gallon. The terms in the last three lines 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 noted by Lapan and Moschini (2009), the first best policy entails oil import tariffs, corn export tariffs, and a tax on carbon emissions.[13] 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).[14] Specifically, it is shown that the "first best" policy instruments are[15]

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

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

[13] Article 1, Section 9 of the U.S. Constitution states: "No Tax or Duty shall be laid on Articles exported from any State," so that the first best policy could not be supported through export tariffs on corn. However, there are other constitutionally permissible policies that have the same economic consequences as export tariffs.

[14] 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.

[15] To calculate the actual values of the instruments, the equilibrium conditions described earlier must be used in conjunction with equation (18).

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 obligations to the World Trade Organization.[16] 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).[17] Using these policy restrictions and the behavioral conditions outlined earlier, equation (17) can be rewritten as

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

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 be shown that equation (17A) reduces to[18]

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

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

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

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[19]

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

where

$$\rho = \frac{\beta\Delta'}{\beta\Delta' - D_f' + \beta\Delta'(\beta_2/\beta)^2(D_f'/D_b')} \in (0,1).$$

Note that $\tilde{b}^{sub} = \tilde{b}^{sb} + (1-\rho)(t^0 - t^{sb})$. 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.

[16] 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.

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

[18] The paper by Lapan and Moschini (2009) contains the details, but the logic underlying equation (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.

[19] This formula differs from the corresponding one of Lapan and Moschini (2009) because here we explicitly allow for the presence of petroleum by-products, 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 by-products), of course, the two conditions are identical.

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[20]

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

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

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

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

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 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 by-products $D_h(p_h)$. 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 USDA (http://www.ers.usda.gov/Data/FeedGrains) and data for oil, gasoline, and oil refinery by-products are obtained from the U.S. Energy Information Administration (EIA; http://www.eia.doe.gov). Ethanol quantity data are from the Renewable Fuels Association (RFA; http://www.ethanolrfa.org), and ethanol prices are provided by the Nebraska Energy Office (NEO; http://www.neo.ne.gov/statshtml/66.html). More specific information on sources of data used is provided in the tables that follow.

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 taxes, which are, on average, equal to \$0.203/gallon. Hence, for gasoline, $t^0 = \$0.39$. However, because 1.0 gallon of ethanol equals only 0.69 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.[21] Prices of fuel and (unblended) gasoline are calculated from arbitrage conditions, which

[20] 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 by-products.

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

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	$\bar{\varepsilon}_o$	3.00	de Gorter and Just (2009b)
Domestic supply elasticity of corn	ε_c	0.30	Westhoff (priv. comm., 2010)
Foreign demand elasticity of corn	$\bar{\eta}_c$	−1.50	Food and Agricultural Policy Research Institute (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 by-products	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	76,000	National Renewable Energy Laboratory (2008)
Gasoline heat content (BTUs/gallon)	γ_g	110,000	National Renewable Energy Laboratory (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 (\$/tCO_2)	$\tilde{\sigma}'(\cdot)$	20	Stern (2007), National Highway Traffic Safety Administration (2009)

Table 1B. Calculated Parameters Used in the Model

Parameter	Symbol	Value	Source/Explanation
Derived supply elasticity of ethanol	ε_e	5.01	$\varepsilon_e = (\varepsilon_c^s S_c - \eta_c D_c - \bar{\eta}_c \bar{D}_c)\alpha p_e / Q_c p_c$
Derived supply elasticity of gasoline	ε_g	1.61	$\varepsilon_g = (\varepsilon_o S_o + \bar{\varepsilon}_o \bar{S}_o)\beta p_g / x_o p_o$
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	$\alpha = \dfrac{a\gamma}{1-\delta_1\delta_2}$
Petroleum by-product production coefficient (GEEG/barrel)[a]	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)	$\sigma'(\cdot)$	0.226	$\sigma'(\cdot) = \tilde{\sigma}'(\cdot) CE_g/1000$

Note: [a]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], http://tonto.eia.doe.gov/dnav/pet/pet_pnp_pct_dc_nus_pct_m.htm).

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.[22] The crude oil price of \$61.00/barrel is the refiner's composite acquisition cost of crude oil, the weighted

[22] This calculation method ensures 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.

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

Variable	Symbol	Value	Source/Explanation
Fuel tax ($/gallon)	t^0	0.39	Sum of federal tax 18.4 ¢/gal and weighted average of state tax 20.6 ¢/gal (EIA)[a]
Ethanol subsidy ($/gallon)	b^0	0.45	RFS2
Oil price ($/barrel)	p_o	61.0	Composite acquisition cost of crude oil (EIA)[b]
Corn price ($/bushel)	p_c	3.74	Weighted average farm price of corn (Feed Grains Database, USDA)[c]
Ethanol price ($/gallon)	p_e^v	1.79	Ethanol average rack price in Omaha, NE
DDGS price ($/ton)	p_d	114.4	Wholesale price in Lawrenceburg, IN (Feed Grains Database, USDA)[d]
Domestic oil supply (billion barrels)	S_o	1.93	Production plus adjustments and stock changes (EIA)[e]
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)[f]
Foreign corn import demand (billion bushels)	$\bar{D}_c$	1.86	Net export (Feed Grains Database, USDA)

Notes: [a]These tax values are taken from the EIA table “Federal and State Motor Fuels Tax,” http://www.eia.doe.gov/pub/oil_gas/petroleum/data_publications/petroleum_marketing_monthly/current/pdf/enote.pdf.
[b]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.
[c]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
[d] DDGS price comes from table “By-product Feeds: Average Wholesale Price, Bulk, Specified Markets” (Feed Grains Data, USDA). http://www.ers.usda.gov/Data/FeedGrains/Table.asp?t=16
[e]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
[f]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

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 by-product in ethanol production, DDGS, is $114.40/t (metric ton), which reflects the wholesale price in Lawrenceburg, Indiana. We used EIA data to calculate a weighted average retail price, excluding taxes, for petroleum by-products in the oil refining process; this price index is denoted p_h, and its 2009 value is $1.76/GEEG.[23] The prices of the “other” inputs used in gasoline and ethanol production, w_g and w_e, are derived from the zero profit condition, $w_g = p_g + \beta_2 p_h / - p_o/\beta =$ $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.

[23] Because prices for all the by-products of the refining process were not available, the price index we constructed uses the prices of only 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 by-products in the oil refining process.

Productivity Parameters

One bushel of corn produces approximately 2.80 gallons of ethanol (Eidman 2007); thus $\alpha = 2.80$. The production of ethanol generates by-products that are useful as animal feed (and thus can replace corn in that use). The nature of such by-products 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.[24] According to the RFA, such a process generates as a by-product about 17 lbs of DDGS per bushel of corn; given that there are 56 lbs in a bushel, then $\delta_1 = 0.303$. The DDGS price relative to the corn price is captured by the parameter $\delta_2 = 0.776$, calculated as described in table 1A from the data discussed in the foregoing. Given the assumption of perfect

[24] 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.

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

Variable	Symbol	Value	Source/Explanation
Net ethanol subsidy ($/GEEG)	$\tilde{b}^o$	0.477[a]	$\tilde{b}^o = b^o/\gamma - (1-\gamma)t^o/\gamma$
Ethanol price ($/GEEG)	p_e	2.59[a]	$p_e = p_e^v/\gamma$
Fuel price ($/GEEG)	p_f	2.50[a]	$p_f = p_e - \tilde{b}^o + t^o$
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 by-products ($/GEEG)	p_h	1.76	Weighted average retail price excluding taxes (EIA)[b]
Quantity of petroleum by-products (billion GEEGs)	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 by-product value (billion bushels)	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[a]	$x_e = \gamma x_e^v$
Gasoline supply(billion GEEGs)	x_g	123.6	$x_g = D_f^v - x_e^v$
Fuel demand (billion GEEGs)	D_f	131.0	$D_f = x_g + x_e$

Note: [a]Ethanol subsidy, quantity and price are expressed in GEEG units (see text).
[b]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.

substitution between corn and DDGS in feed use, each processed bushel of corn generates, as a by-product, the equivalent of $\delta_1\delta_2 = 0.24$ bushels of corn.[25] Hence, the ethanol production coefficient, accounting for by-product value, is $\alpha = 2.53$ GEEG/bushel.

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 United States. 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 GEEGs. 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 GEEGs. Final fuel consumption, measured in GEEGs, is the sum of gasoline and ethanol consumption in the same units, $x_f = x_g + x_e = 131.0$ billion GEEGs. The assumed fixed-proportions technology in oil refining gives the calculated yield of gallons of gasoline per barrel of crude oil as $\beta = x_g/x_o = 23.6$ GEEGs/barrel.[26] Given β, the yield of petroleum by-products (in gallons)

[25] 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 (Environmental Protection Agency 2010).

[26] Alternatively, one could recover the β parameter from refinery yields data reported by EIA, e.g., $\beta = (42\text{ gallon/barrel}) \times$

from a barrel of crude oil is calculated to be $\beta_2 = 21.1$.[27]

Carbon Emissions

We use the carbon emission rate of gasoline, measured as carbon dioxide (CO_2), of 11.29 kg/GEEG (Wang 2007). As for the net carbon dioxide emissions of ethanol, in our baseline 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 with feedstock credits but without land use changes reported by Searchinger et al. (2008).[28] These values, in turn, imply that the relative pollution efficiency of ethanol to gasoline (i.e., the parameter λ) is around 0.75 in our benchmark case, a parameterization that is consistent with EPA (2010). There is, of course, considerable uncertainty (and controversy) about ethanol's actual carbon dioxide emissions. For example, Searchinger et al. (2008) estimate that when they account for land use changes, the net carbon emission of ethanol is 93% larger than that of gasoline.[29] To capture the influence of such uncertainty, the sensitivity analysis carried out later will consider the range [0.5, 2] for the parameter λ.

Carbon Emissions Cost

There are many 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, 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 2007) has a higher estimate of approximately \$80/tCO_2, due to a lower discount rate applied to future economic damage from climate change. The National Highway Traffic Safety Administration (2009) calculates its proposed corporate average fuel economy 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. 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, and this is the mean value for the global cost of carbon used by the National Highway Traffic Safety Administration (2009). The EPA (2008) derives estimates of the social carbon cost using the subset of estimates in Tol's (2008) survey and reports average global values of \$40/tCO_2 (for studies using a 3% discount rate) and \$68/tCO_2 (for studies using a 2% discount rate).

Because of the U.S.-centered welfare function used here, the pollution externality cost used in our modeling framework should arguably reflect local and global warming costs to the United States. In the baseline we use a value of \$20/tCO_2, which essentially is the estimate provided by the *Stern Review*, adjusted to reflect the U.S. share of the world economy. Whereas some might think that the reference parameter of the *Stern Review* is perhaps too high,[30] others might yet argue that it is the global damage due to carbon emission that ought to be considered. Also, as noted by a reviewer, other externality costs—associated with congestion, accidents, and noncarbon pollution—are not explicitly taken into account.[31] In the end, because of the uncertainty and controversy surrounding this parameter, one might want to rely on sensitivity analysis to explore the impact of alternative parametric assumptions. For the sensitivity analysis discussed later, we take the global value of the *Stern Review*

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

[27] 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.

[28] The feedstock credits refer to the carbon benefit of devoting land to biofuels (Searchinger et al. 2008).

[29] Hertel et al. (2010) provide a lower estimate of ILUC emissions, which is roughly one-fourth the value estimated by Searchinger et al. (2008). But their estimates still suggest the pollution inefficiency of ethanol relative to gasoline when accounting for ILUC.

[30] Using a more conventional discount rate, Hope and Newbery (2008) find that the (global) carbon cost from the Stern report could be reduced to the range of \$20–\$25/tCO_2.

[31] 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 (expressed in year 2000 dollars). They also account for external congestion costs of 3.5 ¢/mile and an external accident cost of 3 ¢/mile.

estimate of \$80/tCO_2 as the upper bound of the range we consider, with a lower bound of \$5/tCO_2. 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 \$20/tCO_2 for the cost of carbon dioxide pollution, $\sigma'(\cdot) = \$0.23/\text{GEEG}$.

Elasticities

The elasticity values that we use are taken from the literature to reflect the consensus on the available econometric evidence. For the corn supply elasticity we rely on estimates by the Food and Agricultural Policy Research Institute (P. Westhoff, private communication, 2010) and set $\varepsilon_c = 0.3$ in our benchmark,[32] with a range of [0.1, 0.5] used in the sensitivity analysis. The elasticity of domestic food/feed demand of $\eta_c = -0.2$ is from de Gorter and Just (2009b), and we explore the range [−0.5, −0.1] in the sensitivity analysis. The estimates for the elasticity of foreign corn import demand range from an inelastic (short-run) value of −0.30 used by Gardiner and Dixit (1986) to a considerably more elastic value reported by the country commodity linked system of the Economics Research Service of the USDA, which, following a sustained exogenous shock to the world price of corn only, obtains an implied elasticity of net foreign corn imports in the third year of −2.41. We use a benchmark value for this parameter of $\bar{\eta}_c = -1.5$, which is consistent with a popular modeling platform (Food andAgricultural Policy Research Institute 2004), and we carry out a sensitivity analysis within the range of [−3, −1].

For the elasticities of domestic oil supply, we follow de Gorter and Just (2009b) and assume $\varepsilon_o = 0.2$, with the range [0.1, 0.5] explored in the sensitivity analysis. This is a more inelastic assumption than that suggested by Toman, Griffin, and Lempert (2008), who provide a range of [0.2, 0.6] for the long-run domestic oil supply elasticity with a baseline value of 0.4. For foreign export oil supply elasticity, we assume the baseline value of $\bar{\varepsilon}_o = 3$, which is similar to the 2.63 value used by de Gorter and Just (2009b), and analyze the range [1, 5] in the sensitivity analysis. The elasticity of fuel demand is assigned a benchmark value of $\eta_f = -0.5$, with the range [−0.9, −0.2], as suggested by Toman, Griffin, and Lempert (2008), which is fairly similar to the value and range considered by Parry and Small (2005). Not much explicit evidence exists on the elasticity of petroleum by-product demand, hence we adopt the same baseline value and range as the elasticity of fuel demand. 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.[33]

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:[34]

1. *Laissez faire*, with no border or domestic taxes or subsidies
2. No ethanol policy: current fuel tax but without ethanol subsidy or mandates
3. Status quo, with the current fuel tax and ethanol policy
4. The first best: use of border policies and domestic policies
5. The second best: the fuel tax and ethanol subsidy chosen optimally
6. Ethanol subsidy chosen optimally; fuel tax set at its current level
7. Ethanol mandate chosen optimally; fuel tax set at its current level

For each scenario, we report in table 3A the values of the policy instruments and the

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

[33] 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 $\varepsilon_e = 5.01$ and $\varepsilon_g = 1.61$, respectively.

[34] Our analysis does not consider other farm policies, such as deficiency payments. The policies we do consider may make the economic impact of these other policies essentially irrelevant.

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.[35] 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.[36] Our results show that all the policy scenarios improve upon the *laissez faire* equilibrium solution. The presence of a market failure implies that optimally chosen policies must do so, of course, but it is perhaps a bit surprising that seemingly ad hoc policies (like the status quo) also do so. 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.[37]

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 with 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, and a 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 somewhat, as a 6.9 billion gallon decline in gasoline consumption is only partly offset by an increase of 4.73 billion gallons (3.26 billion GEEGs) in ethanol consumption. This (small) drop in fuel consumption, and the substitution of some ethanol for gasoline, leads to a 3% (or a 50.9 million tCO_2) decrease in carbon emissions; at the baseline cost of \$20/tCO_2, this is equivalent to a \$1 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). Relative to *laissez faire*, there is a \$6.7 billion increase in net welfare, which amounts to 58% of the maximum gain achievable by optimum policies. U.S. dependence on foreign oil also declines, as oil imports fall by about 8%.

The column "no ethanol policy" in tables 3A and 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 with 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 nonexistent (only 0.05 billion gallons of production). 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 \$6.2 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 19.2 million tCO_2). Instead, ethanol policies are useful mostly because of their terms-of-trade effects. Comparison of these two scenarios in table 3B also illustrates that the big winners from the

[35] 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.

[36] 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.

[37] We do not explicitly model the fact that energy is an input in the production of corn and ethanol (the calculation of emissions, which uses the life-cycle approach, does account for the energy content of this production). Because in this model resources have to be diverted from production of other goods (the numeraire) to increase corn and ethanol production, this omission would matter if the energy intensity of corn and ethanol production differed substantially from that of the rest of the economy. The EIA estimates that energy use on farms is about 0.9% of total U.S. energy consumption (Newell 2011), a fraction that is very close to the contribution of farm production to U.S. GDP (U.S. Bureau of Economic Analysis 2011). If corn and ethanol production were more energy intensive than other sectors in the economy, the resulting corn and ethanol supply curves would depend upon energy prices and be more inelastic, since increased corn production will raise energy prices, shifting the supply curve leftward. In this case, policies promoting ethanol are likely to lead to even higher increases in corn prices than in our model.

Table 3A. Market Effects of Alternative Policy Scenarios

	Laissez Faire	No Ethanol Policy	Status Quo	First Best	Optimal Tax and Subsidy	Optimal Subsidy	Optimal Mandate
Fuel tax ($/gallon)	0.00	0.39	0.39	0.23	0.96	0.39	0.39
Ethanol subsidy ($/gallon)	0.00	0.00	0.45	0.11	1.02	0.67	0.00
Oil tariff ($/barrel)	0.00	0.00	0.00	17.53	0.00	0.00	0.00
Corn tariff ($/bushel)	0.00	0.00	0.00	1.26	0.00	0.00	0.00
Fuel price ($/GEEG)	2.36	2.64	2.50	2.75	2.74	2.44	2.47
Gasoline price ($/GEEG)	2.36	2.25	2.11	2.52	1.78	2.05	1.98
Ethanol price ($/gallon)	1.63	1.43	1.79	1.78	1.95	1.96	2.01
U.S. Oil price ($/barrel)	62.8	62.0	61.0	75.7	58.7	60.5	60.1
U.S. Corn price ($/bushel)	3.17	2.44	3.74	3.71	4.32	4.38	4.56
Petroleum by-product price ($/GEEG)	1.56	1.65	1.76	2.00	2.02	1.81	1.86
Gasoline quantity (billion GEEGs)	130.5	127.4	123.6	115.1	114.3	121.7	119.9
Ethanol quantity (billion gallons)	6.03	0.05	10.76	13.94	15.51	16.02	17.45
Corn production (billion bushels)	12.55	11.78	13.15	13.12	13.76	13.83	14.01
Corn demand (billion bushels)	8.61	8.93	8.35	8.37	8.10	8.07	7.99
Corn export (billion bushels)	2.29	2.83	1.86	0.94	1.43	1.38	1.25
Oil domestic supply (billion barrels)	1.94	1.94	1.93	2.03	1.92	1.93	1.93
Oil import (billion barrels)	3.57	3.45	3.29	2.84	2.91	3.21	3.14

Note: 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)

	No Ethanol Policy	Status Quo	First Best	Optimal Tax and Subsidy	Optimal Subsidy	Optimal Mandate
Social welfare ($ billion)	0.5	6.7	11.5	9.9	7.5	8.2
Pollution effect ($ billion)	1.4	1.0	2.6	2.6	0.8	1.1
Tax revenue ($ billion)	49.7	47.6	78.5	108.5	43.0	53.6
P.S. Oil supply ($ billion)	−1.5	−3.4	25.8	−7.9	−4.3	−5.2
P.S. Corn supply ($ billion)	−8.8	7.4	7.0	15.2	16.0	18.4
C.S. Corn demand ($ billion)	6.4	−4.9	−4.6	−9.6	−10.1	−11.5
C.S. Fuel demand ($ billion)	−36.4	−18.7	−49.6	−48.3	−9.8	−14.3
C.S. Petroleum by-product ($ billion)	−10.2	−22.3	−48.1	−50.5	−28.2	−33.9
CO_2 emission (million tCO_2)	−70.1	−50.9	−128.7	−128.7	−41.4	−54.2

Note: P.S. = producer surplus; C.S. = consumer surplus. Under *laissez faire* the pollution effect is $30.2 billion and the CO_2 emission level is 1,509 million tons.

ethanol policy are corn producers and fuel consumers.

The First Best Policies

In the baseline scenario, the marginal emissions damage is $20/$tCO_2$ and thus the first best policy entails a tax on carbon emissions of $20/$tCO_2$, in addition to oil import and corn export tariffs. This carbon tax is equivalent, in our model, to a gasoline tax of $0.23/GEEG. Since in the baseline model ethanol is assumed to pollute less than gasoline, and since the $0.23 tax is assumed levied on gallons of *fuel*, then a gross subsidy to ethanol of $0.11/gallon is required to support the first best solution. Thus, the first best policies entail a $0.17/GEEG tax on ethanol, a $0.23/GEEG tax on gasoline, a $17.53/barrel import tariff on oil, and a

\$1.26/bushel export tariff on corn.[38] These policies would increase welfare by \$11.5 billion compared with the *lassez faire* scenario, and \$4.8 billion relative to the status quo. Compared with the *laissez faire* scenario, the combined effect of these policies is to increase U.S. oil prices by about 21%, while world oil prices fall by about 7%. Despite the corn export tariff, U.S. corn prices increase by 17% (world corn prices rise by 58%); 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 emissions fall by 8.5%. U.S. dependence on foreign oil falls sharply, as imports fall by 20%, 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 with 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 \$4.8 billion compared with the status quo, there is a significant redistribution of income away from consumers and corn producers to oil producers and the government. About a third of the welfare gain is accounted for by the decline in pollution costs.

Second Best Policies: Fuel Taxes and Ethanol Subsidies

The second best fuel tax and ethanol subsidy are presented in tables 3A and 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 an equal reduction in carbon emissions. In addition, oil imports are only 2.5% larger than under first best policies. The first best oil tariff of \$17.53/barrel (at 23.6 gallons per barrel) amounts to a gasoline tax of \$0.74/gallon; combined with the \$0.23/gallon tax for pollution damages, this means that the first best policies are similar to an overall fuel tax of \$0.97, which is remarkably close to the second best tax of \$0.96, as given in table 3A.[39] 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 \$0.96/gallon and a small net subsidy on ethanol of \$0.09/GEEG (the second best subsidy of \$1.02/gallon for ethanol more than offsets the fuel tax). Ethanol production in this scenario reaches 15.5 billion gallons, slightly above the 2015 mandate level of 15 billion gallons. Relative to the first best, the domestic corn price increases 16%. Thus, the fuel tax increase largely substitutes for the unavailability of the oil import tariff, and the ethanol subsidy increase partially offsets the impact on the world corn price of the unavailability of the corn export tariff.[40] Compared with *laissez faire*, these policies reduce world oil prices by 6.5% and increase world corn prices by 36%. Relative to the first best, world oil prices increase by a very modest \$0.53/barrel and world corn prices fall by a more substantial \$0.65/bushel.

Even though the second best policy captures 86% of the gains achievable by the first best policy mix (relative to *laissez faire*), the distributional effects differ. Compared with 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 with 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,

[38] As noted by one of the Journal's editors, the fact that the first best gasoline tax is actually smaller than the status quo (average) fuel tax of \$0.39 needs to be interpreted with care. In the status quo, of course, we do not have optimal oil import and corn export taxes. Furthermore, here we are focusing on only the carbon externality rationale for fuel taxation, which in fact could be invoked to address other mileage-related external costs associated with fuel consumption (Parry, Walls, and Harrington 2007).

[39] The reason the gasoline tax 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 production.

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

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 (15.51 billion gallons) along with the appropriate fuel tax (which can be shown to equal $0.86/gallon).

Optimal (Constrained) Ethanol Policy

The last two columns of tables 3A and 3B 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 the next-to-last column, an ethanol subsidy is the only discretionary policy instrument; and in the scenario of the last column, 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 with 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 tables 3A, the optimal ethanol subsidy is $0.67/gallon when the fuel tax is fixed at $0.39/GEEG, higher than the status quo subsidy level but, as predicted by the theory, well below the second best subsidy level that applies when fuel taxes are also chosen optimally. However, because here the fuel tax is held at $0.39/gallon fuel tax, the "net" subsidy to ethanol is actually $0.40/GEEG (as opposed to a net subsidy of only $0.09/GEEG in the second best scenario). Compared with the second best scenario, ethanol production increases by 3.3% and slightly exceeds the 2015 mandate level of 15 billion gallons. Compared with 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 welfare benefits of adjusting the subsidy away from its status quo value are minimal, and the environmental benefits are actually negative.

As shown in Lapan and Moschini (2009), an ethanol mandate is equivalent to a revenue-neutral ethanol subsidy and fuel tax. Since the last column 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. Of course, by construction, the welfare level that is attained here is lower than that associated with the optimal second best policy. Compared with 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.[41] This ethanol consumption level exceeds the RFS2 mandate requirement of 15 billion gallons per year of conventional biofuel (corn ethanol) in 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.[42] Carbon 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 slightly, because of the replacement of some gasoline by ethanol. 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.

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 the ethanol subsidy and fuel tax optimally, 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,

[41] 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.

[42] World corn and oil prices are important because they reflect the terms of trade for the United States and thus are one component of the welfare impact of each policy.

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 in 2015, as do all of the constrained policies we considered. Still, the clear lesson is that fuel taxes are a more powerful instrument for reducing carbon emissions and increasing welfare than are ethanol policies.

Sensitivity Analysis

In order to investigate the robustness of our conclusions, we varied the nine 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. Needless to say, the optimized value of the relevant policy instruments changed with the change in these basic parameters. There are several results that are common to all sensitivity analysis experiments (see the tables in the supplementary Appendix online for more details):

- For all cases considered, the status quo policies dominated *laissez faire* and in all cases, except when foreign oil export supply is relatively inelastic, delivered at least 44% 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 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 \$5/tCO_2). The mandate also resulted in lower pollution than *laissez faire* in all cases except when ethanol pollutes more than gasoline ($\lambda = 2.0$).
- 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 76% 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 86%).
- 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 ($\bar{\varepsilon}_o = 5$). 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).

As an additional sensitivity analysis exercise we carried out a Monte Carlo simulation meant to represent our uncertainty about the model's true parameters. Specifically, the parameters of the model were randomly drawn 100,000 times, from a beta distribution consistent with the ranges reported in table 4, with the shape parameters of this distribution calibrated with the so-called PERT (Program Evaluation and Review Technique) methodology (Davis 2008)—see the Appendix for more details—and for each parameter vector we calculated the optimal values of the policy instruments for the various scenarios analyzed. One way to interpret the results of this Monte Carlo experiment is as a robustness check on the magnitude of the policy tool parameters that we computed in our baseline. Within this perspective, some of our main conclusions are re-emphasized by the Monte Carlo simulation. For example, for the second best scenario we find that the optimal fuel tax and ethanol subsidy remain significantly above the status quo level. Specifically, taking

Table 4. Parameters and Values Used in the Sensitivity Analysis

Parameter	Symbol	Baseline	Range
Cost of CO_2 emission (\$/tCO_2)	$\sigma'(\cdot)$	20	[5, 80]
Ethanol CO_2 emission efficiency	λ	0.75	[0.5, 2.0]
Elasticity of fuel demand	η_f	−0.5	[−0.9, −0.2]
Elasticity of petroleum by-product demand	η_h	−0.5	[−0.9, −0.2]
Elasticity of foreign corn import demand	$\bar{\eta}_c$	−1.5	[−3.0, −1.0]
Elasticity of foreign oil export supply	$\bar{\varepsilon}_o$	3.0	[1.0, 5.0]
Elasticity of domestic corn demand	η_c	−0.20	[−0.5, −0.1]
Elasticity of domestic corn supply	ε_c	0.30	[0.1, 0.5]
Elasticity of domestic oil supply	ε_o	0.20	[0.1, 0.5]

the 10% and 90% of the empirical distribution from the simulation, the fuel tax ranges from \$0.75/gallon to \$1.27/gallon and the ethanol subsidy ranges from \$0.86/gallon to \$1.28/gallon. More details concerning this and other scenarios are reported in table A10.

Conclusion

This article 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 solve for 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 \$0.96/GEEG and ethanol subsidy of \$1.02/gallon would increase ethanol consumption to 15.51 billion gallons, a 44% increase compared with the current (status quo) situation, it would decrease gasoline consumption by 7.5% and reduce emissions by 5.3% compared with 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 17.5 billion gallons, 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.

Finally, a few caveats. In our analysis we have ignored the "blend wall" issue, which might make it difficult to increase ethanol consumption beyond 10% of total fuel use. But of course the blend wall is also ignored by RFS2 and, in any event, such an issue might be addressed as an increasing fleet of vehicles that can utilize E85 fuel becomes available, and/or by allowing newer standard vehicles to use E15 fuel. We have also assumed, as is the norm, that markets are competitive. If imperfect competition were present in some of the markets, this would affect the model both through the specification of equilibrium conditions and through the analysis of optimal policy. For example, if there were monopoly power exercised by a U.S. firm in the corn export market, then this would reduce the benefits derived from government policies that restrict corn exports. On the other hand, if foreign oil exporters were exercising monopoly power, this would mean higher world prices than would otherwise prevail and thus could increase the desirability of U.S. oil import policy or ethanol policies that reduce the demand for oil.

As for directions for future research, the modeling framework that we have presented could be extended to represent explicitly the possibility of trade in ethanol. Such a trade is currently prevented by prohibitive tariffs (as noted earlier, the 2.5% ad valorem import tariff is supplemented by a $0.54/gallon import duty), a condition that we have reflected in the structure of our model. Looking forward, there are at least two reasons to be interested in modeling ethanol border tariffs as active policy instruments. First, it is widely believed that producing ethanol from sugarcane, as done in Brazil, is more efficient than producing ethanol from corn. Opening up ethanol trade would provide the United States with an alternative way to reduce the use of fossil fuel for transportation. Second, reducing or eliminating import tariffs on ethanol might help the United States accomplish the ambitious RFS2 mandates. At present it is clear that whereas the 15-billion-gallon mandate for corn-based ethanol will be easily reached by the planned 2015 year, the RFS2 overall target of 36 billion gallons by 2022 might be problematic because the feasibility of cellulosic ethanol and other advanced biofuels is lagging expectations. Because the EPA has certified sugarcane ethanol as an advanced biofuel, imports of sugarcane ethanol (from Brazil, say) could help satisfy the RFS2 mandate for noncellulosic advanced biofuel (and, perhaps more generally, for all nonconventional biofuel if the EPA were to allow noncellulosic advanced biofuel to substitute for cellulosic ethanol). In such a context, of course, an important question to be studied is how reductions or eliminations of this tariff would affect U.S. markets and U.S. welfare. This problem is not trivial, because the benefits of this imported ethanol could be at least partly offset by the fact that U.S. imports will drive up the world price of sugarcane ethanol and thus reduce its use in other countries as a substitute for oil. This, in turn, will increase foreign emissions and world oil prices, both of which will have adverse consequences for U.S. welfare. The full characterization of such ethanol trade impacts is left for future research.

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