Welfare impacts of alternative bioefuel and energy policies

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Abstract

We employ an open economy general equilibrium model to investigate the effects of government energy policy, with emphasis on corn-based ethanol, on the U.S. economy. The model specification incorporates world and domestic markets, assumes pollution costs from fuel consumption, and allows endogenous determination of equilibrium quantities and prices for oil, corn and ethanol. The model is calibrated to represent a recent benchmark data set for 2009 and is used to simulate the positive and normative effects of alternative policies. We find that a second best policy of a fuel tax and ethanol subsidy approximates fairly closely the welfare gains associated with the first best policy (optimal carbon tax and tariffs on traded goods).The largest economic gains to the U.S. economy from these energy policies arise from the impact of policies on the U.S.'s terms of trade, particularly in the oil market. We also find that, conditional on the current fuel tax, an optimal ethanol mandate is superior to an optimal ethanol subsidy. In the benchmark case the optimal mandate slightly exceeds 15 billion gallons of ethanol.

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

This version: 30 April 2010. For a more updated version of this manuscript, check the website of the Department of Economics at Iowa State University (http://www.econ.iastate.edu/).

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1. Introduction

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

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

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

Given these ambitious targets and government policy geared to implement them, it is important to have a clear understanding of the welfare implications of policies which impact biofuels production. This topic has been the subject of a few studies, including de Gorter and Just (2009a, 2009b), that have elucidated some critical economic effects. 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 consumption instead of biofuels. They (2009b) also develop a framework to analyze the interaction effects of a biofuel tax credit and a price contingent farm subsidy. The annual rectangular deadweight costs – which arise because they conclude that ethanol would not be commercially viable without government intervention – dwarf in value the traditional triangular deadweights costs of farm subsidies.

Elobeid and Tokgoz (2008) set up a multimarket international ethanol model to analyze the influence of trade liberalization and the removal of the federal tax credit in the U.S. on ethanol markets. They find that the removal of current tariffs on imported ethanol will lead to a 13.6% decrease in the U.S. domestic ethanol price and a 3.7% increase of ethanol's share in U.S. fuel consumption. With the removal of both tax credits (54 cents/gallon at the time of the study) and tariffs, their study predicts that U.S. ethanol consumption will fall by 2.1% and the price of ethanol will fall by 18.4%.

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

In considering the effectiveness of ethanol in reducing GHG emissions, one issue that arises is that of "indirect land use" effects. It is argued that diverting feed corn to ethanol production in the United States might bring new marginal land into production elsewhere in order to satisfy the increased demand for agricultural output (Searchinger et. al., 2008), an

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

indirect effect of biofuel mandates that could be quite sizable. To assess the global economic and land use impacts of biofuel mandates, Hertel, Tyner and Birur (2008) use a computable general equilibrium model (CGE), which is built upon the standard Global Trade Analysis (GTAP) modeling framework. To jointly meet the biofuel mandate policies of the United States (15 billion gallons of ethanol used by 2015) and the EU (6.25% of total fuel as renewable fuel by 2015), they find that coarse grains acreage in the United States is up by 10%, oilseeds acreage in the EU increases dramatically by 40%, the cropland areas in the United States would increase by 0.8%, and about one third of these changes occur due to the EU mandate policy. The U.S. and EU mandate policies jointly reduce the forest and pasture land areas of the United States by 3.1% and 4.9%, respectively.

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

In addition, sugarcane ethanol qualifies as an advanced biofuel according to the overall result of the EPA's ILUC modification, since its calculated average of 61% GHG reduction compared to baseline gasoline already exceeds the 50% GHG reduction threshold for advanced biofuels, and it actually meets the 60% GHG reduction standard for cellulosic ethanol.

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

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

Our results consistently show that the largest economic gains to the U.S. from policy intervention come from the impact of policies on the U.S.'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 we have not accounted for any of the "national security" gains that could arise from reduced U.S. dependence on imported oil.

The rest of this paper is organized as followed. The next section reviews and extends the analytical model by Lapan and Moschini (2009). Section 3 presents the equilibrium conditions of the model so that, in conjunction with parameter estimates given in section 5, our results can be readily replicated. Section 4 provides the definition of our welfare measure and shows how (constrained) optimal policy can be determined. Section 6 discusses the results of our simulations, comparing the relative efficacy of alternative policies and investigating the sensitivity of these results to parametric values. The numerical results of the simulations are contained in tables at the end of the paper. The last section of the paper provides some concluding remarks.

2. Model Review

We adapt and extend the model developed in Lapan and Moschini (2009) to make it more suitable to simulate the consequences of alternative policies directed toward reducing U.S. emissions and reducing U.S. reliance on oil imports. The main extension is to recognize that when oil is refined other products, in addition to gasoline, are produced (e.g., distillate fuel oil, jet fuel, etc.). We aggregate all the non-gasoline output into a single good called petroleum byproducts.

The model is a stylized economy with three basic commodities: a numeraire good, corn (food) output and oil. In addition, there is a processing sector that refines oil into gasoline and other petroleum byproducts, and another sector that converts corn into ethanol, which may then be blended with gasoline to create the fuel used by households. Consumers are assumed to have quasi-linear preferences (which can then be aggregated into a representative consumer) with utility function:

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

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

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

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

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

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

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

(VI) foreign oil export supply curve, $\overline{S}_o\left(p_o^w\right)$

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

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

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

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

2.1. *Oil Refining Sector*

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

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

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

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

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

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

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

2.2. *Ethanol Production Sector*

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

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

where x_e is ethanol output and z_e the amount of other inputs used per unit of ethanol output. Because the energy content of ethanol is much lower than that of gasoline, 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" (GEEG) units.[6] The production parameter α is crucial in determining the economic viability and consequences of ethanol and it is defined as:

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

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

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 byproduct per bushel of corn input used to produce ethanol; and δ_2 represents the relative price of DDGS, compared to the price of corn. That is, if one bushel of corn input yields a gallons of ethanol (in volume terms) and δ_1 units of DDGS which can then be resold as a corn-substitute at a relative price of δ_2, then the *net* amount of corn required to produce a gallons of ethanol is only $(1-\delta_1\delta_2)$.

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

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

3. Equilibrium

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

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

(7) $S_c\left(p_c\right) = D_c\left(p_c\right) + \bar{D}_c\left(p_c^w\right) + x_c$ (Corn Market Equilibrium)

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

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

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

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

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

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

In equations (12) and (13), τ_o, τ_c are the oil import, and corn export, specific tariffs respectively (assumed to be non-prohibitive, so trade still occurs). To close the model, we must distinguish between the case in which market policies, like fuel taxes and ethanol subsidies are used, and the "mandate" case in which a binding ethanol mandate is used.

3.1. *Equilibrium with Fuel Taxes and Ethanol Subsidies*

Let *t* be the tax, per gallon, on fuel, and *b* be the (blending) subsidy for ethanol (measured in GEEG units). Then, since gasoline and ethanol are modeled as perfect substitutes for consumers, arbitrage relations imply:[9]

(14A) $p_g = p_f - t$

(15A) $p_e = p_g + b = p_f + \left(b - t\right)$

Thus, for the case of taxes and subsidies, equations (7)-(13), (14A) and (15A) can be used to calculate the equilibrium, given the policy parameters $\left\{\tau_o, \tau_c, t, b\right\}$.

3.2. *Equilibrium with Mandates*

With a binding ethanol mandate (denoted by x_e^M) the quantity of ethanol produced becomes

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

exogenous. From the production relationship $x_c = x_e / \alpha$, with an exogenous binding mandate the market clearing equation (7) becomes:

$$(14B) \quad S_c(p_c) = D_c(p_c) + \bar{D}_c(p_c^w) + (x_e^M / \alpha)$$

The zero profit condition in fuel production, together with the blending requirement, provide the other condition needed to solve the model: assuming there may be exogenous fuel taxes and ethanol subsidies, this condition is

$$(15B) \quad \left[p_f(x_g + x_e^M) - t\right] \cdot (x_g + x_e^M) = p_g(x_g) \cdot x_g + (p_e - b) \cdot x_e^M$$

Equation (15B) states that the price of fuel is a weighted average of the price of its components (ethanol, gasoline), where the amount of ethanol is exogenously determined. Also note that we allow for both a (binding) ethanol mandate and an ethanol subsidy. Thus, with a mandate, the equilibrium is calculated using equations (8)-(13), (14B) and (15B). As shown in Lapan and Moschini (2009), the impact of an ethanol mandate is equivalent to a combination of fuel taxes and ethanol subsidies that are revenue neutral for the government.

4. Welfare

In defining welfare, we assume all tax revenue is returned to domestic consumers and that there are no externalities other than that due to carbon emissions. Domestic welfare could be calculated using the indirect utility function, the profit function for the domestic oil and corn industries and government tax revenue, or by using the direct utility function, 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 (equation 1), we have:

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

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

To understand how the optimal (or second best) policies are determined, take the total differential of (16) and rearrange terms to yield:[10]

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

The first three terms in (17) relate to domestic resource allocation decisions, whereas the last two relate to trade decisions, and for each term optimality entails equating marginal benefit to marginal cost. Thus, θ' is the value to consumers of additional corn consumption, C' is the marginal cost of corn production, and hence optimality requires $\{\theta' = C'\}$. Similarly, the second term – relating to ethanol production – says that the marginal value of fuel to consumers, less the pollution cost, should be equated to the marginal cost of producing ethanol. A similar interpretation applies to the third term, where the term in square brackets is the net *social* value of another unit of refined gasoline and byproducts, and $\left[\omega_g + (\Omega'/\beta)\right]$ is the extraction and refining cost of producing that gallon. The two terms on the second row relate to trade

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

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 (or MRS) 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, specifically it is $p_o^w + \bar{S}_o(dp_o^w / d\bar{S}_o)$. Similarly, for corn exports, the marginal value perceived by a competitive corn exporter is p_c^w whereas the marginal revenue for the country as a whole is $p_c^w + \bar{D}_c(dp_c^w / d\bar{D}_c)$. Thus, as shown in Lapan and Moschini (2009), the first best policy entails oil import tariffs, corn export tariffs, and a tax on carbon emissions. The "carbon tax" is 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). Specifically, it is shown that the "first best" policy instruments are:[11]

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

In our analysis, such a first best scenario provides an important (and insightful) benchmark for

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[11] To calculate the actual values of the instruments, the equilibrium conditions described in Section 3 must be used in conjunction with (17).

other, perhaps more realistic, policy scenarios. Another useful benchmark is the "*laissez faire*" scenario, i.e., the unfettered competitive equilibrium with $t = b = \tau_o = \tau_c = 0$. In fact, all welfare calculations are reported as differences relative to the *laissez faire*, and comparisons of each policy scenario with the first best provide information as to the efficacy of the various second best policies considered. Note that in all scenarios except the first best we restrict tariffs to be zero (i.e., $\tau_o = \tau_c = 0$) so that, realistically, they presume that the United States is in compliance with its WTO obligations.[12] 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).[13] Using these policy restrictions and the behavioral conditions outlined earlier, (17) can be rewritten as:

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

Thus, when tariffs are not permitted, in determining the welfare consequences of domestic policy instruments, one must consider their impact on the terms of trade as well as on carbon emissions. As we shall see from the simulations, under many plausible scenarios, it is these "large country" effects which dominate the welfare calculations. When there are no border policies, it can be shown that (17A) reduces to:[14]

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

Here $\Delta(p_o) \equiv \beta\left(\bar{S}_o(p_o) + S_o(p_o)\right)$ is the supply of unblended gasoline, and $Q(p_c) \equiv \left\{S_c(p_c) - D_c(p_c) - \bar{D}_c(p_c)\right\}$ is the residual supply of corn for ethanol. When both fuel

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[12] 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.

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

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

taxes and ethanol subsidies can be used, the second best policies are:

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

where the superscript "*sb*" denotes second best. Finally, 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 the optimal ethanol subsidy, as a function of the exogenous fuel tax, t^0, is:[15]

$$
(20) \qquad
\begin{aligned}
b^{sub} &= \left(\frac{\bar{D}_c}{\alpha Q'} - \lambda \sigma' \right) + \left\{ \rho \left(\sigma' + \frac{\beta \bar{S}_o}{\psi'} \right) + \left(1-\rho\right) t^0 \right\} \quad = b^{sb} + \left(1-\rho\right)\left(t^0 - t^{sb}\right) \\
\rho &= \frac{\beta \Delta'}{\beta \Delta' - D_f' + \beta \Delta' \left(\beta_2 / \beta\right)^2 \left(D_f' / D_b'\right)} \in \left(0,1\right)
\end{aligned}
$$

Note that, when the fuel tax is not a choice variable and $t^0 < t^{sb}$, then the subsidy will generally be lower than the second best subsidy and this subsidy will be increasing in the exogenous tax rate.

When only the mandate is the choice variable, it can be shown that the first order condition for an optimal choice of the mandate reduces to:[16]

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

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

---

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

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

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

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

5. Calibration of the Model

The baseline model is calibrated to fit 2009 data using linear supply and demand curves. In order to calibrate the model, we need to specify the values of the exogenous parameters and the value of the policy variables in this baseline period. In addition, we also need to specify the domestic and world import demand functions for corn $D_c(p_c)$ and $\bar{D}_c(p_c^w)$, the domestic supply of corn $S_c(p_c)$, the domestic and world export supply functions for oil $S_o(p_o)$ and $\bar{S}_o(p_o^w)$, the demand for fuel $D_f(p_f)$ and the demand for petroleum byproducts $D_h(p_h)$. If these functions come from a two parameter family of functions, as for the linear functional forms that we will be using, each demand or supply function can be "calibrated" using an estimate of the elasticity (of supply or demand) for that function and the value of the relevant variables in the baseline period.

Table 1 gives the assumed baseline values, and sources, for the primitive parameters (e.g., elasticities) used in the calibration of the model, along with the value of some other calculated parameters, and their method of calculation, which are provided to ease the interpretation of the model. Table 2 gives the primary sources (or methods of calculation) and the 2009 value used for each baseline variable, including the policy variables. Some parameters are drawn from a comprehensive survey of the literature, while others are calculated from their definitions in terms of more primitive terms. In general, data for corn utilization and price are gathered from the Feed Grain Database of the U.S. Department of Agriculture (USDA),[17] and data for oil, gasoline and oil refinery byproducts are obtained from the U.S. Energy Information Administration (EIA) website at http://www.eia.doe.gov/. Ethanol quantity data are from the Renewable Fuel Association (RFA) website and ethanol prices are provided by the Nebraska Energy Office

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[17] http://www.ers.usda.gov/Data/FeedGrains/

(NEO) website at http://www.neo.ne.gov/statshtml/66.html. More specific information on sources of data used is provided in the tables that follow.

5.1. Prices in the Baseline

Because ethanol has a lower energy content than gasoline, its quantity, price and subsidy level used in the simulation are all converted to be expressed per gasoline energy-equivalent gallons (GEEG). Currently, fuel consumption (blended gasoline with ethanol) is subject to the federal tax of \$0.184/GEEG, plus the weighted average state tax of \$0.203/GEEG, hence $t^0 = \$0.39$ /GEEG. Ethanol production has a tax credit of \$0.45/gallon when blended with gasoline, which is equivalent to a subsidy, in gasoline energy-equivalents units of $b = \$0.65$ /GEEG. The U.S. ethanol price of \$1.79/gallon is the 2009 average rack price F.O.B. Omaha, Nebraska, and its price of (\$2.59/GEEG) is derived from that rack price.[18] Prices of fuel and (unblended) gasoline are calculated from arbitrage conditions which are assumed to hold in the *status quo*, that is: $p_f = p_e - b^0 + t^0 = \$2.33$ /GEEG, and $p_g = p_e - b^0 = \$1.94$ /GEEG.[19] The crude oil price of \$61.00/barrel is the refiner's composite acquisition cost of crude oil, the weighted average of acquisition costs of domestic and imported oil. The corn price of \$3.74/bushel uses the averaged farm price. The USDA price of the byproduct in ethanol production, DDGS, is \$114.40/t (metric ton), which reflects the wholesale price in Lawrenceburg, IN. We used EIA data to calculate a weighted average retail price, excluding taxes, for petroleum byproducts in the oil refining process; this price index is denoted p_h, and its 2009 value is \$1.76/GEEG.[20] The prices of the "other" inputs used in gasoline and ethanol production, w_g and w_e, are derived from the zero profit condition: $w_g = p_g + \beta_2 p_h / \beta - p_o / \beta = \$0.91$ /GEEG, $w_e = p_e - p_c / \alpha = \$1.11$ /GEEG, respectively. The estimated productivity parameters α, β and β_2 are discussed

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

[19] This calculation method is necessary for the internal consistency of our model. A question, perhaps, is how close this calculated value is to 2009 observed data. From EIA data, the average retail price of all grades and all formulation 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.

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

below.

5.2. Productivity Parameters

One bushel of corn produces approximately 2.80 gallons of ethanol (Eidman, 2007); thus $a = 2.80$. The production of ethanol generates bioproducts that are useful as animal feed (and thus can replace corn in that use). The nature of such bioproducts depends on whether ethanol is produced in a dry milling plant or in a wet milling plant. Because dry milling plants are much more common, we construct the model as if all ethanol is produced in dry milling plants.[21] According to industry sources (RFA), such a process generates as a byproduct about 17 lbs of DDGS per bushel of corn; given that there are 56 pounds in a bushel, then $\delta_1 = 0.303$. The DDGS price relative to the corn price is captured by the parameters $\delta_2 = 0.776$, calculated as described in Table 1 form the data discussed in the foregoing. Given the assumption of perfect substitution between corn and DDGS in feed use, then each processed bushel of corn generates, as a byproduct , the equivalent of $\delta_1\delta_2 = 0.24$ bushels of corn.[22] Hence, the ethanol production coefficient, accounting for byproduct value, is $\alpha = 2.53$ GEEG/bushel.

5.3. Quantities in the Baseline

For the baseline scenario, we use domestic production including stock changes and other adjustments to measure domestic supply, net exports of corn to measure foreign demand, and net imports of oil to measure foreign oil supply. In the *status quo* (for 2009), there are 13.15 billion bushels of corn and 1.93 billion barrels of domestic oil produced in the U.S. The quantities of foreign corn demanded (US exports) and oil supplied (US imports) were 1.86 billion bushels and 3.29 billion barrels, respectively. Corn utilization consists of three main uses: domestic food/feed use (exclusive of ethanol use), foreign demand (exports) and ethanol use. The U.S. ethanol production of 10.76 billion gallons (RFA data) corresponds to 7.43 billion GEEG. Given the assumed fixed-proportion technology of ethanol production, 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

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

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

reports data for the finished motor gasoline product, including blended ethanol, of 134.4 billion gallons, which measures total fuel consumption in volumetric units. Subtracting ethanol production (in volumetric units) from the figure for finished motor gasoline gives unblended gasoline's contribution to total fuel consumption, $x_g = 123.6$ billion GEEG units. Final fuel consumption, measured in GEEG units is the sum of gasoline and ethanol consumption in the same units, $x_f = x_g + x_e = 131.0$ billion GEEG units. The assumed fixed-proportions technology in oil refining gives the calculated yield of gallons of gasoline per barrel of crude oil as: $\beta = x_g / x_o = 23.6$ GEEG/barrel.[23] Given β, the yield of petroleum byproducts (in gallons) from a barrel of crude oil is calculated to be $\beta_2 = 21.1$.[24]

5.4. Carbon emissions

The carbon emission rate of gasoline, measured as carbon dioxide (CO_2), is 11.29 kg/GEEG (Wang, 2007). The estimated net carbon dioxide emissions rate of ethanol has a considerable range, which depends on feedstock sources and the accounting for indirect land use changes. We apply the rate of 8.42 kg/GEEG of CO_2 from the life cycle perspective suggested by Farrel et al. (2006), which is close to the emission rate of corn ethanol without feedstock credits reported in Searchinger et. al. (2008). There is, of course, considerable uncertainty (and controversy) about ethanol's actual carbon dioxide emissions. For example, Searchinger et al.(2008) estimate the following specific CO_2 rates: 5.934 kg/GEEG for corn ethanol with feedstock credits, and 19.164 kg/GEEG for corn ethanol without feedstock credits but with accounting for land use changes.[25] These values, in turn, imply that the relative pollution efficiency of ethanol to gasoline

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

[24] 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.

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

(i.e., the parameter λ) is around 0.75 in the benchmark case, with the range from 0.52 to 1.70 .[26] To capture the influence of such uncertainty on the optimal values of the policy instruments, some sensitivity analysis on the impact of ethanol's emissions rate will be carried out.

5.5. Carbon dioxide emissions cost

There are extensive estimates regarding the social cost of carbon dioxide emissions. Tol (2009) surveys 232 published estimates of the marginal damage cost of carbon dioxide. The mean of these estimates is a marginal cost of carbon emissions of \$105/tC (metric ton carbon), which is equivalent to \$28.60/tCO_2, with a standard deviation equivalent to \$243/tC (\$66/tCO_2), where social costs are measured in 1995 dollars. The widely-cited "Stern Review" (Stern et al., 2006) has a higher estimate of approximately \$80/tCO_2, due to a lower discount rate applied to future economic damage from climate change. Using a more conventional discount rate, Hope and Newbery (2006) find the carbon cost from the Stern report could be reduced to the range of \$20-\$25/tCO_2.

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

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

The pollution externality cost used in our paper is meant to account for local and global warming costs. We use the value of \$33/tCO_2 which, as discussed, is consistent with NHTSA

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

(2009). For our sensitivity analysis we explore the implications of different values for this cost, in the range of \$2/tCO$_2$ - \$100/tCO$_2$. The lower end of this range is of some interest because it corresponds to the NHTSA estimate of the impact of CO$_2$ pollution on the domestic economy only. Other externality costs associated with congestion, accidents and non-carbon pollution are not explicitly taken into account.[27] Given the assumed linear cost function of the emissions externality $\sigma(\cdot)$, the marginal effect $\sigma'(\cdot)$ represents the normalized constant marginal emissions damage from gasoline. Given our assumption of $\$33/\text{tCO}_2$ for the cost of carbon dioxide pollution, $\sigma'(\cdot) = 37$ cents/GEEG.

5.6. Elasticities

The elasticity estimates are obtained from the literature to reflect the best available econometric evidence. As most of the studies suggest that the short run corn supply elasticity is within the range of [0.2, 0.4], and the long run supply elasticity is 0.5, we pick a value of $\varepsilon_c = 0.23$ from the USDA (2007).[28] The elasticity of domestic food/feed demand of $\eta_c = -0.2$ is from de Gorter and Just (2009b). The estimates for the elasticity of foreign corn import demand $(\overline{\eta}_c)$ range from an inelastic value of -0.30 (short run value) used by Gardiner and Dixit (1986), to a considerably more elastic value of -2.41, reported by the country commodity linked system performed by Economics Research Service at the USDA. They get implied partial elasticities of foreign behavior with respect to a sustained exogenous shock to the world price of corn only, the implied elasticity of net imports in the 3rd year is -2.41. We use the value of -1.74, obtained from the 2004 FAPRI Missouri documentation, and also carry out sensitivity analysis within the range of [-3.0, -0.3]. Estimates for the elasticities of domestic oil supply (ε_o) of 0.2 and foreign export oil supply $(\overline{\varepsilon}_o)$ of 2.63 are drawn from de Gorter and Just (2009b).[29] The range of [0.6, 5.0] for elasticity of foreign export oil supply is considered for the purpose of sensitivity analysis.

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[27] 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 of \$25/tC. They also account for external congestion costs of 3.5 cent/mile, and external accident cost of 3 cent/mile.

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

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

The elasticity of fuel demand η_f is assigned the benchmark value of -0.5, with the range [-0.9, -0.2], as suggested by Toman, Griffin and Lempert (2008), which is consistent with Parry and Small (2005) as well (they use an elasticity of gasoline demand of -0.55, with the range [-0.9, -0.3]). As for elasticities of gasoline and ethanol supply, the construction of our model does not need these as primitive parameters, although the implied elasticities of the derived ethanol supply and gasoline supply are easily derived for the purpose of comparison with other models.[30]

6. Results

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

(i) *Laissez-faire*, with no border or domestic taxes or subsidies;
(ii) The first best, when border policies and domestic policies are used;
(iii) The second best: the fuel tax and ethanol subsidy are chosen optimally;
(iv) The ethanol subsidy is chosen optimally, the fuel tax is set at its current level;
(v) An ethanol mandate is chosen optimally, the fuel tax is set at its current level.

For each scenario, we report on Table 4A the values of the policy instruments and the equilibrium value of the simulated variables. On Table 4B, for the simulated *laissez faire* equilibrium we report pollution emissions, trade flows and the distribution of welfare (consumer and producer surpluses) among the various parties. We then report, for each of the cases in which some active policy is used, the changes in these variables relative to the *laissez faire* scenario.[31] 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.[32] Perhaps the most striking thing about our results is that all scenarios improve upon

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[30] Quantities are given by production technology and prices are found from long run equilibrium conditions, as explained in the text. Given these quantities and prices, the implied elasticities (in the baseline case) of the derived ethanol supply and gasoline supply can be calculated as per the formulae reported in Table 1 to yield $\varepsilon_e = 4.73$ and $\varepsilon_g = 1.30$, respectively.

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

[32] 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

the *laissez faire* equilibrium solution. In particular, the *status quo* equilibrium with "ad hoc" levels of the ethanol subsidy and the fuel tax, captures over one-half of the maximum gain that can be achieved with first-best policies.

6.1. Status Quo

The *status quo* values for prices and quantities reflect the actual (average) values of those variables for 2009. Compared to the simulated *laissez faire* equilibrium, the fuel tax of $0.39/GEEG and the gross ethanol subsidy of $0.45/gallon lead to higher (retail) fuel prices, higher ethanol prices, a very modest 3% decline in (world and domestic) oil prices but a significant 32% increase in corn prices. Consequently, the combined policy causes domestic fuel consumption to fall – but just barely – as a 7.7 billion gallon decline in gasoline consumption is offset by a 7.1 billion gallon increase in ethanol consumption (a 4.9 billion increase in GEEG units). This (small) drop in fuel consumption – and the substitution of some ethanol for gasoline – leads to a 3% (or a 46.1 million tCO_2) decrease in carbon dioxide emissions; at the baseline cost of $33/$tCO_2$, this is equivalent to a $1.5 billion decrease in pollution costs. As Table 4B shows, the principal beneficiaries of this *status quo* policy are the government (higher tax revenue) and corn producers, while consumers are hurt by higher prices and oil producers are hurt by the fuel tax. As previously noted, relative to the *status quo* there is a $9 billion increase in net welfare – 56% of the maximum gain achievable by optimum policies – and U.S. dependence on foreign oil declines, as oil imports fall by about 9%.

6.2. The First Best Policies

In the baseline scenario, the marginal emissions damage is $33/$tCO_2$ and thus the first best policy entails a tax on carbon dioxide emissions of $33/$tCO_2$, in addition to oil import and corn export tariffs. This tax on carbon dioxide emissions is equivalent, in our model, to a gasoline tax of $.37/GEEG, which is remarkably close to the *status quo* (average) fuel tax of $.39. Since in the baseline model ethanol is assumed to pollute less than gasoline, and since the $.37 tax is assumed levied on *fuel*, then a subsidy to ethanol of $.07/gallon (or $.102/GEEG) is required to lower the *net* tax on ethanol. Thus, the first best policies entail a 27.8 cent/GEEG tax on ethanol, a 37 cent/GEEG tax on gasoline, a $19.32/barrel import tariff on oil, and a $1.30/bushel export tariff on corn. These policies would increase welfare by $16.0 billion compared to the *lassez faire* scenario, and $7.0 billion compared to the *status quo.* Compared to the *laissez faire* scenario, the combined effect of these policies is to increase U.S. oil prices by over 21%, while world oil prices

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that affect equilibrium values.

fall by slightly over 9%. Despite the corn export tariff, U.S. corn prices increase by 16.6% (world corn prices rise by over 62%); due to the conversion of corn into ethanol, the negative impact on U.S. corn prices of the corn export tariff is overwhelmed by the positive impact of higher domestic oil prices. Overall fuel consumption falls significantly, and ethanol replaces some gasoline, so carbon dioxide emissions fall by almost 11%. U.S. dependence on foreign oil falls sharply, as imports fall by nearly 24%, oil consumption falls and domestic oil production rises. From a welfare perspective, domestic oil producers and corn producers both gain and the government gains significant tax revenue, but consumers lose both because of higher oil (and fuel) prices and because of higher corn prices.

Compared to current policies, the first best policy leads to a significant reduction in oil imports, fuel consumption and pollution, but only a modest 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 due to the oil import tariff. Thus, while the implementation of first best policies bring a welfare gain of $7.0 billion compared to the *status quo*, there is a significant redistribution of income away from consumers and corn producers to oil producers and the government. Moreover, more than half of the welfare gain is accounted for by the decline in pollution costs.

6.3. Second Best Policies: Fuel taxes and ethanol subsidies

The second best fuel tax and ethanol subsidy are presented in the fourth column. Interestingly, we see that these policies perform almost as well as the first best policies in terms of the welfare gain, and actually result in a (very slightly) larger reduction in carbon dioxide emissions. In addition, oil imports are only 3% larger than under first best policies. The first best oil tariff of $19.32/barrel (at 23.6 gallons per barrel) is similar to a gasoline tax of $.82/gallon; combined with the $.37/gallon tax for pollution damages, this means the first best policies are similar to an overall fuel tax of $1.19, which is remarkably close to the second best tax of $1.18, as given in Table 4A.[33] We also see from the table that, relative to the first best, the ethanol subsidy increases significantly; the second best subsidy of $.83/gallon is equivalent to a subsidy of $1.20/GEEG, so that overall there is a small net subsidy to ethanol production. This results in an increase in ethanol production to 13 billion gallons, not too far below the 2015 mandate level of 15 billion gallons. The combined policies also lead to a nearly 20% increase in domestic corn

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

prices. Thus, the fuel tax increases largely offset the elimination of the oil import tariff and the ethanol subsidy increase partially offsets the impact on the world corn price of the elimination of the corn export tariff.[34] Compared to the *laissez faire*, these policies reduce world oil prices by 9% and increase world corn prices by over 42%; relative to the first best, world oil prices increase by a very modest $0.50/barrel and world corn prices fall by a more substantial $0.56/bushel.

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

6.4. Optimal Ethanol Subsidy with Status Quo Fuel Tax

Columns (5) and (6) of Table 4A both fix the fuel tax at its current rate of $0.39/gallon and consider only ethanol policy as being discretionary – an ethanol subsidy in column (5) and an ethanol mandate in column (6). For both cases it is seen that, while there are significant welfare gains relative to the *laissez faire* equilibrium, the gains compared to the *status quo* are not large; thus, in terms of our second best policy instruments, the fuel tax has a potentially larger impact on welfare than does ethanol policy.

As shown in the fifth column of Table 4A, the optimal ethanol subsidy, when the fuel tax is fixed at $0.39/GEEG, is $0.58/gallon, remarkably close to the *status quo* subsidy level and, as predicted by the theory, well below the second best subsidy level that applies when fuel taxes are also chosen optimally. However, for the case of the $.39/gallon fuel tax, the "net" subsidy to ethanol is actually $0.45/GEEG, as opposed to a net subsidy of only $.02/GEEG in the second best scenario. Compared to the second best scenario, ethanol production increases by 5.4%, and still falls short of the 2015 mandate level of 15 billion gallons. Compared to the second best, the lower fuel tax means that gasoline consumption also increases, so CO_2 emissions are not only higher than in the second best, they are higher than in the *status quo* situation (Table 4B). Overall, then, given the fuel tax, the benefits of adjusting the subsidy away from its *status quo* value are minimal, and the environmental benefits are negative.

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

6.5.Optimal Ethanol Mandate with Status Quo Fuel Tax

As noted in Lapan and Moschini (2009), an ethanol mandate is equivalent to a revenue neutral ethanol subsidy and fuel tax. Since column (6) combines this mandate with the *status quo* fuel tax, and since this combined effective fuel tax is lower than the second best combination of fuel tax and ethanol subsidy, the optimal mandate yields higher welfare than the optimal subsidy policy (column 5). Of course, by construction, the welfare level that is attained here is lower than that associated with the optimal second best policy (column 4). Compared to the optimal subsidy policy, since raising the ethanol mandate simultaneously raises the effective fuel tax, gasoline consumption is lower under the mandate than under the subsidy whereas ethanol production (and hence the price of ethanol) exceeds that under any other policy.[35] This ethanol consumption level exceeds the RFS2 mandate requirement of 15 billion gallons per year of conventional biofuel (corn ethanol) by 2015. The mandate also leads to higher domestic corn prices than under any of the other policies and world corn prices are higher only in the first best case when a corn export tariff is used. World oil prices are lower than under the *status quo* or the optimal ethanol subsidy, but higher than under the first or second best policies.[36] Carbon dioxide emissions are lower than under the optimal ethanol subsidy but higher than under the first or second best policies. These emissions decrease relative to the *status quo* even though total fuel consumption increases by 0.6 GEEG as the replacement of some gasoline by ethanol is sufficient to overcome the increase in overall fuel consumption. Welfare, by definition, is higher than under the *status quo*, and also higher than under the optimal subsidy, but considerably lower than under first or second best policies. In other words, the mandate is superior to an ethanol subsidy but not nearly as effective as an (optimally) chosen fuel tax.

6.7. 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 optimally choose the ethanol subsidy and fuel tax, this second best policy combination comes surprisingly close to matching the first best policy in terms of welfare gains and carbon emission reductions. Naturally, the additional restriction to only one free policy instrument – the ethanol subsidy or the ethanol mandate – leads to further welfare declines. In either of these cases, since fuel taxes (or oil import tariffs)

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[35] In the case when 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.

[36] 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.

are not choice variables, it is desirable to increase ethanol consumption (and price), with the larger increase coming under the mandate due to the fact that raising the mandate increases the effective tax on fuel. Due to this effective tax, the ethanol mandate yields higher welfare and higher ethanol utilization than the ethanol subsidy, and, as noted, only the optimal mandate leads to fulfillment of the RFS2 mandate on conventional biofuel by 2015. Still, the clear lesson is that fuel taxes are a more powerful instrument for reducing carbon dioxide emissions and increasing welfare than are ethanol policies.

6.8. Sensitivity Analysis

In order to investigate the robustness of our conclusions, we varied key parameters one at a time, recalibrated the model (when necessary) to the *status quo* 2009 baseline, and then explored the welfare implications of alternative policies. The alternative values for each of the parameters that we considered are summarized in Table 3 and refer to the following parameters: (i) cost of carbon dioxide emission; (ii) relative pollution efficiency of ethanol; (iii) elasticity fuel demand; (iv) elasticity of foreign corn import demand; (v) elasticity of foreign oil export supply; (vi) elasticity of petroleum byproduct demand.

Needless to say, the optimized value of the relevant policy instruments changed with the change in these basic parameters but there are several results that are common to all scenarios:

1. For all cases considered, the *status quo* policies dominated *laissez faire* and in all cases, except when foreign oil export supply is very inelastic, delivered at least 40% of the maximal benefits achievable with first best policies.
2. The *optimal mandate* policy dominated the optimal subsidy policy in all cases and it resulted in the highest use of ethanol in all cases considered. Nevertheless, in most cases it did not significantly outperform the *status quo* in welfare terms, the one exception being when foreign oil export supply was very inelastic.
3. In all cases where ethanol emitted less pollution than gasoline (per GEEG), the optimal mandate resulted in lower pollution than the optimal ethanol subsidy (even when carbon dioxide was priced at \$2/tCO_2). The mandate also resulted in lower pollution than *laissez faire* except when the foreign oil export supply elasticity was very low – in this case the potential welfare gains associated with higher ethanol use, through the terms of trade effect on oil, were so large that CO_2 emissions increased relative to *laissez faire*.
4. In all cases, though, the carbon emissions reduction 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 that 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.

5. The welfare gains achievable with the second best policy of fuel taxes and ethanol subsidies was greater than 80% of the maximum gains achievable in all cases *except* one – when the foreign elasticity of demand for corn imports was very low (-.30); in this case, the second best instruments were not a good proxy for a corn export tariff (for this case, the optimal corn export tariff was a not credible $6.47/bushel).
6. The case where optimal policy delivered small gains – and hence where it did not improve much on other policies, such as the *status quo* or the optimal mandate - was when the world oil export supply elasticity was large (5.0). This illustrates the dominating role played by the oil market on the potential gains from government policy.

Tables providing the details of the sensitivity analysis are omitted for space reasons (they will be made available in a future revised version). A summary of some of the salient sensitivity results is as follows. The variation in parameters has, in most cases, a very predictable impact on policy variables. When the cost of CO_2 is reduced to $2/t$CO_2$, the first best gasoline tax is only 2cents/gallon, and the relative attractiveness of ethanol *because* of its lower pollution emissions is negligible. Nevertheless, the first best policies – which do not include a measurable ethanol subsidy – not only deliver significant welfare gains compared to the *status quo*, but they also result in sharp increases in ethanol production and – despite a $1.18/bushel tax on corn exports – a 25% increase in the U.S. corn price. This outcome is driven by the $20.34/barrel oil import tariff, which drives up domestic fuel prices and increases the competitiveness of ethanol. In the second best case, the high fuel tax proxies for the oil import tariff, and the ethanol subsidy (the net ethanol subsidy is $.26/GEEG) partly proxies for a corn export tariff. Because of these two policies, the second best price of corn is $4.21/bushel, considerably higher than in the first best situation (though the world price of corn is 11% lower than in the first best case); and the world price of oil in the second best case is only 1% higher than in the first best case, indicating that the fuel tax is a much better proxy for an oil import tariff than is the ethanol subsidy for a corn export tariff. Finally, given an exogenous fuel tax of $.39/GEEG, the optimal subsidy is larger than the *status quo* level, and thus a binding ethanol mandate can improve upon both the *status quo* and an ethanol subsidy. Note that, even without a carbon-pollution rationale for ethanol mandates, the impact of the mandate on world oil and corn prices is such that ethanol production under the mandate exceeds the current mandated level for 2015.

Raising the cost of CO_2 to \$100/tCO_2 has predictable effects on first, and second, best policies and outcomes. The first best fuel tax increases to \$1.13/gallon – reflecting the costs of emissions – and due to the assumption ethanol releases less pollution, a gross subsidy of \$.20/gallon (equivalent to \$.29/GEEG) is part of the first best solution. The higher fuel tax, by itself, would reduce U.S. imports and this, in turn, means that tariffs will be lower than under the case where the pollution tax was minimal. Note that in this case the second best policy, while still a good proxy for first best policies, far outperforms the case in which only ethanol policy is discretionary. Indeed, given the existing fuel tax, the optimal subsidy – and the welfare outcome - is only slightly above the *status quo*ta level. In this case, the ethanol mandate leads to a considerable improvement over the ethanol subsidy and to considerably more ethanol output than the subsidy. The reason for the dominance of the mandate is because the tax on fuel is very low compared to its second best level (\$.39 versus \$1.84), and hence the implicit fuel tax embodied in the mandate is more important than the implicit subsidy. One less transparent result, perhaps, is that ethanol production – under either the optimal subsidy or the optimal mandate – is lower when pollution costs are high. That is, while more ethanol on the market crowds out some gasoline, total fuel consumption expands as ethanol production increases, and the efficiency gain of using ethanol is not sufficient to offset the pollution costs of the expanded fuel consumption. Thus, the argument for an ethanol mandate is not really because of ethanol's relative pollution efficiency, but rather because of both the implicit tax on fuel and also the terms of trade effect. Clearly, then, in the logic of this model, combining an ethanol subsidy with the mandate is very poor policy.

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

Varying the elasticity of domestic demand for fuel does not have very dramatic results. As one would expect, the oil import tariff – or, in the case of the second best, the fuel tax – will be higher when fuel demand is inelastic. Also, given the fuel tax, the optimal ethanol subsidy – or ethanol mandate - will be higher when domestic fuel demand is inelastic. The basic result that the fuel tax/ethanol subsidy regime is a close substitute for first best policy still holds, as do other results.

Altering the elasticity of foreign corn import demand is a bit more illuminating. Hardly surprising, the first best corn export tariff varies inversely with this elasticity, but the impact on the optimal oil tariff is minimal (and the first best carbon tax is unaffected). The most notable result, perhaps, is that the second best instruments do not perform as well, in a relative sense, when the foreign corn demand is very inelastic. This is not a surprise because, whereas the fuel tax does a good job of approximating an import tariff (given the low domestic oil supply elasticity), the ethanol subsidy – or mandate – is not a very good substitute for the corn export tariff. Thus, when foreign corn demand is inelastic, the second best policies – and ethanol policies alone – are not as effective. Still, ethanol subsidies are useful – and in the case when fuel taxes are not endogenous, the optimal mandate exceeds 17 billion bushels.

The foreign oil export supply elasticity plays a predictable, but crucial, role. Naturally, the optimal oil tariff varies inversely with this elasticity, as do the net gains from first best policy (as compared to *laissez faire*). The second best policy still achieves over 80% of the gain achievable with the first best policy. Perhaps the most noticeable effect is that, as the export supply elasticity increases, the relative performance of the ethanol only policy (compared to the first best) improves, because the higher foreign supply elasticity means that the gains obtained from taxing foreign oil become less important.

7. Conclusion

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

There are several interesting findings. First, the second best instruments of a fuel tax and an ethanol subsidy come close to replicating the outcomes under the first best policy combination of oil import tariffs, corn export tariffs and a carbon tax. For our baseline model, the second best fuel tax of $1.18/GEEG and ethanol subsidy of $0.83/gallon would increase ethanol consumption to 8.99 billion GEEG units (13.03 billion gallons), a 21% increase compared to the current (*status quo*) situation, it would decrease gasoline consumption by 9% and it would reduce emissions by 8%, as compared to the *status quo*.

In addition, the ethanol mandate, when used optimally in conjunction with the existing fuel tax would achieve the highest ethanol consumption, of approximately 15.7 billion gallons (10.8 billion GEEG), which exceeds the RFS mandate on conventional biofuel of 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 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. Since we have not included any other putative gain from reducing oil imports – such as an increase in national security from reduced dependence on imports, which may result in a reduction of the defense budget and in overseas military conflicts – we have probably significantly underestimated the potential gains associated with policies that reduce oil imports.

Table 1A – Primitive Parameters

Parameter	symbol	value	Source/explanation
Domestic Supply Elasticity of Oil	ε_o	0.20	de Gorter and Just (2009b)
Foreign Supply Elasticity of Oil	$\bar{\varepsilon}_o$	2.63	de Gorter and Just (2009b)
Domestic Supply Elasticity of Corn	ε_c	0.23	USDA (2007)
Foreign Demand Elasticity of Corn	$\bar{\eta}_c$	-1.74	FAPRI (2004)
Domestic Demand Elasticity of Corn	η_c	-0.20	de Gorter and Just (2009b)
Demand Elasticity of Fuel	η_f	-0.50	Toman, Griffin and Lempert (2008)
Demand Elasticity of Petroleum Byproducts	η_h	-0.50	Assumed equal to η_f
Ethanol Produced by one bushel of corn	a	2.8 gallon/bushel	Eidman (2007)
DDGS produced by one bushel of corn	δ_1	0.303	$\delta_1 = \frac{17\text{lbs}}{\text{bushel}} \Big/ \frac{56\text{lbs}}{\text{bushel}}$
DDGS relative price to Corn	δ_2	0.776	$\delta_2 = \left(\frac{\$114.4}{\text{t}} \times \frac{56\text{lbs}}{\text{bushel}}\right) \Big/ \left(\frac{\$3.74}{\text{bushel}} \times \frac{2205\text{lbs}}{\text{t}}\right)$
Gasoline Production Coefficient	β	23.6 GEEG/barrel	$\beta = x_g / x_o$
Ethanol Heat Content	γ_e	76000 BTUs/gallon	NREL (2008)
Gasoline Heat Content	γ_g	110000 BTUs/gallon	NREL (2008)
CO_2 emissions Rate of Gasoline	CE_g	11.29 kg/GEEG	Wang (2007)
CO_2 emissions Rate of Ethanol	CE_e	8.42 kg/GEEG	Farrel et al. (2006)
Marginal emissions Damage	$\tilde{\sigma}'(\cdot)$	\$33/tCO_2	NHTSA (2009)

Table 1B – Calculated Parameters

Parameter	symbol	value	Source/explanation
Derived Supply Elasticity of Ethanol	ε_e	4.73	$\varepsilon_e = (\varepsilon_c^s S_c - \eta_c D_c - \bar{\eta}_c \bar{D}_c)\alpha p_e / Q_c p_c$
Derived Supply Elasticity of Gasoline	ε_g	1.30	$\varepsilon_g = (\varepsilon_o S_o + \bar{\varepsilon}_o \bar{S}_o)\beta p_g / x_o p_o$
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	α	2.53 GEEG/bushel	$\alpha = \frac{a\gamma}{1-\delta_1\delta_2}$
Petroleum Byproduct Production Coefficient [1]	β_2	21.1 GEEG/barrel	$\beta_2 = 42\frac{\text{gallon}}{\text{barrel}}*1.065-\beta$
Gasoline Energy Equivalent Rate	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	$\sigma'(\cdot)$	\$0.372/GEEG	$\sigma'(\cdot) = \tilde{\sigma}'(\cdot) CE_g / 1{,}000$

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

Table 2A – Variables at the Calibrated Point (value from raw data)

Variable	Symbol	Value	Source/explanation
Fuel tax	t^0	39 cents/GEEG	sum of federal tax 18.4 cents/GEEG and weighted average of state tax 20.6 cents/GEEG (EIA).[1]
Ethanol subsidy	b^0	45 cents/gallon	RFS2
Oil price	p_o	$61.0/barrel	composite acquisition cost of crude oil (EIA).[2]
Corn price	p_c	$3.74/bushel	weighted average farm price of corn (Feed Grains Database, USDA).[3]
Ethanol price on volumetric basis	p_e^v	$1.79/gallon	ethanol average rack price in Omaha, Nebraska
DDGS price	p_d	$114.4/t	wholesale price in Lawrenceburg, IN (Feed Grains Database, USDA).[4]
Domestic oil supply	S_o	1.93 billion barrels	production plus adjustments and stock changes (EIA).[5]
Foreign oil supply	$\bar{S}_o$	3.29 billion barrels	net import (EIA).
Ethanol supply on volumetric basis	x_e^v	10.76 billion gallons	domestic production (RFA).
Fuel demand on volumetric basis	D_f^v	134.4 billion gallons	finished motor gasoline including ethanol (EIA).
Domestic corn supply	S_c	13.15 billion bushels	domestic production (Feed Grains Database, USDA).[6]
Foreign corn import demand	$\bar{D}_c$	1.86 billion bushels	net export (Feed Grains Database, USDA).

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

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

Variable	Symbol	Value	Source/explanation
Ethanol price	p_e	\$2.59/GEEG	$p_e = \gamma p_e^v$
Fuel price	p_f	\$2.33/GEEG	$p_f = p_e + t^o - b^o$.[1]
Gasoline price	p_g	\$1.94/GEEG	$p_g = p_e - b^o$
Price of inputs other than corn in ethanol production	ω_e	\$1.11/GEEG	$\omega_e = p_e - p_c / \alpha$
Price of inputs other than oil in gasoline production	ω_g	\$0.91/GEEG	$\omega_g = p_g + \beta_2 p_h / \beta - p_o / \beta$
Price index of petroleum byproducts	p_h	\$1.76/GEEG	weighted average retail price excluding taxes (EIA).[2]
Quantity index of petroleum byproducts	x_h	110.3 billion GEEG	$x_h = \beta_2 x_o$
Oil supply	x_o	5.22 billion barrels	$x_o = S_o + \bar{S}_o$.
Corn used in ethanol production accounting for byproduct value	Q_c	2.94 billion bushel	$Q_c = x_e / \alpha$
Domestic corn demand as food/feed uses,	D_c	8.35 billion bushels	$D_c = S_c - \bar{D}_c - Q_c$
DDGS supply	x_d	0.89 billion bushel	$x_d = \delta_1 Q_c$
Ethanol supply on GEEG	x_e	7.43 billion GEEG	$x_e = \gamma x_e^v$
Gasoline supply	x_g	123.6 billion GEEG	$x_g = D_f^v - x_e^v$
Fuel demand on GEEG	D_f	131.0 billion GEEG	$D_f = x_g + x_e$

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

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

Table 3 – Sensitivity Analysis of Selected Parameters

Parameter	Symbol	Baseline	Range
Cost of CO_2 emission	$\sigma'(\cdot)$	\$33/tCO_2	[2 , 100] \$/tCO_2
Ethanol CO_2 emission efficiency	λ	0.75	[0.52 , 1.70]
Elasticity of Fuel Demand	η_f	-0.5	[-0.9 , -0.2]
Elasticity of Foreign Corn Import Demand	$\overline{\eta}_c$	-1.74	[-3.0 , -0.3]
Elasticity of Foreign Oil Export Supply	$\overline{\varepsilon}_o$	2.63	[0.6 , 5.0]
Elasticity of Oil Byproduct Demand	η_h	-0.5	[-0.9 , -0.2]

Table 4A -- Simulation Results in Calendar Year 2009

Variable	*Laissez Faire* (1)	*Status quo* (2)	First Best (3)	Optimal Tax & Subsidy (4)	Optimal Subsidy (5)	Optimal Mandate (6)
Fuel Tax ($/GEEG)	0.00	0.39	0.37	1.18	0.39	0.39
Ethanol Subsidy ($/gallon)[1]	0.00	0.45	0.07	0.83	0.58	0.00
Oil Tariff ($/barrel)	0.00	0.00	19.32	0.00	0.00	0.00
Corn Tariff ($/bushel)	0.00	0.00	1.30	0.00	0.00	0.00
Fuel Price ($/GEEG)	2.23	2.33	2.69	2.68	2.29	2.31
Gasoline Price ($/GEEG)	2.23	1.94	2.32	1.51	1.90	1.84
Ethanol Price ($/gallon)	1.54	1.79	1.67	1.87	1.89	1.96
U.S. Oil Price ($/barrel)	63.2	61.0	76.5	57.7	60.7	60.2
U.S. Corn Price ($/bushel)	2.83	3.74	3.30	4.04	4.13	4.38
Oil Byproduct Price ($/GEEG)	1.54	1.76	2.06	2.09	1.79	1.84
Gasoline Quantity (billion GEEG)	131.3	123.6	112.9	112.0	122.6	120.8
Ethanol Quantity (billion gallons)	3.65	10.76	11.43	13.03	13.74	15.68
Corn Production (billion bushels)	12.41	13.15	12.79	13.39	13.46	13.66
Corn Demand (billion bushels)	8.76	8.35	8.55	8.22	8.18	8.07
Corn Export (billion bushels)	2.65	1.86	1.12	1.61	1.53	1.31
Oil Domestic Supply (billion barrels)	1.95	1.93	2.03	1.91	1.93	1.93
Oil Import (billion barrels)	3.60	3.29	2.74	2.82	3.25	3.18

Notes: (1) Ethanol price, subsidy and quantity are converted into GEEG units in simulation.

Table 4B -- Simulation Results in Calendar Year 2009

	Laissez Faire	Changes Relative to *Laissez Faire*				
		Status quo	First Best	Optimal Tax & Subsidy	Optimal Subsidy	Optimal Mandate
Variable	(1)	(2)	(3)	(4)	(5)	(6)
CO_2 Emission (million tCO_2)	1504.1	-46.1	-163.0	-163.4	-40.1	-49.0
Pollution ($ billion)	49.6	-1.5	-5.4	-5.4	-1.3	-1.6
Tax Revenue ($ billion)	0.0	46.3	98.7	131.7	43.5	51.3
Corn Export ($ billion)	7.5	-0.5	-2.3	-1.0	-1.2	-1.8
Oil Import ($ billion)	227.9	-27.1	-71.3	-64.9	-30.5	-36.5
P.S. Oil Supply ($ billion)	110.4	-4.3	26.3	-10.6	-4.8	-5.8
P.S. Corn Supply ($ billion)	31.9	11.7	6.0	15.6	16.8	20.2
C.S. Corn Demand ($ billion)	86.0	-7.8	-4.1	-10.3	-11.0	-13.0
C.S. Fuel Demand ($ billion)	318.6	-13.3	-59.2	-58.1	-8.4	-10.5
C.S. Oil Byproduct($ billion)	218.5	-25.0	-57.0	-59.5	-28.1	-33.6
Social Welfare ($ billion)	715.7	9.0	16.0	14.2	9.3	10.2

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