BIOFUELS AND LEAKAGES IN THE FUEL MARKET

DUSAN DRABIK AND HARRY DE GORTER

Department of Applied Economics and Management, Cornell University, USA

E-mail: dd387@cornell.edu, hd15@cornell.edu

ABSTRACT

Leakage in the fuel market differs, depending on whether ethanol production is determined by a tax credit or consumption mandate. Two components of market leakage are distinguished: domestic and international. Leakage with both a tax credit and a consumption mandate depends on market elasticities and consumption/production shares, with the former having a bigger impact. Leakage is also more sensitive to changes in market supply and demand elasticities in the country not introducing biofuels. Although positive with a tax credit, market leakage can be negative with a consumption mandate, meaning that one gallon of ethanol can replace more than a gallon of gasoline. We also show that being a small country biofuels producer does not necessarily mean that leakage for this country is 100 percent. Our numerical estimates show that one gallon of ethanol replaces approximately 0.2-0.3 gallons of gasoline in the U.S.

Contributed paper at the
IATRC Public Trade Policy Research and Analysis Symposium
'Climate Change in World Agriculture: Mitigation, Adaptation, Trade and Food Security'
Universität Hohenheim, Stuttgart, Germany, June 27-29, 2010

Biofuels and Leakages in the Fuel Market

1 Introduction

Although U.S. ethanol policies have historically been motivated primarily by concerns related to energy security, local air pollution and farm income support, nevertheless U.S. legislation was introduced in 2007 that require ethanol to reduce greenhouse gas (GHG) emissions by 20 percent relative to the gasoline it is *assumed* to replace. The 20 percent figure was the estimate based on "life-cycle accounting" (LCA), a "well to wheel" measure of GHGs emissions in the production of gasoline, and a "field to fuel tank" measure for ethanol production (Farrell et al. 2006). U.S. law simply required future life-cycle emissions from ethanol production to not exceed the historical average. Otherwise, ethanol was not eligible for tax credits or for being counted towards the mandate.

With the recent concern over global climate change in the United States, the corn-ethanol lobby quickly seized upon the benefits of ethanol in reducing GHG emissions. But this strategy back-fired because LCA is inherently flawed, first highlighted by Searchinger et al. (2008) showing U.S. corn-ethanol emits more GHGs relative to gasoline if changes in the use of land (e.g. converting forest into crop land), called indirect land use change (iLUC), is taken into consideration. This sparked a controversy that reached a fever pitch and both the Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) were then authorized to revise their 20 percent estimate to include iLUCs.

CARB made their ruling on iLUC in April of 2009 while the EPA made their ruling in February 2010. In the interim, farm state politicians had threatened to vote against proposed climate change legislation unless the EPA excluded iLUC emissions in their calculation of the sustainability standard. But the long overdue EPA ruling included not only an estimate of iLUC but also a revised and substantially lower LCA estimate. As a result, even with iLUC, corn-ethanol still meets the threshold, provided relatively more 'clean' inputs like natural gas are used instead in the production of ethanol.

This paper addresses the issue of whether corn-ethanol still meets the 20 percent threshold if market 'leakages' other than iLUC are also taken into account. More specifically, the estimated LCA savings in emissions from a gallon of ethanol assumes ethanol replaces an (energy equivalent) gallon of gasoline, i.e., LCA assumes there is no market leakage in the fuel market. But there inevitably is leakage in fuel markets, as there are in land and other markets related to biofuels production and consumption, and this leakage may be positive or negative, depending on the biofuel policy. Consumption subsidies like the U.S. blender's tax credit or the EU's tax exemption at the retail fuel pump result in one more gallon of ethanol on the market that will not replace an entire gallon of gasoline. If a mandate is in place, it is possible that market leakage in the fuel market is negative, possibly replacing more than a gallon of gasoline, possibly offsetting to some degree emissions from iLUC. However, we show that leakage in the fuel market is infinite when adding a tax credit to a binding mandate (the tax credit results in an increase in gasoline consumption only, with no effect on ethanol production).

This paper develops a formal definition of leakage in oil markets due to the ethanol production. If fuel prices decline as a result of produced ethanol, then total fuel consumption increases, resulting in displacement of oil. This is called leakage. The difference between the increase in total fuel use and ethanol supply is the amount of oil replaced. Our definition includes both 'a domestic' and 'international' component[1], and is differentiated from that used by the IPCC which implicitly nets out domestic leakage[2]. We develop formulae for alternative policy scenarios. We show how the level of leakage varies by policy instrument, home and foreign supply and demand elasticities for oil, the home supply elasticity for ethanol, and the share of the home country in world oil production and consumption.

Leakage with either a tax credit or a mandate depends on market elasticities and consumption/production shares, with the former group of parameters having a bigger impact. Furthermore, leakage is shown to be more sensitive to changes in market parameters of the country not introducing biofuels. While market leakage is always positive with a tax credit, it can be negative with a consumption mandate. This means that one gallon of ethanol could potentially replace more than one gallon of gasoline. We find that if a small country trader in fuel markets, then the effects of a tax credit on market leakage differ, depending on whether it is an oil importer or exporter. Therefore, market leakage for a small country in world oil markets that produces biofuels does not necessarily have to be 100 percent. Our numerical estimates show that in the case of the United States, one gallon of ethanol actually replaces approximately 0.2-0.3 gallons of gasoline. This raises the issue of whether corn-ethanol still meets the 20 percent CO_2 reduction requirement, given that life-cycle accounting assumes ethanol replaces gasoline one to one.

The remainder of this paper is organized as follows. The next section defines and analyzes market leakage due to a blender's tax credit. In Section 3, we analyze market leakage under a consumption mandate. The discussion includes the effect on leakage of adding a tax credit to a binding mandate. Section 4 investigates what the implications for leakage are if a country introducing ethanol is either a small country importer or exporter of oil. The relationship between market and carbon leakage is addressed in Section 5. Numerical estimates of leakage and their sensitivity analyses are provided in the penultimate section. The last section discusses the results and gives some concluding remarks.

2 Leakage in the fuel market with a biofuel tax credit

2.1 Leakage defined

Broadly defined, leakage resulting from an environmental policy can be viewed as a measure of ineffectiveness of that policy. The most widely used definition of carbon leakage is that of the IPCC[3] which compares carbon savings in a country with the resulting carbon increase outside that country. We argue that this definition needs to be augmented to take an account of changes in domestic carbon emissions resulting from the policy. Moreover, both the IPCC definition and the current literature concentrate on carbon leakage and do not distinguish 'market leakage' due to biofuels policies, i.e. how many gallons of oil have actually been replaced by one gallon of ethanol. We show how market leakage and the relative carbon intensities of a fossil fuel and a biofuel determine carbon leakage.

There are at least two axes around which leakage can be classified and defined. The first one differentiates the form of leakage, i.e., market and carbon leakage while the second differentiates location of leakage, i.e., domestic vs. international leakage. One complements the other but we show that both can be studied separately. Their importance and a mutual relationship are best explained with an example.

Assume a country where all emissions are capped irrespective of their origin. With an emissions cap in the Home country, there is no domestic leakage by definition and thus an environmental policy can only have international leakage. In this case, our definition of carbon leakage is identical to that of the IPCC. Assume further that ethanol is produced in a sufficient quantity in the Home country such that world fuel price declines as a result. Clearly, fuel demand increases not only internationally but also domestically – an indication of domestic and international market leakage. Note that domestic market leakage occurs in spite of the cap because the latter regulates emissions but not quantities.

Why is the concept of market leakage important? LCA assumes that one gallon of ethanol replaces one gallon of gasoline. Taking into consideration only international market leakage biases the estimates of market leakage downward – the more so the more important domestic market leakage is. This means that one (energy equivalent) gallon of ethanol seems like to replace more gasoline than it actually does (but still less than one gallon because of international leakage). Subsequently, a biased estimate of the substitution potential of ethanol relative to gasoline may lead to a biased ethanol sustainability threshold as computed by LCA.

Alternatively, assume that only emissions from a subset of sectors (the ones that are deemed to pollute most) are capped. Suppose agriculture and forestry are not capped (which is currently the case in the U.S.). In this case, not only can domestic market leakage occur but also domestic carbon leakage. The former would bias the life-cycle accounting calculations for ethanol sustainability threshold for the reason explained above and the latter would not be reflected in the IPCC definition of carbon leakage at all. For the two reasons, we find it important to distinguish market leakage from carbon leakage and also make a distinction between international and domestic leakage.

Coming back to the widely used definition by the IPCC, in the Fourth Assessment Report, for carbon leakage we read: "*the part of emissions reductions in Annex B countries that may be offset by an increase of the emissions in the non-constrained countries above their baseline levels*". For example, Wooders et al. (2009) translate this into:

$$\text{leakage}=\frac{\text{increase in emissions outside the country}}{\text{decrease in emissions inside the country}}$$

The IPCC definition of leakage does not directly address the notion of domestic leakage. Instead, the "decrease in emissions inside the country" refers to a net emissions decrease, i.e. after domestic leakage has been accounted for. This is confirmed by Murray (2008) who argues that the internal response (i.e. domestic leakage) should be captured with a national accounting system and therefore be netted out. This means the literature defines the denominator in the above formula as intended reduction in emissions inside the country minus domestic leakage. But if all countries of the word were a party to the Kyoto Protocol (or any other agreement) committing its signatories to reduce greenhouse gas (GHG) emissions, would carbon leakage be zero? The IPCC formula would argue so but our analysis includes domestic leakage and so our formula defines the denominator to be the intended decrease in emissions inside the country.

2.2 Autarky leakage due to a tax credit

The quantity of ethanol is expressed in gasoline-equivalent gallons (GEG) which is the amount of ethanol it takes to equal the mileage achieved by a gallon of gasoline (a gallon of gasoline is approximately 1.43 (=1/0.7) gallons of ethanol). Likewise, all prices are expressed in cents per GEG, but for notational ease this will be denoted as ¢/gal.

Consider Figure 1 that depicts the initial market equilibrium fuel price P_0 determined by the intersection of the downward sloping fuel demand curve D_F, and supply curve, S_F in a closed economy. For now let us assume that all oil is used in the transportation sector only. We relax this assumption later when we have two demand curves for oil. Suppose *E* gallons of ethanol are produced as a result of a blender's tax credit with the intention to *replace* the same quantity of oil. This exogenous increase in fuel supply is depicted by a parallel shift of S_F to S_F' by the amount *E* (Figure 1). The original intention of this policy was to replace *ab* gallons of oil but due to the higher supply of fuel, a new market equilibrium is established at a lower fuel price (P_1). This results in higher fuel consumption given by the point *b.* As a result, the quantity of oil actually replaced is *ac* while the quantity *bc* is *displaced*, the latter representing 'market leakage' due to the policy.

In the event of a perfectly elastic demand for fuel, the gasoline market price does not change with ethanol production and so stays at P_0. Fuel consumption would now shift to point *d*. In this case, oil was displaced with the introduction of ethanol one-to-one and market leakage is therefore 100 percent. We will show this mathematically later. This must also be the result if the country in question is a small exporter who faces a perfectly elastic foreign demand.

Formally, we define market leakage L in Figure 1 as *bc/ab*. Note that the IPCC definition is not able to accommodate leakage in this situation as there is no country outside the treaty. The distance *bc* can be expressed as $\eta_D CdP/P_0$ and that of *ab* by $-\eta_S QdP/P_0$, where η_D and η_S are the demand and supply elasticities in the initial equilibrium, *C* and *Q* denote consumption and production of gasoline, respectively (*C*=*Q*), and *dP* signifies a drop in fuel price after ethanol has been delivered on the market. Substituting these expressions[4] in the leakage formula, we have

$$L^T_{autarky} = \frac{\eta_D}{\eta_D - \eta_S} \quad \text{where } 0 \le L^T_{autarky} \le 1 \tag{1}$$

where we used the fact that *ac* + *cb*=*ab*. This formula shows leakage in the fuel market due to a biofuel tax credit in autarky depends on demand and supply elasticities of the gasoline market in the initial equilibrium.

Suppose $L^{T}_{autarky} = 0.2$. It means that one gallon of ethanol (in energy equivalent) replaces approximately 0.8 gallons of gasoline, and the rest, 0.2 gallons, are displaced. It also follows that under this setting there is no leakage if (1) demand for fuel is perfectly inelastic, or (2) supply of gasoline is perfectly elastic. On the other hand, leakage is 100 percent if (1) gasoline supply is perfectly inelastic, or (2) demand for fuel is perfectly elastic. These conclusions change if we allow for trade, to which we now turn.

2.3 Leakage due to a tax credit and international trade in fuel

In this section we introduce international trade in oil with a blender's tax credit. For example, the U.S. imports around 60 percent of its oil consumption and gasoline used for transportation represents about 45 percent of total domestic oil consumption[5].

Assume no initial ethanol production with the world fuel market equilibrium as depicted in Figure 2 where the Home country is an importer. Total fuel demand in each country is given by the horizontal sum of transportation and non-transportation demand curves. The initial fuel price, P_{w0}, is where excess demand, ED_H, equals excess supply, ES_F. Consumption of oil used in transportation and non-transportation sectors is denoted by C_{HT0} and C_{HN0}, respectively for the Home country and C_{FT0} and C_{FN0} for the Foreign country. Home and Foreign country's production of oil is denoted by Q_{H0} and Q_{F0}, respectively.

Suppose there is a consumption subsidy (a blender's tax credit) for ethanol in the Home market. This increases domestic production of ethanol (not shown). Depict this exogenous (taxpayer financed) increase in fuel supply as a shift of S_H to S'_H by the distance E in the first panel of Figure 2. As domestic supply of fuel increases, excess demand shifts down to ED_H' creating a new world fuel price P_{w1} which must be less than P_{w0} because world fuel supply has increased.

This exogenous increase in ethanol does not replace the same amount of gasoline. World fuel consumption increases as a result. There are two components of leakage with trade. The first is *domestic* leakage, represented by an increase in total fuel consumption in the Home country while *international* leakage is defined as an increase in total fuel consumption in the Foreign country. Note that with this policy both leakages are always non-negative as each sector faces the same decrease in fuel price.

The relative size of domestic and international leakage depends on elasticities and parameters of the fuel markets in both countries. The formula for the magnitude of market leakage due to tax credit-induced production of ethanol is (see Appendix 1):

$$L_{market}^{T} = \frac{\rho_{HT}\eta_{DHT} + \rho_{HN}\eta_{DHN} + \rho_{FT}\eta_{DFT} + \rho_{FN}\eta_{DFN}}{\rho_{HT}\eta_{DHT} + \rho_{HN}\eta_{DHN} + \rho_{FT}\eta_{DFT} + \rho_{FN}\eta_{DFN} - \phi\eta_{SH} - (1-\phi)\eta_{SF}} \tag{2}$$

where ρ stands for a consumption share of a respective oil consumer (transportation and non-transportation) in either country, η denotes elasticity and ϕ denotes a production share of the Home country in world oil production. The first subscripts *D* and *S* signify demand and supply and the latter subscripts *HT*, *HN*, *FT* and *FN* stand for home transportation, home non-transportation, foreign transportation and foreign non-transportation, respectively. By definition $\rho_{HT} + \rho_{HN} + \rho_{FT} + \rho_{FN} = 1$.

The formula (3) holds irrespective of the trade position of the country that places ethanol on the market. Note that if $\rho_{HN} = \rho_{FT} = \rho_{FN} = 0$ and $\phi = 1$, then the country becomes the only country in the world utilizing all its oil for transportation. Expression (2) collapses to the leakage formula for autarky given by (1) and total leakage is thus domestic only.

The relative magnitude of domestic (L_{market}^{D}) and international leakage (L_{market}^{I}) due to a tax credit is not constant and depends on consumption shares and elasticities of transportation and non-transportation demand curves in both countries:

$$\frac{L_{market}^{D}}{L_{market}^{I}} = \frac{\rho_{HT}\eta_{DHT} + \rho_{HN}\eta_{DHN}}{\rho_{FT}\eta_{DFT} + \rho_{FN}\eta_{DFN}} \tag{3}$$

Note that the oil supply elasticities do not appear in (3) as leakage occurs only along demand curves in both countries.

A comparative static exercise on (3) reveals that domestic leakage becomes more important relative to international leakage as:

- the share of transportation and/or non-transportation oil consumption in the Home (Foreign) country increases (decreases),
- the transportation and/or non-transportation demand in the Home (Foreign) country becomes more (less) elastic.

Thus if a country (or a coalition of countries) producing ethanol consumes a substantial share of world oil, then the bias of market leakage estimates when ignoring domestic leakage might be significant. Likewise, if the domestic demand for oil is rather elastic and yet attention is only paid to international leakage, the obtained magnitudes of market leakage are likely to be underestimates of their true value. In section 6, we present a numerical example of how the ratio in equation (3) changes depending on values of different parameters and we will compare it to leakage with a consumption mandate.

2.4 How sensitive is market leakage to changes in market parameters?

With an explicit formula given by (2), we are in a position to analyze in greater detail the effects of key market parameters. Differentiating (2) with respect to its individual parameters we find that leakage decreases, *ceteris paribus*, as:

- transportation and non-transportation demand for fuel becomes less elastic,
- supply of oil in either country becomes more elastic.

The effect on leakage of a change in the consumption (production) share of a country's sector is ambiguous. As the sum of sectors' consumption shares in both countries is one, we choose the non-transportation sector in the Foreign country as a reference point. With that, it is shown (Table 1) that leakage increases with a higher sector's consumption share if the demand for oil of that sector is more elastic than it is of the reference point. The opposite occurs, however, if the demand elasticity for oil in a given sector is less elastic compared to the reference point. Similarly, the magnitude of leakage increases as the Home country becomes a bigger oil producer provided that supply elasticity in the Home country is smaller than in the Foreign country.

One can use the results in Table 1 to examine the sensitivity of leakage to changes in its determinants. Here we present a selection of the possible pairwise comparisons. For example, leakage is more sensitive to the demand elasticity of the transportation sector in the Home country compared to other sectors if the consumption share of the former is bigger than of other sectors (see (4)). Likewise, the magnitude of leakage will react more to a change in supply elasticity of the Home country than of the Foreign country only if the former covers more than a half of the world's supply of fossil fuels (*i.e.* $\phi > 1/2$).

$$
\begin{aligned}
&(a) \quad (\partial L/\partial \eta_{DHT})/(\partial L/\partial \eta_{DHN}) = \rho_{HT}/\rho_{HN} \\
&(b) \quad (\partial L/\partial \eta_{DHT})/(\partial L/\partial \eta_{DFT}) = \rho_{HT}/\rho_{FT} \\
&(c) \quad (\partial L/\partial \eta_{DHT})/(\partial L/\partial \eta_{DFN}) = \rho_{HT}/\rho_{FN} \\
&(d) \quad (\partial L/\partial \eta_{SH})/(\partial L/\partial \eta_{SF}) = \phi/(1-\phi) \\
&(e) \quad (\partial L/\partial \rho_{HT})/(\partial L/\partial \eta_{DHT}) = (\eta_{DHT} - \eta_{DFN})/\rho_{HT} \\
&(f) \quad (\partial L/\partial \rho_{HN})/(\partial L/\partial \eta_{DHN}) = (\eta_{DHN} - \eta_{DFN})/\rho_{HN} \\
&(g) \quad (\partial L/\partial \rho_{FT})/(\partial L/\partial \eta_{DFT}) = (\eta_{DFT} - \eta_{DFN})/\rho_{FT} \\
&(h) \quad (\partial L/\partial \phi)/(\partial L/\partial \eta_{SH}) = (\eta_{SH} - \eta_{SF})/\phi
\end{aligned}
\qquad (4)
$$

The last four rows of (4) (equations (e) to (h)) provide an indication for why the changes in consumption (production) shares typically have a less significant effect than elasticity values. For consumption (production) shares to have a more significant impact, the absolute difference in respective demand (supply) elasticities has to be bigger than a consumption (production) share. But this is less likely to occur as demand elasticities are similar across countries and sectors.

It is interesting to note that if a share of Home country transportation (non-transportation) oil consumption is smaller than that in the Foreign country, or if the Home country produces less than a half of world oil, then leakage will react more on changes in foreign than domestic market elasticities. This is a result of the country size effect, i.e. market changes in a big country have a bigger impact (in absolute terms) in that country than in a smaller one. Take the U.S. as an example where it is the largest consumer of fossil fuels. The value of ρ for the U.S. is 0.15 for the transportation sector and 0.076 for the non-transportation sector. The U.S. oil production share is 0.067. But if one looks at groups of countries at a time (e.g., members of Kyoto), then the situation can be reversed and the Home parameters can be more influential in affecting the leakage outcome.

In order to get more insights into the magnitude of leakage due to a tax credit, we alter key market parameters one by one. The findings are summarized in Table 2. For ease of exposition we will assume the country that places ethanol on the market (Home country) is an importer of fuels.

If the Home country is the only fuel consumer in the world ($\rho_{FT} = 0, \rho_{FN} = 0$), placing ethanol on the market decreases world fuel price generating higher domestic fuel consumption in both sectors and thus higher domestic leakage. Note that even though leakage in this case is by definition all domestic, it is not autarky leakage ($\phi = 1$ would be required).

In the absence of oil production ($\phi = 0$) in the country, both domestic and international leakage results. After total fuel supply has expanded due to ethanol production, fuel price decline with higher total fuel consumption worldwide.

If one demand curve is perfectly inelastic (i.e. $\eta_{DHT} = 0$ or $\eta_{DHN} = 0$ or $\eta_{DFT} = 0$ or $\eta_{DFN} = 0$), international leakage still occurs and domestic leakage occurs in the one sector with a downward sloping demand curve. If, on the other hand, demand for fuel in either sector in the Home country is perfectly elastic, ethanol replaces no oil. It is because oil consumption has not changed, while total fuel consumption has increased by the amount of ethanol production. Market leakage in this case is therefore 100 percent and is domestic leakage only.

It also follows from Table 2 that a perfectly inelastic fuel supply curve in either country leads to both domestic and international leakage. If the fuel price is fixed in the Foreign country due to a perfectly elastic fuel supply curve ($\eta_{SF} \to \infty$), then there is no market leakage.

3 Biofuels leakage due to a consumption mandate

The economics of a biofuels consumption mandate is different than it is the case with a tax credit. It is because unlike a tax credit, which is a taxpayers-financed subsidy on ethanol production, ethanol produced to meet the mandate is financed by a money transfer from oil producers and (under some circumstances) fuel consumers (de Gorter and Just, 2009a). We first explain the functioning of a consumption mandate in the simplest setting. More specifically, we assume no trade and one sector only - transportation. Then we move on to the analysis of leakage due to a consumption mandate with international trade in fuels and two demands (transportation and non-transportation) in each country.

Assume a pre-policy autarky equilibrium in the fuel market depicted in Figure 3. The initial oil price P_O is given by the intersection of oil supply curve, S_O and fuel demand D_F . Now suppose a consumption mandate is introduced that requires *E* gallons of ethanol to be placed on the market. Given an ethanol supply curve S_E and the mandated quantity of ethanol *E*, an ethanol price P_E is determined (Figure 3). So the consumption mandate establishes ethanol market price. As *E* gallons of ethanol are dictated to be consumed, the supply of oil, S_O , is effectively shifted to the right by *E* which is depicted by S_O' .

As this policy affects fuel consumers these have to pay a fuel price that is a weighted average of ethanol price, P_E, and oil price, P_O. The weights are the shares of ethanol and oil in the fuel, respectively:

$$P_F = \frac{E}{E+Q_O} P_E + \frac{Q_O}{E+Q_O} P_O \quad (5)$$

Note that the amount of ethanol, E (as well as its price P_E) is fixed. Therefore the only way how refineries can increase fuel supply is by increasing the quantity of oil Q_O (oil price will adjust according to the inverse oil supply curve). By changing the quantity of oil, price of fuel traces a U-shaped inverse supply curve (a hyperbola). In order to find its minimum, one must find the quantity of oil supplied that solves:

$$\min_{Q_o} P_F = \frac{E}{E+Q_O} P_E + \frac{Q_O}{E+Q_O} S_O^{-1}(Q_O)$$

After some algebra, we arrive at the quantity of oil that minimizes price of fuel:

$$Q_O^{\min} = S_O(P_O) = E\left(\eta_O \frac{P_E(E)}{P_O} - \eta_O - 1\right) \quad (6)$$

At this minimal fuel price total fuel available in the market is given by:

$$Q_F^{\min} = E + Q_O^{\min} = \eta_O E\left(\frac{P_E(E)}{P_O} - 1\right) \quad (7)$$

where η_O is supply elasticity of oil.

The effect of a consumption mandate differs depending on where the fuel demand curve intersects the oil supply. This is depicted in Figure 3. Consider first one specific case where the price of fuel, P_F, is unaffected by the mandate (where $P_F = P_O$,). This will occur when the demand for fuel, D_F, intersects the supply curve for fuel, S_F, and the original supply curve for oil, S_O, at the same point, *a*. The price of oil received by producers falls to P_O^* but consumer fuel price remains at the free market price P_O. The higher market price for ethanol is financed completely by a lower market price to oil producers. The mandate in this specific case exerts monopsony power on oil producers where the excess revenues are transferred to ethanol producers. Fuel consumers are unaffected.

If instead the demand curve for fuel D_F' in Figure 3 intersects S_F above S_O (at P_F'), then the mandate acts as a tax on both oil consumers and producers simultaneously. The consumer price of fuel increases under the mandate, while the market price for fuel decreases. The higher ethanol price is financed by both fuel consumers and oil producers. A third possible equilibrium occurs when the demand for fuel D_F'' intersects S_F below S_O (at P_F''), in which case the high ethanol price is again entirely financed by oil producers but the latter also subsidize fuel consumers with a resulting lower fuel price.

Figure 4 presents the economics of a consumption mandate with international trade and resulting leakages in fuel markets. Each country utilizes oil in the transportation and non-transportation sector, thus two demand curves for oil in each country. The Home country is assumed to be an importer[6]. We show that a consumption mandate always negatively impacts domestic and foreign oil producers; can have an ambiguous effect on domestic fuel consumers, but domestic non-transportation consumers and foreign consumers in both countries are better-off with this policy as they now pay less and consume more.

Assume a pre-policy situation as depicted in Figure 4 where the total domestic demand for oil is given by the horizontal sum of transportation, D_{HT}, and non-transportation, D_{HN}, demand for oil (not shown). Similarly, total demand for oil in the Foreign country is determined by the horizontal sum of D_{FT} and D_{FN}. Total oil supply facing domestic sectors, S_{HTot}, is given by the sum of domestic supply S_H and the foreign excess supply (not shown). Consumers of fuel in the Home country face an oil supply curve, S_{HT}, given by the horizontal difference between S_{HTot} and D_{HN}. Finally, the world oil price P_{O0} is determined by the intersection of the domestic transportation demand curve and the oil supply curve facing the Home country's transportation consumers.

With E gallons of ethanol mandated to be placed on the market, total domestic oil supply effectively shifts to the right, S'_{HTot}, by the quantity of the mandate and so does the oil supply curve facing domestic transportation consumers, S'_{HT}. Transportation consumers in the Home country pay the fuel price which is given by a weighted average of a fixed (by a mandate) ethanol price and a gasoline price. This generates a fuel supply curve S_F depicted in the first panel of Figure 4. The intersection of transportation fuel supply and demand curves gives a fuel price P_F which is in this case higher than the pre-policy price P_{O0}. It means that under the situation in Figure 4, domestic transportation sector implicitly subsidizes international fuel consumption as well as domestic non-transportation oil consumption.

On the other hand, the price received by oil producers worldwide declines to P_{O1} which is the price associated with the new domestic transportation sector consumption C_{HT1} on the expanded oil supply curve, S'_{HT}, facing this transportation sector. A lower price received by oil producers after the policy means that they are the other party financing the ethanol consumption mandate.

From Figure 4, international leakage is given by the sum of the distances $C_{FT0}C_{FT1}$ and $C_{FN0}C_{FN1}$, while the domestic component of leakage by $C_{HT1}C_{HT0}$ plus $C_{HN0}C_{HN1}$. In the specific case in Figure 4, leakage in the domestic transportation sector is negative (because the transportation demand curve intersects the fuel supply to the left of the point *a*, thus causing an increase in fuel price) which alleviates the effect of market leakage. In fact, for certain parameters values, this negative effect can be strong enough to offset not only the positive part of domestic leakage but also international leakage. This is demonstrated in the numerical section of the paper to follow. In that case, total market leakage would be negative meaning that one gallon of ethanol replaces more than one gallon of oil.

But given the possibility of negative leakage with a consumption mandate, two questions arise. First, under what conditions does a consumption mandate result in negative leakage? Second, does a consumption mandate always result in smaller leakage compared to a blender's tax credit for the same quantity of ethanol? The analytical formula for leakage with a consumption mandate is much more complex than it is for a tax credit (see Appendix 2). It is because of the U-shaped fuel supply curve which gives rise to a possibility of negative domestic leakage. Therefore, it is difficult to infer the outcome from these formulae exactly and so numerical simulations are called for. However, we can partially circumvent the analytical complexity by analyzing leakage with both policies under autarky, assuming that all oil is consumed by the transportation sector only. Modeling an autarky outcome is straightforward - one just needs to assume $\rho_{FT} = \rho_{FN} = 0$ and $\phi = 1$. For leakage with a consumption mandate, we then obtain:

$$L^{M}_{Autarky} = \frac{\eta_S}{2(\eta_S - \eta_D)}\left(\left(\left(\frac{1}{\gamma} - \frac{\eta_D - 2\gamma\eta_D}{\gamma\eta_S}\right)^2 - 4\left(\frac{1}{\gamma}\eta_D - \frac{\eta_D^2}{\gamma\eta_S}\right)\left(1 - \psi + \frac{1-\gamma}{\eta_S}\right)\right)^{\frac{1}{2}} + \frac{\eta_D - 2\gamma\eta_D}{\gamma\eta_S} - \frac{1}{\gamma}\right) \tag{8}$$

where ψ denotes the relative price of ethanol and gasoline and γ denotes share of ethanol in world gasoline consumption.

Leakage is negative if the right hand side of (8) is negative. This is true whenever $(1-\psi)\eta_S + 1 - \gamma < 0$. This condition is guaranteed to hold for $\gamma < \frac{1}{2}$, which is easily met for typical values of γ since the share of ethanol in world oil consumption is very small (slightly over 0.5 percent globally in 2008). The above conditions can be summarized by $(1-\psi)\eta_S < \gamma - 1 < -\frac{1}{2}$ which yields $\psi > 1 + \frac{1}{2\eta_S}$. In words the last inequality says that autarky leakage with a consumption mandate is negative only if the relative price of ethanol and oil exceeds a certain level. Suppose a limiting case of a perfectly inelastic oil supply curve ($\eta_S = 0$). Obviously, in this case leakage can never be negative. The opposite extreme occurs when the oil supply curve is perfectly elastic, yielding $\psi > 1$. In summary, given typical values for oil supply elasticity and historical observations of relative ethanol and oil price it is likely that a consumption mandate under autarky could lead to negative leakage.

For the same quantity of ethanol, leakage with a consumption mandate is always smaller than that with a blender's tax credit as total fuel consumption is lower with a mandate (de Gorter and Just 2009c)[7].

What is market leakage when a tax credit is added to a binding consumption mandate?

If you add a blender's tax credit to a binding consumption mandate for ethanol, the tax credit simply subsidizes gasoline consumption, thus contradicting all environmental objectives (de Gorter and Just, 2009a, and Lapan and Moschini, 2009). Leakage of the tax credit in this case is infinity. The explanation is quite intuitive. As explained above, a tax credit does not induce any ethanol production provided that a consumption mandate is binding. It means, therefore that there cannot be any replacement of oil by ethanol. Effectively this makes the denominator in our leakage formula equal zero. On the other hand, additional oil is consumed as a result of combining the two policies together generating a positive value (displacement) in the numerator of the leakage formula. As a result the value of the fraction is infinity.

Interestingly enough, leakage due to a combination of the two policies will be finite. It is because a mandate does replace a certain quantity of oil so the denominator of the formula in Appendix 4 (formula A4-3) is non-zero. However, total leakage of the combination of the two policies will be higher than that due to mandate alone because of the additional oil consumption induced worldwide.

4 Is market leakage for a small country always 100 percent?

Traditionally, a small country is defined as one that is not able to affect the world price of a product by its domestic policy. This means the elasticity of excess supply (demand) for oil facing a small importer (exporter) is flat. Does this mean leakage is now 100 percent, given by distance *cb* in Figure 1? The answer is no for a small country importer of oil and is ambiguous for a small country exporter of oil.

To show this, note that elasticities of excess demand and excess supply curves are determined by domestic supply and demand elasticities and shares of domestic oil consumption (production) in world consumption (production). From Appendix 3,

$$\eta_{ES} = \eta_{SF}\frac{1-\phi}{1-\phi-\rho_{FT}-\rho_{FN}} - \eta_{DFT}\frac{\rho_{FT}}{1-\phi-\rho_{FT}-\rho_{FN}} - \eta_{DFN}\frac{\rho_{FN}}{1-\phi-\rho_{FT}-\rho_{FN}} \tag{9}$$

$$\eta_{ED} = \eta_{DHT}\frac{\rho_{HT}}{\rho_{HT}+\rho_{HN}-\phi} + \eta_{DHN}\frac{\rho_{HN}}{\rho_{HT}+\rho_{HN}-\phi} - \eta_{SH}\frac{\phi}{\rho_{HT}+\rho_{HN}-\phi} \tag{10}$$

Expressions (9) and (10) consist only of parameters that appear in our leakage formula and thus country size and associated leakage can be linked directly.

Following the assumption of the Home being an importer for this country to be small either the foreign supply curve for oil is perfectly elastic or the world oil price is such that trade approaches zero[8] (assuming all other parameters take on non-extreme values):

$$\begin{aligned} &a.)\ \eta_{SF} \to \infty \\ &b.)\ 1-\phi-\rho_{FT}-\rho_{FN} = 0 \end{aligned} \tag{11}$$

Clearly, these conditions are two independent sources of a country being a small trader and can thus have a different effect on the magnitude of leakage. Using similar reasoning, if the Home country is a small exporter, then either the transportation (non-transportation) demand in the other country is perfectly elastic or the world oil price is such that trade approaches zero. This is represented by one of these three conditions:[9]

$$\begin{aligned} &c.)\ \eta_{DHT} \to -\infty \\ &d.)\ \eta_{DHN} \to -\infty \\ &e.)\ \rho_{HT}+\rho_{HN}-\phi = 0 \end{aligned} \tag{12}$$

Having identified instances that make a country small, we are in a position to determine what the magnitude of leakage is in each of these situations and we will show how leakage differs. So being a small trader is not necessarily an indicator of level of leakage. Combining the leakage formula <u>for a tax credit</u> with conditions (a.) – (e.) yields:

(a.) 0

(b.) $$\frac{\rho_{HT}\eta_{DHT}+\rho_{HN}\eta_{DHN}+\rho_{FT}\eta_{DFT}+\rho_{FN}\eta_{DFN}}{\rho_{HT}\eta_{DHT}+\rho_{HN}\eta_{DHN}+\rho_{FT}\left(\eta_{DFT}+\eta_{SH}-\eta_{SF}\right)+\rho_{FN}\left(\eta_{DFN}+\eta_{SH}-\eta_{SF}\right)-\eta_{SH}}$$

(c.) 1

(d.) 1

(e.) $$\frac{\rho_{HT}\eta_{DHT}+\rho_{HN}\eta_{DHN}+\rho_{FT}\eta_{DFT}+\rho_{FN}\eta_{DFN}}{\rho_{HT}\left(\eta_{DHT}+\eta_{SF}-\eta_{SH}\right)+\rho_{HN}\left(\eta_{DHN}+\eta_{SF}-\eta_{SH}\right)+\rho_{FT}\eta_{DFT}+\rho_{FN}\eta_{DFN}-\eta_{SF}}$$

In summary, being an importer or exporter may significantly affect market leakage (and hence carbon leakage) when a country is small. If a small importer imposing a blender's tax credit faces a perfectly elastic supply of oil in the rest of the world, then there is no market leakage associated with this policy (and carbon leakage is negative as shown later). If, on the other hand, a small exporter faces a perfectly elastic demand curve for fuel in the rest of the world, then a tax credit leads to a 100 percent market leakage. In the event that a country is small due to its share in world oil consumption or production, then irrespective of whether or not a country is an importer, market leakage is between zero and 100 percent.

So what are the implications of all of this for a real-world small country such as Canada? Canada is a small exporter of oil. Consumption share of Canada in world oil consumption in 2008 was 2.6 percent and that of production was 3.5 percent (Table 3). Canada is also a producer of biofuels. The above discussion suggests that leakage associated with Canadian ethanol production may be very high.

4 Carbon leakage

Our focus so far has only been on market leakage, i.e. on determining how much gasoline is replaced by 1GEG of ethanol. We concluded that with a blender's tax credit this measure is bounded by zero and one but in theory can be negative with a consumption mandate. But the world's concerns are, however, centered on carbon leakage, or put differently whether or not an implemented policy has actually reduced GHG emissions.

In Appendix 4, we derive a simple but very intuitive formula for carbon leakage applicable for any biofuel policy:

$$L_{CO_2}=\frac{1}{\xi}L_{market}-1 \tag{13}$$

where ξ denotes by how much less CO_2 is emitted from 1GEG of ethanol compared to a gallon of gasoline. Therefore, all comparative statics results derived earlier apply directly to equation (13).

There are two factors that impact carbon leakage (1) market leakage and (2) relative emissions intensities a biofuel and oil. Clearly, higher market leakage and a relatively less clean biofuel magnify carbon leakage. Carbon leakage is zero if $L_{quantity} = \xi$, i.e. the two effects have to balance out. Assuming $\xi = 0.20$ (i.e. ethanol is 20 percent CO_2-cleaner than gasoline as suggested by LCA) 1GEG of ethanol would have to replace 0.8 gallons of gasoline for carbon leakage to be zero. If $L_{market} < \xi$, the effect of market leakage is outweighed by the CO_2 saving effect of ethanol resulting in global CO_2 savings. This means that even if market leakage is positive (but rather small), there still can be global savings in CO_2. Finally, if the effect of market leakage is bigger than the effect or relative carbon intensities, i.e., $L_{market} > \xi$, then carbon leakage is always positive because the CO_2 saving effect is dominated by the market effect and placing ethanol on the market leads to an increase in global CO_2 emissions. We will demonstrate empirically that this is indeed the case for the U.S., Canada and Brazil.

5 A numerical example

In this section, we quantify the magnitude of leakage for the United States, Canada, Brazil and California in 2008. The sources of the data used are listed in Appendix 5. The volumes of oil and ethanol were converted to gasoline-equivalent gallons (GEG)[10] prior to calculating market shares. Parameters' values used for estimates of leakage for individual countries are summarized in the top panel of Table 3.

We assume that ethanol in each country emits 20 percent less CO_2 than gasoline. The figure is based on the life-cycle accounting approach. Although reasonable for the U.S., it is 65 percent for Brazil where ethanol is produced more efficiently.

Out of the three countries analyzed, the U.S. had the highest world consumption and production share of oil, 23 and 7 percent, respectively. Canada and Brazil consumed 2.6 and 2.9 percent of world oil and produced 3.5 and 2.5 percent, respectively. In this exercise we assume the same set of supply and demand elasticities for oil each country.

The bottom panel of Table 3 presents estimates of leakage due to a tax credit and a consumption mandate (only for the U.S.). For the tax credit the magnitudes of market leakage are rather homogenous across countries and definitions, ranging from 0.74 to 0.79. The predominant reason is the same elasticities assumed for each country. We showed in the theoretical part of the paper that for observed data, elasticities are more important determinants of leakage than market shares. There is only a very small difference between magnitudes of leakage calculated by our formula and that of the IPCC. This is because domestic leakage is very small compared to international.

Leakage due to a consumption mandate in 2008 for the U.S. is some 5 percent below that with a tax credit. Albeit this difference is not very significant, it does suggest that a consumption mandate was more effective in combating market leakage than a tax credit. Also, the share of domestic leakage of negative 49 percent in 2008 implies that a decrease in fuel consumption in the transportation sector outweighed the increase in the domestic fuel consumption in the non-transportation sector. This effect was even stronger in 2006 (approximately eleven times so). With an exception of Brazil all other values for carbon leakage are above 200 percent, indicating that policies aimed at placing ethanol on the fuel market with the intention of reducing the CO_2 emissions are not effective. The estimate of carbon leakage for Brazil stands out as it is about thirteen times lower than the others. The reason for this is a much lower carbon intensity relative to gasoline of ethanol produced in Brazil compared to that from the U.S. (0.65 vs. 0.20). This exercise illustrates how sensitive carbon leakage is to relative carbon intensities even if market leakage is about the same in all countries.

In Table 4, we simulate the magnitude of leakage by changing key parameters' values. The parameters used are listed in the bottom panel of the table. Demand elasticity of the non-transportation sector is assumed to be 1.2 times that of transportation one and demand elasticity of transportation sector in the Foreign country is supposed to be 0.9 times that of transportation sector in the Home country. In the Home country 45 percent of oil is utilized for transportation and in the Foreign country this ratio is 36.7 percent. For simplicity, a production share is assumed to be the same as a consumption share and all other parameters values are the same as for the U.S. in 2008 (Table 3).

The table illustrates very well how ours and IPCC's estimates can diverge as domestic component of market leakage takes on its importance. For example, let us look at the case when market share is low and elasticities high. In this situation domestic leakage with a tax credit is very small relative to the international component. This makes the estimates of market leakage with a tax credit almost identical according to both definitions (31.9 vs. 31.0 percent). On the contrary, with a consumption mandate domestic market leakage is not only relatively significant (32.2 percent of the international) but also negative. This is reflected in diverging estimates of market leakage by our approach (negative 3.1 percent) and the IPCC definition (66.3 percent).

6 Conclusions

The notion of leakages in environmental policies aimed at combating global climate change is frequently discussed in the literature (Murray et al., 2004; de Gorter, 2009; Stoft 2009; Hochman et al., 2009). Leakage is a measure of the ineffectiveness of an environmental policy. For example, if the objective of a country (or a bloc of countries) is to reduce 100 units of CO_2 emissions within the country (bloc) but 20 units have been emitted elsewhere as a result of the policy, then carbon leakage is 20 percent.

The objective of this paper was to analyze and compare the impacts of two biofuel policies – a blender's tax credit and a consumption mandate – on leakages in the fuel market. To that end, we first introduce the concept of market leakage. Put simply, market leakage is the share of a gallon of ethanol that displaces gasoline (instead of replacing gasoline). For example, if one gallon of ethanol (in energy equivalent) replaces 0.4 gallons of gasoline, then market leakage is 60 percent.

The international trade framework within which we analyze a blender's tax credit and a consumption mandate gives rise to a distinction between domestic and international leakage. Despite being overlooked by the IPCC, the former might, under plausible assumptions, be a significant factor of total leakage. With hypothetical simulations, we show why domestic leakage has to be included into leakage estimates of various policies and what biases result from not doing so.

We show that market leakages (and hence carbon leakage) of both types of biofuel policies depend on two groups of parameters: (1) elasticities of fuel demand(s) and oil supply both in the country introducing ethanol and the rest of the world; and (2) world oil consumption and production shares of individual countries. We demonstrate that market leakage is more sensitive to changes in the values of elasticities than in production and consumption shares and more so in the country not introducing biofuels.

With a tax credit, both domestic and international leakage is always positive. With a consumption mandate, only international leakage is unambiguously positive while the direction of the domestic component is ambiguous, depending on market parameters. We find that for the same quantity of ethanol, a consumption mandate results in a smaller leakage, making it more appropriate an environmental policy than a tax credit. We show and explain why if a tax credit is added to a binding mandate leakage due to the tax credit is infinite.

For a small country, leakage effects of a blender's tax credit can be ambiguous, depending whether it is an oil importer or exporter. If a country faces a perfectly elastic supply of oil from the rest of the world, then there is no market leakage associated with this policy and carbon leakage is negative, implying that more CO_2 is saved that originally planned. If however, a small oil exporter (like Canada) faces a perfectly elastic demand curve in the rest of the world, then a tax credit leads to 100 percent market leakage.

We have derived a positive causal relation between market leakage and carbon leakage. The latter is, however, negatively correlated with the difference in carbon intensities of a biofuel and oil.

Finally, our numerical estimations for the U.S., Canada and Brazil reveal very similar and high (more than 70 percent) values of market leakage for these countries (keeping elasticities identical for each country) which confirms the theoretical conclusion of market shares not having a strong impact on leakage. Market leakage of 70 to 80 percent means that only 0.2 to 0.3 gallons of gasoline are replaced by one gallon of ethanol. But this in turn means that the assumption used by life-cycle accounting maybe inadequate and so raises serious questions about the efficacy of the ethanol sustainability thresholds (de Gorter and Just 2009b). Moreover, the sustainability threshold for ethanol in the U.S. of 20 percent was based on previous LCA estimates of the same magnitude. In the mean time, however, the EPA have recently updated LCA estimates and show that even with iLUCs, ethanol exceeding the threshold by 1 percent (i.e., the net carbon savings of ethanol compared to gasoline is 21 percent including emissions from iLUC). A market leakage of 70 to 80 percent in the fuel market translates into carbon leakage of 230 to 280 percent So instead of a net carbon savings of 21 percent that includes leakage in land markets, we find a net loss of between 230 to 280 percent if leakage in fuel markets are also included.

References

de Gorter, H. 2009. Integrating Developing Country Agriculture into Global Climate Change Mitigation Efforts. In *Non-Distorting Farm Support to Enhance Global Food Production*, eds. Aziz Elbehri and Alexander Sarris. Rome, Italy: Food and Agriculture Organization (FAO).

de Gorter, H., and D. Just. 2009a. The Economics of a Blend Mandate for Biofuels. *American Journal of Agricultural Economics* 91 (3): 738-750.

———. 2009b. Why Sustainability Standards for Biofuel Production Make Little Economic Sense. Cato Institute *Policy Analysis* No. 647, Washington D.C. http://www.cato.org/pubs/pas/pa647.pdf

———. 2009c. The Social Costs and Benefits of Biofuel Policies with Pre-Existing Distortions. Paper presented at the American Tax Policy Institute Conference, Issues on U.S. Energy Taxes Washington D.C. (forthcoming book chapter by Cambridge University Press, Gilbert E. Metcalf, editor).

Farrell A., R. Plevin, B. Turner, A. Jones, M. O'Hare, and D. Kammen. 2006. Ethanol Can Contribute to Energy and Environmental Goals. *Science* 311(5760): 506–508.

Hochman, G., Rajagopal, D., and Zilberman, D. 2009. The Effect of Biofuel on the International Oil Market. Department of Agricultural and Resource Economics, UCB, UC Berkeley. August. http://deepak.berkeley.edu/OPEC%20biofuel.pdf (last accessed October 2009).

IPCC. Glossary of Terms used in the IPCC Fourth Assessment Report. http://www.ipcc.ch/pdf/glossary/ar4-wg3.pdf

Lapan, H., and G. Moschini. 2009. Biofuel Policies and Welfare: Is the Stick of Mandates Better than the Carrot of Subsidies? Working Paper No. 09010, Department of Economics, Iowa State University, June Ames, Iowa.

Murray, B. C., McCarl, B. A., and Lee, H. 2004. Estimating Leakage from Forest Carbon Sequestration Programs. *Land Economics* 80 (1):109-124.Murray, B. C. (2008). Leakage from an Avoided Deforestation Compensation Policy: Concepts, Empirical Evidence, and Corrective Policy Options. Nicholas Institute for Environmental Policy Solutions, Duke University

Searchinger, T., R. Heimlich, R. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T. Yu. 2008. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land Use Change. *Science* 319 (5867): 1238-1240.

Stoft, Steven. 2009. The Global Rebound Effect Versus California's Low-Carbon Fuel Standard. GLOBAL ENERGY POLICY CENTER Research Paper No. 09-04, October 1. Documentation available at: www.global-energy.org

Wooders, P., Reinaud, J. and Cosbey, A. (2009). Options for Policy-Makers: Addressing Competitiveness, Leakage and Climate Change. International Institute for Sustainable Development.

Table 1: Effects of determinants of market leakage on its magnitude (tax credit)

$\partial\left(L^{T}_{market}\right)/\partial$		Note
η_{DHT}	$-\frac{\rho_{HT}\left(\phi\eta_{SH}+(1-\phi)\eta_{SF}\right)}{\left(\rho_{HT}\left(\eta_{DHT}-\eta_{DFN}\right)+\rho_{HN}\left(\eta_{DHN}-\eta_{DFN}\right)+\rho_{FT}\left(\eta_{DFT}-\eta_{DFN}\right)+\eta_{DFN}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}<0$	
η_{DHN}	$-\frac{\rho_{HN}\left(\phi\eta_{SH}+(1-\phi)\eta_{SF}\right)}{\left(\rho_{HT}\left(\eta_{DHT}-\eta_{DFN}\right)+\rho_{HN}\left(\eta_{DHN}-\eta_{DFN}\right)+\rho_{FT}\left(\eta_{DFT}-\eta_{DFN}\right)+\eta_{DFN}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}<0$	
η_{DFT}	$-\frac{\rho_{FT}\left(\phi\eta_{SH}+(1-\phi)\eta_{SF}\right)}{\left(\rho_{HT}\left(\eta_{DHT}-\eta_{DFN}\right)+\rho_{HN}\left(\eta_{DHN}-\eta_{DFN}\right)+\rho_{FT}\left(\eta_{DFT}-\eta_{DFN}\right)+\eta_{DFN}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}<0$	
η_{DFN}	$-\frac{\left(1-\rho_{HT}-\rho_{HN}-\rho_{FT}\right)\left(\phi\eta_{SH}+(1-\phi)\eta_{SF}\right)}{\left(\rho_{HT}\left(\eta_{DHT}-\eta_{DFN}\right)+\rho_{HN}\left(\eta_{DHN}-\eta_{DFN}\right)+\rho_{FT}\left(\eta_{DFT}-\eta_{DFN}\right)+\eta_{DFN}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}<0$	
η_{SH}	$\frac{\phi\left(\rho_{HT}\left(\eta_{DHT}-\eta_{DFN}\right)+\rho_{HN}\left(\eta_{DHN}-\eta_{DFN}\right)+\rho_{FT}\left(\eta_{DFT}-\eta_{DFN}\right)+\eta_{DFN}\right)}{\left(\rho_{HT}\left(\eta_{DHT}-\eta_{DFN}\right)+\rho_{HN}\left(\eta_{DHN}-\eta_{DFN}\right)+\rho_{FT}\left(\eta_{DFT}-\eta_{DFN}\right)+\eta_{DFN}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}<0$	
η_{SF}	$\frac{(1-\phi)\left(\rho_{HT}\left(\eta_{DHT}-\eta_{DFN}\right)+\rho_{HN}\left(\eta_{DHN}-\eta_{DFN}\right)+\rho_{FT}\left(\eta_{DFT}-\eta_{DFN}\right)+\eta_{DFN}\right)}{\left(\rho_{HT}\left(\eta_{DHT}-\eta_{DFN}\right)+\rho_{HN}\left(\eta_{DHN}-\eta_{DFN}\right)+\rho_{FT}\left(\eta_{DFT}-\eta_{DFN}\right)+\eta_{DFN}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}<0$	
ρ_{HT}	$-\frac{\left(\eta_{DHT}-\eta_{DFN}\right)\left(\phi\eta_{SH}+(1-\phi)\eta_{SF}\right)}{\left(\rho_{HT}\left(\eta_{DHT}-\eta_{DFN}\right)+\rho_{HN}\left(\eta_{DHN}-\eta_{DFN}\right)+\rho_{FT}\left(\eta_{DFT}-\eta_{DFN}\right)+\eta_{DFN}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}>0$	for $\eta_{DHT}<\eta_{DFN}$
ρ_{HT}	$-\frac{\left(\eta_{DHT}-\eta_{DFN}\right)\left(\phi\eta_{SH}+(1-\phi)\eta_{SF}\right)}{\left(\rho_{HT}\left(\eta_{DHT}-\eta_{DFN}\right)+\rho_{HN}\left(\eta_{DHN}-\eta_{DFN}\right)+\rho_{FT}\left(\eta_{DFT}-\eta_{DFN}\right)+\eta_{DFN}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}<0$	for $\eta_{DHT}>\eta_{DFN}$
ρ_{HN}	$-\frac{\left(\eta_{DHN}-\eta_{DFN}\right)\left(\phi\eta_{SH}+(1-\phi)\eta_{SF}\right)}{\left(\rho_{HT}\left(\eta_{DHT}-\eta_{DFN}\right)+\rho_{HN}\left(\eta_{DHN}-\eta_{DFN}\right)+\rho_{FT}\left(\eta_{DFT}-\eta_{DFN}\right)+\eta_{DFN}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}>0$	for $\eta_{DHN}<\eta_{DFN}$
ρ_{HN}	$-\frac{\left(\eta_{DHN}-\eta_{DFN}\right)\left(\phi\eta_{SH}+(1-\phi)\eta_{SF}\right)}{\left(\rho_{HT}\left(\eta_{DHT}-\eta_{DFN}\right)+\rho_{HN}\left(\eta_{DHN}-\eta_{DFN}\right)+\rho_{FT}\left(\eta_{DFT}-\eta_{DFN}\right)+\eta_{DFN}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}<0$	for $\eta_{DHN}>\eta_{DFN}$
ρ_{FT}	$-\frac{\left(\eta_{DFT}-\eta_{DFN}\right)\left(\phi\eta_{SH}+(1-\phi)\eta_{SF}\right)}{\left(\rho_{HT}\left(\eta_{DHT}-\eta_{DFN}\right)+\rho_{HN}\left(\eta_{DHN}-\eta_{DFN}\right)+\rho_{FT}\left(\eta_{DFT}-\eta_{DFN}\right)+\eta_{DFN}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}>0$	for $\eta_{DFT}<\eta_{DFN}$
ρ_{FT}	$-\frac{\left(\eta_{DFT}-\eta_{DFN}\right)\left(\phi\eta_{SH}+(1-\phi)\eta_{SF}\right)}{\left(\rho_{HT}\left(\eta_{DHT}-\eta_{DFN}\right)+\rho_{HN}\left(\eta_{DHN}-\eta_{DFN}\right)+\rho_{FT}\left(\eta_{DFT}-\eta_{DFN}\right)+\eta_{DFN}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}<0$	for $\eta_{DFT}>\eta_{DFN}$
ϕ	$\frac{\left(\eta_{SH}-\eta_{SF}\right)\left(\rho_{HT}\left(\eta_{DHT}-\eta_{DFN}\right)+\rho_{HN}\left(\eta_{DHN}-\eta_{DFN}\right)+\rho_{FT}\left(\eta_{DFT}-\eta_{DFN}\right)+\eta_{DFN}\right)}{\left(\rho_{HT}\left(\eta_{DHT}-\eta_{DFN}\right)+\rho_{HN}\left(\eta_{DHN}-\eta_{DFN}\right)+\rho_{FT}\left(\eta_{DFT}-\eta_{DFN}\right)+\eta_{DFN}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}>0$	for $\eta_{SH}<\eta_{SF}$
ϕ	$\frac{\left(\eta_{SH}-\eta_{SF}\right)\left(\rho_{HT}\left(\eta_{DHT}-\eta_{DFN}\right)+\rho_{HN}\left(\eta_{DHN}-\eta_{DFN}\right)+\rho_{FT}\left(\eta_{DFT}-\eta_{DFN}\right)+\eta_{DFN}\right)}{\left(\rho_{HT}\left(\eta_{DHT}-\eta_{DFN}\right)+\rho_{HN}\left(\eta_{DHN}-\eta_{DFN}\right)+\rho_{FT}\left(\eta_{DFT}-\eta_{DFN}\right)+\eta_{DFN}-\phi\eta_{SH}-(1-\phi)\eta_{SF}\right)^2}<0$	for $\eta_{SH}>\eta_{SF}$

Table 2: Magnitude of market leakage if parameters take extreme values. Home country is assumed to be an importer*

		L^T_{market}	Location of leakage**
1.	$\rho_{FT}=0, \rho_{FN}=0$	$\frac{\rho_{HT}\eta_{DHT}+\rho_{HN}\eta_{DHN}}{\rho_{HT}\eta_{DHT}+\rho_{HN}\eta_{DHN}-\phi\eta_{SH}-(1-\phi)\eta_{SF}}$	domestic
2.	$\rho_{HT}=0, \rho_{HN}=0$	$\frac{\rho_{FT}\eta_{DFT}+\rho_{FN}\eta_{DFN}}{\rho_{FT}\eta_{DFT}+\rho_{FN}\eta_{DFN}-\phi\eta_{SH}-(1-\phi)\eta_{SF}}$	international
3.	$\phi=1$	$\frac{\rho_{HT}\eta_{DHT}+\rho_{HN}\eta_{DHN}+\rho_{FT}\eta_{DFT}+\rho_{FN}\eta_{DFN}}{\rho_{HT}\eta_{DHT}+\rho_{HN}\eta_{DHN}+\rho_{FT}\eta_{DFT}+\rho_{FN}\eta_{DFN}-\eta_{SH}}$	domestic & international
4.	$\phi=0$	$\frac{\rho_{HT}\eta_{DHT}+\rho_{HN}\eta_{DHN}+\rho_{FT}\eta_{DFT}+\rho_{FN}\eta_{DFN}}{\rho_{HT}\eta_{DHT}+\rho_{HN}\eta_{DHN}+\rho_{FT}\eta_{DFT}+\rho_{FN}\eta_{DFN}-\eta_{SF}}$	domestic & international
5.	$\eta_{DHT}=0$	$\frac{\rho_{HN}\eta_{DHN}+\rho_{FT}\eta_{DFT}+\rho_{FN}\eta_{DFN}}{\rho_{HN}\eta_{DHN}+\rho_{FT}\eta_{DFT}+\rho_{FN}\eta_{DFN}-\phi\eta_{SH}-(1-\phi)\eta_{SF}}$	domestic & international
6.	$\eta_{DHT}\to-\infty$	1	domestic
7.	$\eta_{DHN}=0$	$\frac{\rho_{HT}\eta_{DHT}+\rho_{FT}\eta_{DFT}+\rho_{FN}\eta_{DFN}}{\rho_{HT}\eta_{DHT}+\rho_{FT}\eta_{DFT}+\rho_{FN}\eta_{DFN}-\phi\eta_{SH}-(1-\phi)\eta_{SF}}$	domestic & international
8.	$\eta_{DHN}\to-\infty$	1	domestic
9.	$\eta_{DFT}=0$	$\frac{\rho_{HT}\eta_{DHT}+\rho_{HN}\eta_{DHN}+\rho_{FN}\eta_{DFN}}{\rho_{HT}\eta_{DHT}+\rho_{HN}\eta_{DHN}+\rho_{FN}\eta_{DFN}-\phi\eta_{SH}-(1-\phi)\eta_{SF}}$	domestic & international
10.	$\eta_{DFT}\to-\infty$	1	international
11.	$\eta_{DFN}=0$	$\frac{\rho_{HT}\eta_{DHT}+\rho_{HN}\eta_{DHN}+\rho_{FT}\eta_{DFT}}{\rho_{HT}\eta_{DHT}+\rho_{HN}\eta_{DHN}+\rho_{FT}\eta_{DFT}-\phi\eta_{SH}-(1-\phi)\eta_{SF}}$	domestic & international
12.	$\eta_{DFN}\to-\infty$	1	international
13.	$\eta_{SH}=0$	$\frac{\rho_{HT}\eta_{DHT}+\rho_{HN}\eta_{DHN}+\rho_{FT}\eta_{DFT}+\rho_{FN}\eta_{DFN}}{\rho_{HT}\eta_{DHT}+\rho_{HN}\eta_{DHN}+\rho_{FT}\eta_{DFT}+\rho_{FN}\eta_{DFN}-(1-\phi)\eta_{SF}}$	domestic & international
14.	$\eta_{SH}\to\infty$	0	
15.	$\eta_{SF}=0$	$\frac{\rho_{HT}\eta_{DHT}+\rho_{HN}\eta_{DHN}+\rho_{FT}\eta_{DFT}+\rho_{FN}\eta_{DFN}}{\rho_{HT}\eta_{DHT}+\rho_{HN}\eta_{DHN}+\rho_{FT}\eta_{DFT}+\rho_{FN}\eta_{DFN}-\phi\eta_{SH}}$	domestic & international
16.	$\eta_{SF}\to\infty$	0	

* 2., 3., 10., 12, and 14. are only meaningful for an exporter.
** Based on equation (3)

Table 3: Estimates of leakage for selected countries in 2008 *

	Parameters													
	ξ	ρ_{HT}	ρ_{HN}	ρ_{FT}	ρ_{FN}	ϕ	γ	η_{DHT}	η_{DHN}	η_{DFT}	η_{DFN}	η_{SH}	η_{SF}	ψ**
USA	0.200	0.101	0.126	0.283	0.489	0.067	0.005	-0.260	-0.260	-0.400	-0.400	0.200	0.100	1.912
Canada	0.200	0.005	0.021	0.357	0.617	0.035	0.000	-0.260	-0.260	-0.400	-0.400	0.200	0.100	
Brazil	0.650	0.011	0.018	0.356	0.615	0.025	0.005	-0.260	-0.260	-0.400	-0.400	0.200	0.100	
California***	0.200	0.009	0.012	0.359	0.620	0.126	0.008	-0.260	-0.260	-0.400	-0.400	0.200	0.100	

	Our definition of leakage						IPCC definition of leakage					
	Tax credit				Consumption mandate		Tax credit				Consumption mandate	
	USA	Canada	Brazil	California	US (2006)	US (2008)	USA	Canada	Brazil	California	US (2006)	US (2008)
Total quantity leakage	0.775	0.793	0.794	0.779	0.644	0.721	0.743	0.790	0.791	0.777	0.553	0.646
% Domestic	16.1%	1.7%	1.9%	1.4%	-535.5%	-49.0%						
% Foreign	83.9%	98.3%	98.1%	98.6%	635.5%	149.0%						
CO_2 leakage	2.876	2.964	0.222	2.896	2.218	2.604	2.717	2.950	0.217	2.884	1.766	2.232

* Results of leakage due to the U.S. consumption mandate are also provided for 2006

** Leakage due to mandate is calculated only for the USA. Prices of ethanol and oil are expressed in dollars per gasoline-equivalent gallon

*** The base for California is the U.S.

Source: Appendix 5

Table 4: Sensitivity of market leakage to parameters' values and definition

Comparison of leakage magnitudes

Our definition:			**Elasticities**		
			Low	Medium	High
Tax credit		Low	0.484	0.328	0.319
	Shares	Medium	0.485	0.328	0.320
		High	0.486	0.329	0.321
Consumption mandate		Low	0.435	0.318	-0.031
	Shares	Medium	0.436	0.167	0.006
		High	0.437	0.169	0.008
IPCC definition:			**Elasticities**		
			Low	Medium	High
Tax credit		Low	0.473	0.158	0.310
	Shares	Medium	0.338	0.210	0.203
		High	0.053	0.028	0.027
Consumption mandate		Low	0.363	0.355	0.663
	Shares	Medium	1.084	0.042	-0.170
		High	-0.169	-0.032	-0.073

Ratio of domestic and international leakage

			Elasticities		
			Low	Medium	High
Tax credit		Low	0.044	0.044	0.044
	Shares	Medium	0.840	0.840	0.840
		High	15.965	15.965	15.965
Consumption mandate		Low	-0.708	-0.593	-0.322
	Shares	Medium	0.549	-3.566	1.520
		High	10.102	10.224	9.357
			Low	Medium	High
Parameters' values		$\rho=\phi=$	0.050	0.500	0.950
		η_{DHT}	-0.100	-0.260	-0.500
		η_{SH}	0.100	0.500	1.000
		γ	0.005	0.005	0.005
		ψ	1.912	1.912	1.912

Note: ρ=share of domestic oil consumption in world consumption
ϕ=share of domestic oil production in world production
$\rho_{HT}=0.67*\rho$ $\rho_{HN}=0.33*\rho$ $\rho_{FT}=0.55*(1-\rho)$ $\rho_{FN}=0.45*(1-\rho)$
$\eta_{DHN}=0.9*\eta_{DHT}$ $\eta_{DFT}=1.2*\eta_{DHT}$ $\eta_{DFN}=1.2*0.9*\eta_{DHT}$
$\eta_{SF}=1.2*\eta_{SH}$

Figure 1: Autarky Leakage with a Tax Credit

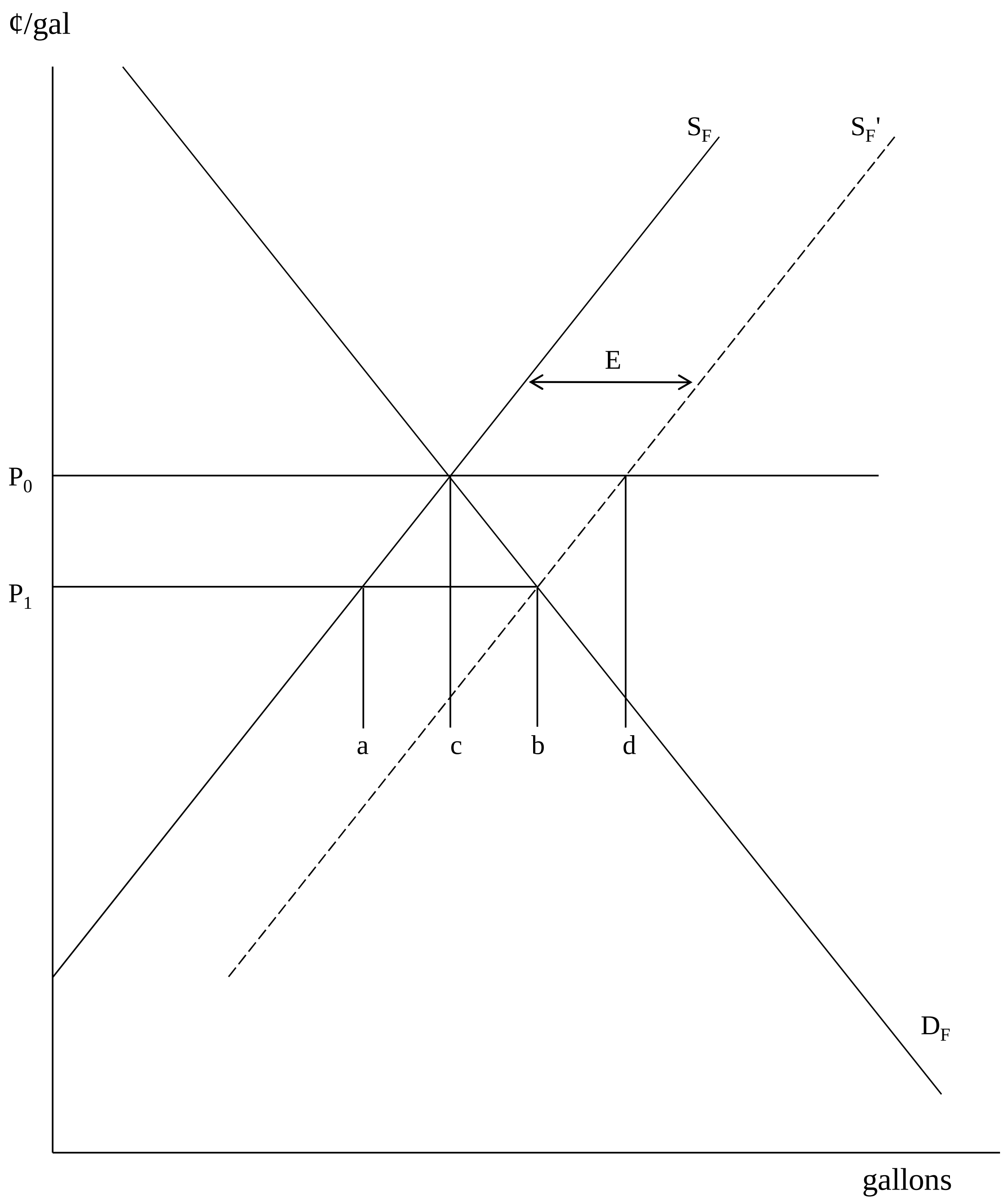


Figure 2: Leakage with a Tax Credit and International Trade

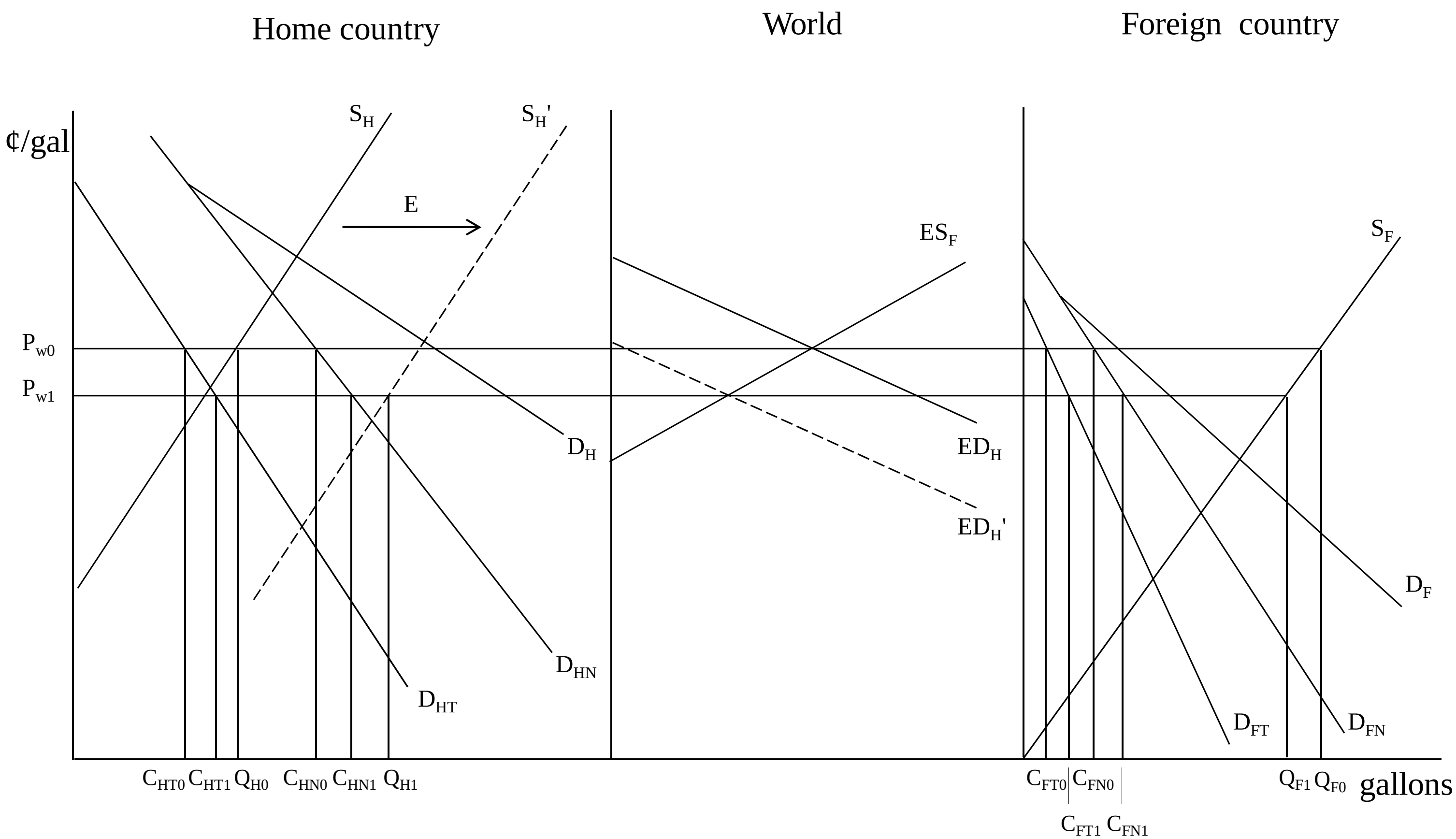


Figure 3: Consumption Mandate with an Endogenous Oil Price

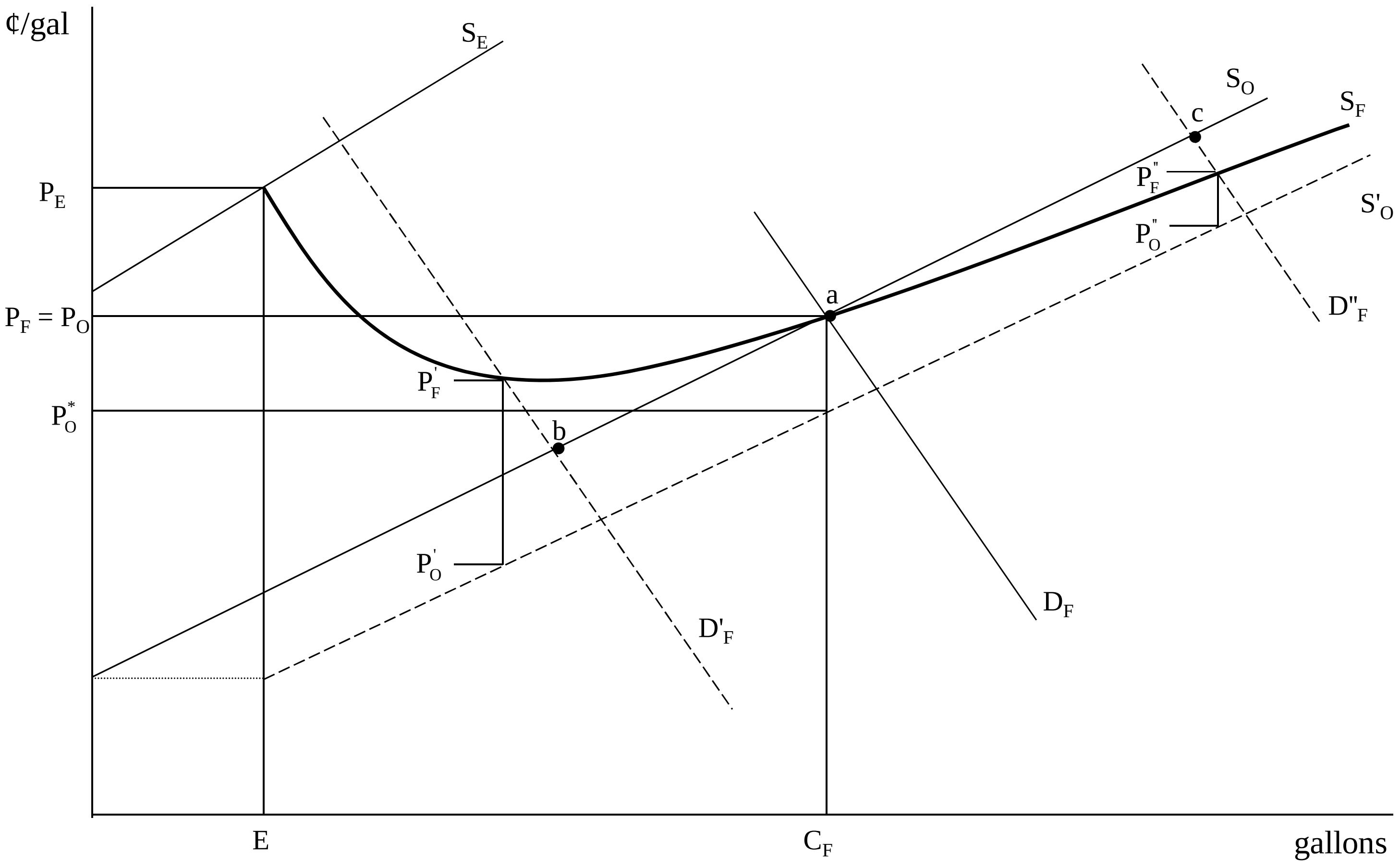
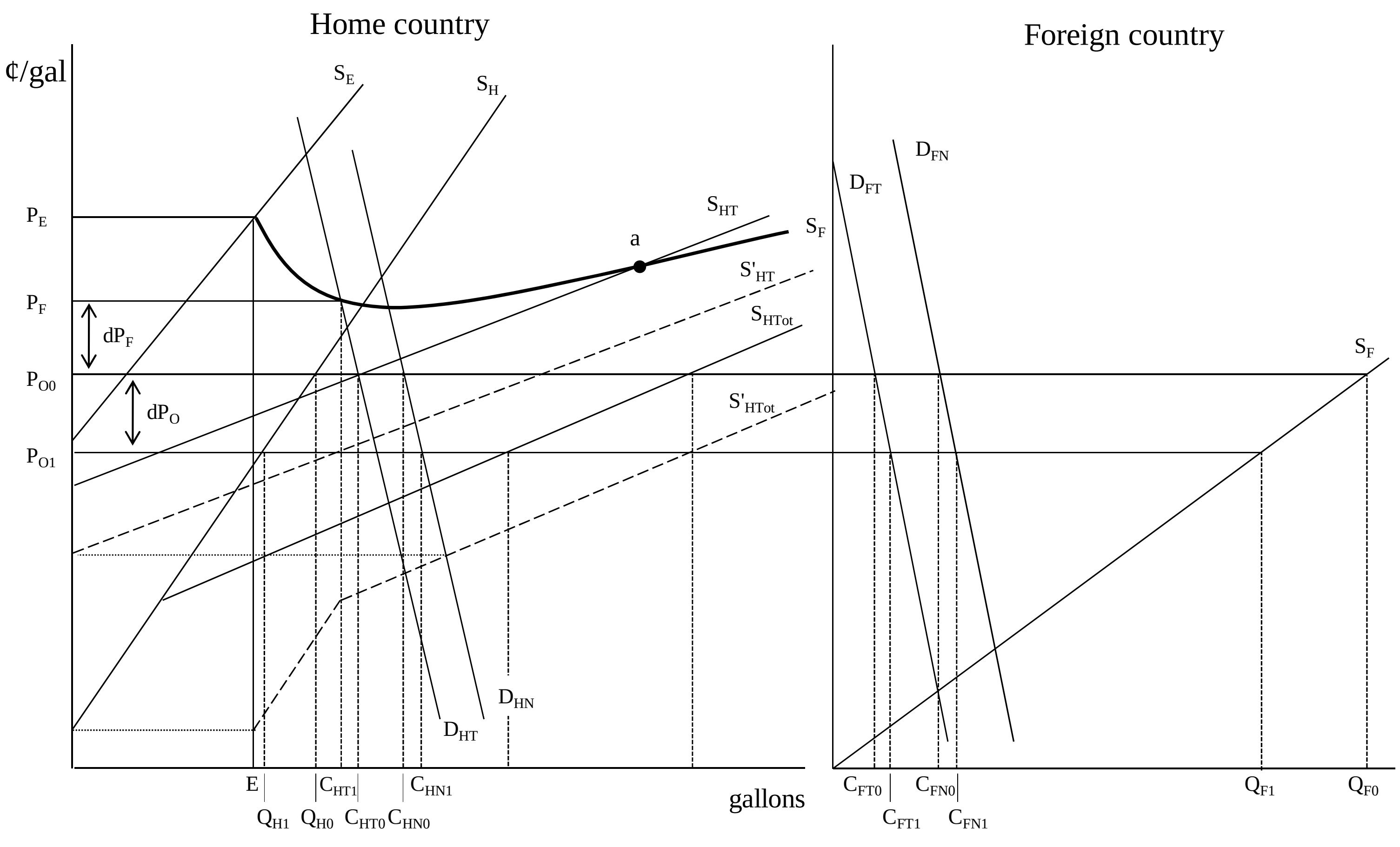


Figure 4: Leakage with a Consumption Mandate and International Trade



Appendix 1: Derivation of market leakage with to a tax credit

In the equilibrium oil imports (M) must equal oil exports (X) prior to and after the policy, therefore:

$$\Delta M = \Delta X$$

$$\left(D_{HT}\left(P_{w1}\right)+D_{HN}\left(P_{w1}\right)-\left(S_H\left(P_{w1}\right)+E\right)\right)-\left(D_{HT}\left(P_{w0}\right)+D_{HN}\left(P_{w0}\right)-S_H\left(P_{w0}\right)\right)= \qquad \text{(A1-1)}$$
$$\left(S_F\left(P_{w1}\right)-\left(D_{FT}\left(P_{w1}\right)+D_{FN}\left(P_{w1}\right)\right)\right)-\left(S_F\left(P_{w0}\right)-\left(D_{FT}\left(P_{w0}\right)+D_{FN}\left(P_{w0}\right)\right)\right)$$

From this, the new quantity of ethanol can be expressed as:

$$E = D_{HT}\left(P_{w1}\right)-D_{HT}\left(P_{w0}\right)+D_{HN}\left(P_{w1}\right)-D_{HN}\left(P_{w0}\right)+D_{FT}\left(P_{w1}\right)-D_{FT}\left(P_{w0}\right)+D_{FN}\left(P_{w1}\right)-D_{FN}\left(P_{w0}\right)$$
$$-\left(S_H\left(P_{w1}\right)-S_H\left(P_{w0}\right)\right)-\left(S_F\left(P_{w1}\right)-S_F\left(P_{w0}\right)\right)$$

(A1-2)

Or more succinctly:

$$E = \Delta D_{HT} + \Delta D_{HN} + \Delta D_{FT} + \Delta D_{FN} - \Delta S_H - \Delta S_F$$
$$E = \eta_{DHT} C_{HT0}\frac{dP}{P_{w0}} + \eta_{DHN} C_{HN0}\frac{dP}{P_{w0}} + \eta_{DFT} C_{FT0}\frac{dP}{P_{w0}} + \eta_{DFN} C_{FN0}\frac{dP}{P_{w0}} - \eta_{SH} Q_{H0}\frac{dP}{P_{w0}} - \eta_{SF} Q_{F0}\frac{dP}{P_{w0}}$$

(A1-3)

where dP / P_{w0} denotes a percentage change in the world oil price due to additional E units of ethanol on the market. The expression for E in (A1-3) is positive because the price change is negative.

With a tax credit $\Delta C_F = \eta_{DHT} C_{HT0}\frac{dP}{P_{w0}} + \eta_{DHN} C_{HN0}\frac{dP}{P_{w0}} + \eta_{DFT} C_{FT0}\frac{dP}{P_{w0}} + \eta_{DFN} C_{FN0}\frac{dP}{P_{w0}}$.

For market leakage we obtain:

$$L^T_{market} = \frac{\Delta C_F}{E} = \frac{\eta_{DHT} C_{HT0} + \eta_{DHN} C_{HN0} + \eta_{DFT} C_{FT0} + \eta_{DFN} C_{FN0}}{\eta_{DHT} C_{HT0} + \eta_{DHN} C_{HN0} + \eta_{DFT} C_{FT0} + \eta_{DFN} C_{FN0} - \eta_{SH} Q_{H0} - \eta_{SF} Q_{F0}} \qquad \text{(A1-4)}$$

Multiply both the numerator and the denominator of (A1-4) by $\frac{1}{C_{H0}+C_{F0}}$ and note that $C_{H0}+C_{F0} \equiv Q_{H0}+Q_{F0}$, where $C_{i0} \equiv C_{iT0}+C_{iN0}$ for $i=\{H,F\}$. Define $\rho_T = \frac{C_{HT0}}{C_{H0}+C_{F0}}$, $\rho_N = \frac{C_{HN0}}{C_{H0}+C_{F0}}$, and $\phi = \frac{Q_{H0}}{Q_{H0}+Q_{F0}}$. This yields:

$$L^T_{market} = \frac{\rho_{HT}\eta_{DHT} + \rho_{HN}\eta_{DHN} + \rho_{FT}\eta_{DFT} + \rho_{FN}\eta_{DFN}}{\rho_{HT}\eta_{DHT} + \rho_{HN}\eta_{DHN} + \rho_{FT}\eta_{DFT} + \rho_{FN}\eta_{DFN} - \phi\eta_{SH} - (1-\phi)\eta_{SF}} \geq 0 \text{ and } \leq 1 \qquad \text{(A1-5)}$$

Appendix 2: Derivation of market leakage with a consumption mandate

From Figure 4 we have: $\Delta C_F = \eta_{DHT} \frac{C_{HT0}}{P_{O0}} dP_F + \left(\eta_{DHN} C_{HN0} + \eta_{DFT} C_{FT0} + \eta_{DFN} C_{FN0}\right) \frac{dP_O}{P_{O0}}$

where P_{O0} is the initial oil price, dP_F is a change in price of oil used for transportation in the Home country, and dP_O denotes change in world oil price. We also have:

$$\begin{aligned} P_{O1} &= P_{O0} + dP_O \\ dP_F &= P_F - P_{O0} \end{aligned} \qquad \text{(A2-1)}$$

Moreover, in Figure 4:

$$C_{HT1} = C_{HT0} + \eta_{DHT} \frac{C_{HT0}}{P_{O0}} dP_F \qquad \text{(A2-2)}$$

and oil consumption less ethanol in the Home country has to equal domestic oil production and imports from abroad:

$$\begin{aligned} &C_{HT1} + C_{HN1} - E = Q_{H1} + X \\ &C_{HT0} + \eta_{DHT} \frac{C_{HT0}}{P_{O0}} dP_F + C_{HN0} + \eta_{DHN} \frac{C_{HN0}}{P_{O0}} dP_O - E = Q_{H0} + \eta_{SH} \frac{Q_{H0}}{P_{O0}} dP_O + X \end{aligned} \qquad \text{(A2-3)}$$

where

$$X = Q_{F1} - \left(C_{FT1} + C_{FN1}\right) = Q_{F0} + \eta_{SF} \frac{Q_{F0}}{P_{O0}} dP_O - \left(C_{FT0} + \eta_{DFT} \frac{C_{FT0}}{P_{O0}} dP_O + C_{FN0} + \eta_{DFN} \frac{C_{FN0}}{P_{O0}} dP_O\right) \qquad \text{(A2-4)}$$

is export of oil from the Foreign country after the policy.

Substituting (A2-4) into (A2-3) and solving for dP_O yields:

$$dP_O = \frac{\eta_{DHT} C_{HT0} dP_F - E P_{O0}}{\eta_{SH} Q_{H0} + \eta_{SF} Q_{F0} - \eta_{DFT} C_{FT0} - \eta_{DFN} C_{FN0} - \eta_{DHN} C_{HN0}} \qquad \text{(A2-5)}$$

With a consumption mandate price for fuel, P_F, paid by consumers in the Home country is a weighted average of the ethanol and oil prices where the weights are fuels' shares in final consumption:

$$P_F = \frac{E}{C_{HT1}} P_E + \frac{C_{HT1} - E}{C_{HT1}} P_{O1} \qquad \text{(A2-6)}$$

Now we combine (A2-1), (A2-2), (A2-5), and (A2-6) and solve the system for dP_F. After rearranging the terms, we arrive at a quadratic equation in dP_F of the form

$$a\left(dP_F\right)^2 + bdP_F + c = 0$$

with

$$\begin{aligned}
a &= \eta_{DHT}\frac{C_{HT0}}{P_{O0}}\left(\frac{\eta_{SH}Q_{H0}+\eta_{SF}Q_{F0}-\eta_{DFT}C_{FT0}-\eta_{DFN}C_{FN0}-\eta_{DHT}C_{HT0}-\eta_{DHN}C_{HN0}}{\eta_{SH}Q_{H0}+\eta_{SF}Q_{F0}-\eta_{DFT}C_{FT0}-\eta_{DFN}C_{FN0}-\eta_{DHN}C_{HN0}}\right)<0\\
b &= C_{HT0}+\frac{2\eta_{DHT}C_{HT0}E-\eta_{DHT}\left(C_{HT0}\right)^2}{\eta_{SH}Q_{H0}+\eta_{SF}Q_{F0}-\eta_{DFT}C_{FT0}-\eta_{DFN}C_{FN0}-\eta_{DHN}C_{HN0}}\\
c &= E\left(P_{O0}-P_E+\frac{P_{O0}\left(C_{HT0}-E\right)}{\eta_{SH}Q_{H0}+\eta_{SF}Q_{F0}-\eta_{DFT}C_{FT0}-\eta_{DFN}C_{FN0}-\eta_{DHN}C_{HN0}}\right)
\end{aligned} \tag{A2-7}$$

We exclude both the possibility of no solution ($D<0$), in which case demand curve for fuel in the Home country would lie below the U-shaped fuel supply curve, as well as the possibility of only one solution ($D=0$) – demand for fuel curve would be a tangent to the supply curve. Out of the two solutions to (A2-7) we pick the one pertaining to the stable equilibrium characterized by higher fuel consumption in the Home country. Associated with that equilibrium is the smaller value for dP_F . Because in our case $a<0$, we consider only

$$dP_F = \frac{-b+\sqrt{D}}{2a}$$

This solution requires that $D>0$. This is satisfied if

$$\begin{aligned}
\psi &< 1+\frac{\rho_{HT}-\gamma}{\phi\eta_{SH}+(1-\phi)\eta_{SF}-\rho_{FT}\eta_{DFT}-\rho_{FN}\eta_{DFN}-\rho_{HN}\eta_{DHN}}\\
&\quad -\frac{\left(1+\dfrac{2\gamma\eta_{DHT}-\rho_{HT}\eta_{DHT}}{\phi\eta_{SH}+(1-\phi)\eta_{SF}-\rho_{FT}\eta_{DFT}-\rho_{FN}\eta_{DFN}-\rho_{HN}\eta_{DHN}}\right)^2}{\dfrac{4\eta_{DHT}\gamma}{\rho_{HT}}\left(\dfrac{\phi\eta_{SH}+(1-\phi)\eta_{SF}-\rho_{FT}\eta_{DFT}-\rho_{FN}\eta_{DFN}-\rho_{HT}\eta_{DHT}-\rho_{HN}\eta_{DHN}}{\phi\eta_{SH}+(1-\phi)\eta_{SF}-\rho_{FT}\eta_{DFT}-\rho_{FN}\eta_{DFN}-\rho_{HN}\eta_{DHN}}\right)}
\end{aligned} \tag{A2-8}$$

Define $A=\sqrt{D}$, then we obtain:

$$\frac{A}{C_w}=\left(\begin{aligned}
&\rho_{HT}^2\left(1+\frac{2\gamma\eta_{DHT}-\rho_{HT}\eta_{DHT}}{\phi\eta_{SH}+(1-\phi)\eta_{SF}-\rho_{FT}\eta_{DFT}-\rho_{FN}\eta_{DFN}-\rho_{HN}\eta_{DHN}}\right)^2\\
&-4\gamma\rho_{HT}\eta_{DHT}\left(\frac{\phi\eta_{SH}+(1-\phi)\eta_{SF}-\rho_{FT}\eta_{DFT}-\rho_{FN}\eta_{DFN}-\rho_{HT}\eta_{DHT}-\rho_{HN}\eta_{DHN}}{\phi\eta_{SH}+(1-\phi)\eta_{SF}-\rho_{FT}\eta_{DFT}-\rho_{FN}\eta_{DFN}-\rho_{HN}\eta_{DHN}}\right)\\
&\times\left(1-\psi+\frac{\rho_{HT}-\gamma}{\phi\eta_{SH}+(1-\phi)\eta_{SF}-\rho_{FT}\eta_{DFT}-\rho_{FN}\eta_{DFN}-\rho_{HN}\eta_{DHN}}\right)
\end{aligned}\right)^{\frac{1}{2}}$$

where C_w is the world consumption of oil prior to the policy.

$$dP_F = \frac{-b+\sqrt{D}}{2a} = \frac{-\frac{b}{C_w}+\frac{A}{C_w}}{2\frac{a}{C_w}}$$

After some algebra we obtain:

$$dP_F = \frac{\frac{A}{C_w} - \rho_{HT} - \frac{2\eta_{DHT}\rho_{HT}\gamma - \eta_{DHT}\rho_{HT}^2}{\phi\eta_{SH} + (1-\phi)\eta_{SF} - \rho_{FT}\eta_{DFT} - \rho_{FN}\eta_{DFN} - \rho_{HN}\eta_{DHN}}}{2\rho_{HT}\eta_{DHT}\left(\frac{\phi\eta_{SH} + (1-\phi)\eta_{SF} - \rho_{FT}\eta_{DFT} - \rho_{FN}\eta_{DFN} - \rho_{HT}\eta_{DHT} - \rho_{HN}\eta_{DHN}}{\phi\eta_{SH} + (1-\phi)\eta_{SF} - \rho_{FT}\eta_{DFT} - \rho_{FN}\eta_{DFN} - \rho_{HN}\eta_{DHN}}\right)} P_{O0} \quad \text{(A2-9)}$$

Substitute (A2-9) into (A2-5) to get:

$$dP_O = \left(\frac{\frac{A}{C_w} - \rho_{HT} - \frac{2\eta_{DHT}\rho_{HT}\gamma - \eta_{DHT}\rho_{HT}^2}{\phi\eta_{SH} + (1-\phi)\eta_{SF} - \rho_{FT}\eta_{DFT} - \rho_{FN}\eta_{DFN} - \rho_{HN}\eta_{DHN}}}{2\left(\phi\eta_{SH} + (1-\phi)\eta_{SF} - \rho_{FT}\eta_{DFT} - \rho_{FN}\eta_{DFN} - \rho_{HT}\eta_{DHT} - \rho_{HN}\eta_{DHN}\right)} - \frac{\gamma}{\phi\eta_{SH} + (1-\phi)\eta_{SF} - \rho_{FT}\eta_{DFT} - \rho_{FN}\eta_{DFN} - \rho_{HN}\eta_{DHN}} \right) P_{O0} \quad \text{(A2-10)}$$

Finally, define

$$B = \frac{A}{C_w}$$

to obtain the formula for market leakage with a consumption mandate:

$$L_{market}^M = \frac{\Delta C_F}{E} = \left(\frac{\left(\phi\eta_{SH} + (1-\phi)\eta_{SF}\right)\left(B + \frac{\rho_{HT}^2\eta_{DHT} - 2\rho_{HT}\gamma\eta_{DHT}}{\phi\eta_{SH} + (1-\phi)\eta_{SF} - \rho_{FT}\eta_{DFT} - \rho_{FN}\eta_{DFN} - \rho_{HN}\eta_{DHN}} - \rho_{HT}\right)}{2\gamma\left(\phi\eta_{SH} + (1-\phi)\eta_{SF} - \rho_{FT}\eta_{DFT} - \rho_{FN}\eta_{DFN} - \rho_{HT}\eta_{DHT} - \rho_{HN}\eta_{DHN}\right)} - \frac{\rho_{HN}\eta_{DHN} + \rho_{FT}\eta_{DFT} + \rho_{FN}\eta_{DFN}}{\phi\eta_{SH} + (1-\phi)\eta_{SF} - \rho_{FT}\eta_{DFT} - \rho_{FN}\eta_{DFN} - \rho_{HN}\eta_{DHN}} \right)$$

with

$$B = \left(\rho_{HT}^2\left(1 + \frac{2\gamma\eta_{DHT} - \rho_{HT}\eta_{DHT}}{\phi\eta_{SH} + (1-\phi)\eta_{SF} - \rho_{FT}\eta_{DFT} - \rho_{FN}\eta_{DFN} - \rho_{HN}\eta_{DHN}}\right)^2 - 4\gamma\rho_{HT}\eta_{DHT}\left(\frac{\phi\eta_{SH} + (1-\phi)\eta_{SF} - \rho_{FT}\eta_{DFT} - \rho_{FN}\eta_{DFN} - \rho_{HT}\eta_{DHT} - \rho_{HN}\eta_{DHN}}{\phi\eta_{SH} + (1-\phi)\eta_{SF} - \rho_{FT}\eta_{DFT} - \rho_{FN}\eta_{DFN} - \rho_{HN}\eta_{DHN}}\right) \times \left(1 - \psi + \frac{\rho_{HT} - \gamma}{\phi\eta_{SH} + (1-\phi)\eta_{SF} - \rho_{FT}\eta_{DFT} - \rho_{FN}\eta_{DFN} - \rho_{HN}\eta_{DHN}}\right) \right)^{\frac{1}{2}}$$

Appendix 3: Elasticity of excess supply and demand curves

At price p the Foreign country will export:

$$X(p) = Q_F(p) - C_{FT}(p) - C_{FN}(p) \qquad \text{(A3-1)}$$

Differentiating both sides with respect to price and manipulating yields:

$$\frac{dX(p)}{dp} = \frac{dQ_F(p)}{dp} - \frac{dC_{FT}(p)}{dp} - \frac{dC_{FN}(p)}{dp}$$

$$\frac{dX(p)}{dp}\frac{p}{X(p)}\frac{X(p)}{p} = \frac{dQ_F(p)}{dp}\frac{p}{Q_F(p)}\frac{Q_F(p)}{p} - \frac{dC_{FT}(p)}{dp}\frac{p}{C_{FT}(p)}\frac{C_{FT}(p)}{p}$$

$$-\frac{dC_{FN}(p)}{dp}\frac{p}{C_{FN}(p)}\frac{C_{FN}(p)}{p}$$

$$\eta_{ES} = \eta_{SF}\frac{Q_F}{X} - \eta_{DFT}\frac{C_{FT}}{X} - \eta_{DFN}\frac{C_{FN}}{X}$$

$$\eta_{ES} = \eta_{SF}\frac{Q_F}{Q_F - C_{FT} - C_{FN}} - \eta_{DFT}\frac{C_{FT}}{Q_F - C_{FT} - C_{FN}} - \eta_{DFN}\frac{C_{FN}}{Q_F - C_{FT} - C_{FN}}$$

Now define $C_W = C_{HT} + C_{HN} + C_{FT} + C_{FN}$. Then

$$\eta_{ES} = \eta_{SF}\frac{\frac{Q_F}{C_W}}{\frac{Q_F}{C_W} - \frac{C_{FT}}{C_W} - \frac{C_{FN}}{C_W}} - \eta_{DFT}\frac{\frac{C_{FT}}{C_W}}{\frac{Q_F}{C_W} - \frac{C_{FT}}{C_W} - \frac{C_{FN}}{C_W}} - \eta_{DFN}\frac{\frac{C_{FN}}{C_W}}{\frac{Q_F}{C_W} - \frac{C_{FT}}{C_W} - \frac{C_{FN}}{C_W}}$$

Which can be re-written using the notation in previous appendices as

$$\eta_{ES} = \eta_{SF}\frac{1-\phi}{1-\phi-\rho_{FT}-\rho_{FN}} - \eta_{DFT}\frac{\rho_{FT}}{1-\phi-\rho_{FT}-\rho_{FN}} - \eta_{DFN}\frac{\rho_{FN}}{1-\phi-\rho_{FT}-\rho_{FN}} \qquad \text{(A3-2)}$$

Similarly, for the excess demand curve of the Home country we obtain:

$$\eta_{ED} = \eta_{DHT}\frac{\rho_{HT}}{\rho_{HT}+\rho_{HN}-\phi} + \eta_{DHN}\frac{\rho_{HN}}{\rho_{HT}+\rho_{HN}-\phi} - \eta_{SH}\frac{\phi}{\rho_{HT}+\rho_{HN}-\phi} \qquad \text{(A3-3)}$$

Appendix 4: Derivation of a general leakage formula

Denote by e_O and e_E the emissions of CO_2 per GEG of oil and ethanol, respectively. In order to compare by how much CO_2-cleaner ethanol is compared to oil, we define ξ as the relative difference between e_O and e_E:

$$\xi = \frac{e_O - e_E}{e_G} \qquad \text{(A4-1)}$$

Originally (denoted by 0) only oil is consumed. Therefore, total fuel consumption is given by the sum of oil consumption in both countries:

$$C_{O0} = C_{HO0} + C_{FO0}$$

After E GEGs of ethanol have been placed on the market (denoted by 1), world fuel consumption is given by:

$$C_{O1} = E + C_{HO1} + C_{FO1} \qquad \text{(A4-2)}$$

Leakage due to introduction of ethanol expressed in GEG is the change in world fuel consumption:

$$\Delta C_O = C_{O1} - C_{O0} = E + C_{HO1} + C_{FO1} - C_{HO0} - C_{FO0} = E + \Delta C_{HO} + \Delta C_{FO}$$

Market leakage in relative terms is given by:

$$L_{market} = \frac{\Delta C_O}{E} = \frac{E + \Delta C_{HO} + \Delta C_{FO}}{E} \qquad \text{(A4-3)}$$

The equation above can be manipulated to get the CO_2 leakage:

$$\begin{aligned} L_{CO_2} &= \frac{(1-\xi)e_O E + e_O(\Delta C_{HO} + \Delta C_{FO})}{\xi e_O E} = \frac{1-\xi}{\xi} + \frac{\Delta C_{HO} + \Delta C_{FO}}{\xi E} = \frac{1-\xi}{\xi} + \frac{\Delta C_O - E}{\xi E} \\ &= \frac{1-\xi}{\xi} + \frac{\Delta C_O}{\xi E} - \frac{E}{\xi E} = \frac{1}{\xi}\frac{\Delta C_O}{E} - 1 \end{aligned} \qquad \text{(A4-4)}$$

Thus we get:

$$L_{CO_2} = \frac{1}{\xi} L_{market} - 1 \qquad \text{(A4-5)}$$

Appendix 5: Data sources

Description	Source	Link
Oil consumption: Brazil, Canada, United States, World	Energy Information Administration (EIA)	http://tonto.eia.doe.gov/cfapps/ipdbproject/iedindex3.cfm?tid=5&pid=57&aid=1&cid=ww,BR,CA,US,&syid=2005&eyid=2009&unit=TBPD
Oil consumption: California	EIA	http://tonto.eia.doe.gov/dnav/pet/pet_crd_crpdn_adc_mbblpd_a.htm
Oil production: Brazil, Canada, United States, World	EIA	http://tonto.eia.doe.gov/cfapps/ipdbproject/iedindex3.cfm?tid=5&pid=54&aid=2&cid=ww,BR,CA,US,&syid=2005&eyid=2009&unit=TBPD
Oil production: California	EIA	http://tonto.eia.doe.gov/dnav/pet/pet_cons_refmg_d_SCA_VTR_mgalpd_a.htm
Ethanol Production: Brazil, Canada, United States	Food and Agricultural Policy Research Institute (FAPRI)	http://www.fapri.iastate.edu/tools/outlook.aspx
Ethanol Production: California	Los Angeles Times	http://latimesblogs.latimes.com/greenspace/2008/10/california-etha.html
Ethanol Production: World	EIA	http://tonto.eia.doe.gov/cfapps/ipdbproject/iedindex3.cfm?tid=79&pid=80&aid=1&cid=ww,BR,CA,US,&syid=2004&eyid=2008&unit=TBPD
Ethanol prices	Official Nebraska Government Website	http://www.neo.ne.gov/statshtml/66.html

Endnotes

[1] de Gorter (2009) is probably the first to formally make the distinction between domestic and international leakage.

[2] One can implicitly assume that the "emissions reductions in Annex B countries" as referred to in the IPCC definition of leakage are the final reductions after domestic leakage has been accounted for.

[3] The Intergovernmental Panel on Climate Change.

[4] It is to be noted that these expressions are only local approximations as demand and supply elasticities typically vary along the curves. However, for small enough price changes of oil due to biofuels production (which happen in reality), these approximations are sufficient.

[5] The United States imported about 57% of the petroleum that was consumed domestically during 2008. (http://www.eia.doe.gov/energy_in_brief/foreign_oil_dependence.cfm). For the 45 percent share of transportation in total U.S. oil consumption see http://www.eia.doe.gov/pub/oil_gas/petroleum/analysis_publications/oil_market_basics/demand_text.htm.

[6] This represents the case of the U.S. which is the world's largest ethanol producer, is an importer of oil and has an ethanol consumption mandate.

[7] This can be easily shown for the autarky case. For leakage with a consumption mandate to be smaller than with a tax credit, it must be the case that:

$$\frac{\eta_S}{2(\eta_S-\eta_D)}\left(\left(\left(\frac{1}{\gamma}-\frac{\eta_D-2\gamma\eta_D}{\gamma\eta_S}\right)^2-4\left(\frac{1}{\gamma}\eta_D-\frac{\eta_D^2}{\gamma\eta_S}\right)\left(1-\psi+\frac{1-\gamma}{\eta_S}\right)\right)^{\frac{1}{2}}+\frac{\eta_D-2\gamma\eta_D}{\gamma\eta_S}-\frac{1}{\gamma}\right)<\frac{\eta_D}{\eta_D-\eta_S}$$

where the left-hand side is the expression (8) and the right-hand side the expression (1). This is satisfied whenever:

$$\psi > 1-\frac{\gamma}{\eta_S-\eta_D}$$

Note that the right-hand side of the last expression is never bigger than one which means that if the ratio of ethanol and gasoline price is at least one the condition is satisfied. But with a binding consumption mandate it must always be the case and therefore we conclude that leakage with a consumption mandate is always smaller than with a blender's tax credit for the same quantity of ethanol.

[8] Denote by ρ the share of total oil consumption in the Home country in world oil consumption. Then we have $\rho_{FT}+\rho_{FN}=1-\rho$. Substituting this into condition b.), we obtain $\rho=\phi$. For this to happen, oil consumption in the Home country must equal oil production and so trade is effectively zero. Note, however, that this does not imply autarky.

[9] It can be shown that condition e.) is equivalent to condition b.).

[10] Gasoline-equivalent gallon (GEG) is the amount of alternative fuel it takes to equal the energy content of one liquid gallon of gasoline. One barrel of oil contains 5.8 million BTU of energy (http://bioenergy.ornl.gov/papers/misc/energy_conv.html). There are 42 gallons to a barrel yielding approximately 138,095 BTU per gallon of oil. One gallon of gasoline is equivalent to 115,000 BTU. This means 0.833 gallons of oil have the same energy content as one gallon of gasoline. Similarly, 1.429 gallons of ethanol are equivalent to 1 gallon of gasoline in terms of energy. To convert oil and ethanol into gasoline equivalent we thus multiply oil quantity by 1.20 (=1/0.833) and ethanol quantity by 0.70 (=1/1.429).