

THREE ESSAYS ON WELFARE EFFECTS OF GOVERNMENT INTERVENTION

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Reducing greenhouse gas (GHG) emissions is critical to mitigating climate change and achieving greater energy security. The desire to understand what governmental tools and how to apply to protect the local and global environment effectively and efficiently is a core driver for researches in the subfield of environmental economics. Despite the progress made in the modeling of social welfare with environmental externalities, many questions regarding second-best biofuel policies, interaction between biofuel policies and finance system, and connection between trade and the environment remain unanswered.

To date, the indirect, general effects of biofuel policies on the general economy, through “fiscal interaction effects” have largely been ignored. The thesis designs a general equilibrium model to investigate the fiscal interaction effects of tax credit policy. The marginal costs caused by tax credit are higher than the marginal benefits. In the second-best setting with pre-existing fuel tax and labor tax, tax credit is welfare reducing. The optimal second-best tax credit is estimated at the level of \$0.22/GEEG (\$0.15/gallon), which is 67% lower than the current tax exemption. Monte Carlo analysis shows that the probability of tax credit at \$0.22/GEEG or less is 29% and at the current level or less is 72%.

Next the thesis analyzes the effects of the quantitative ethanol mandate from both positive and welfare perspectives. Given the pre-existing government distortions, ethanol mandate is welfare enhancing. In the presence of fuel tax and labor tax, the net welfare gain caused by the ethanol mandate is estimated to be 8.61 billion dollars while the net welfare loss caused by tax credit is estimated to 26.87 billion dollars. Consistent with previous studies, the results show that the ethanol mandate dominates tax credit.

Last, the thesis analyzes the effects of an *ad valorem* tariff on the local and global environment and total social welfare using a modified Bertrand duopoly model with environmentally differentiated products. The results show that tariff imposed by the developed country improves the local and global environment while reducing the social welfare. If the developed country has a high environmental standard, the country should restrict its imports of the dirty products. If the less developed country restricts the imports of clean products from the developed country, its social welfare and the local and global environment will get worse compared to a free trade case.

BIOGRAPHICAL SKETCH

Qinwen Tan, raised in Hunan, China, graduated in 2005 from Renmin University of China in Environmental Studies. She proceeded to her Master's degree in Economics, in order to combine her study of Environmental Science and Ecology with Economics and Social Sciences. In the fall of 2007, Qinwen started her Ph.D. program at Cornell University with an almost perfect GRE. During her five years of studying Applied Economics and Management, she has received fellowships four times, teaching assistantships five times and research assistantship two times. In August 2012, Qinwen will earn a Doctor of Philosophy in Economics degree from Cornell University.

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CHAPTER 1

OVERVIEW

This chapter describes the motivating forces behind the three studies that make up this thesis and offers an overview of the methodologies, findings and conclusions.

1.1 INTRODUCTION

Reducing greenhouse gas (GHG) emissions is critical to mitigating climate change and achieving greater energy security. The desire to understand what governmental tools to use and how to apply them effectively and efficiently in order to protect and improve the environment without compromising the function of economic system is a core driver of environmental economics researches. Despite the progress made in the modeling and analyzing of social welfare considering environmental externalities, many questions regarding second-best biofuel policies, interaction between biofuel policies with the finance system, and the real connection between trade and the environment remain unanswered.

This thesis tackles three major questions. First, how to design and apply biofuel policies for policymakers? Because when tax credit implemented with a blend mandate, the tax credit actually subsidizes gasoline consumption (De Gorter and Just, 2008), instead of ethanol consumption. In my first study, I focus on analyzing the second-best tax credit policy. The second-best mandate policy is investigated in the second study and the ranking between the two policies is made as a strong policy implication. The second research question is how the biofuel policies affect the environment, finance system and the total social welfare? Using a general equilibrium model, I investigate the welfare effects of tax credit and ethanol mandate policies given the pre-existing fuel tax and labor tax in the first and second study. The third question asks, in the asymmetric global economy how to apply trade policies to better the local and global

environment? To address this question the third study designs and analyzes a modified Bertrand duopoly model with environmentally differentiated products. In the Bertrand-Nash equilibrium, the effects of an ad valorem tariff on the local and global environment and on the total social welfare are analyzed.

A number of important results arise from this research. Those with the broadest implications can be summarized as follows. First, in the second-best setting tax credit policy is welfare reducing. In the methodology of fiscal policy interaction, the positive effects come in the form of Pigovian welfare gain, subsidy-interaction effect in ethanol market and tax-interaction effect in labor market. The negative effects are associated with the primary economic cost and subsidy-interaction effect in gasoline market. My estimates of the welfare effects show that the negative effects are significantly higher than the positive effects. Second, the estimate of the second-best tax credit is \$0.22/GEEG (\$0.15/gallon), which is 67% lower than the current tax exemption of \$0.475/GEEG (\$0.45/gallon). The results is consistent with the previous studies that there exists “water” in the tax credit and a significant part of the policy is redundant (De Gorter and Just, 2010). Third, I find that given the pre-existing government distortions, the ethanol mandate is welfare enhancing. In the presence of fuel tax and labor tax, the net welfare gain caused by the ethanol mandate is estimated to be \$8.61 billion while the net welfare loss caused by tax credit in the same second-best setting is \$26.87 billion. Consistent with previous studies, the estimates show that the ethanol mandate dominates the tax credit. Fourth, in a modified Bertrand-Nash equilibrium, tariff imposed by the developed country improves the local and global environment while reducing the social welfare and tariff imposed by the less developed country worsens the local and global environment and the total social welfare.

In sum, the hope is that this thesis offers a useful contribution to the fields of environmental economics and international trade. Findings are clear and well-defined and open up a number of potential avenues for future research.

This chapter is organized as follows. Section 1.2 introduces the first study on second-best tax credit policy. Section 1.3 previews the welfare study on second-best mandate policy and

ranks the two biofuel policies and Section 1.4 introduces a modified Bertrand duopoly model on analyzing the effects of trade policy on environment and social welfare.

1.2 SECOND-BEST TAX CREDIT

This section introduces the research presented in the second chapter on second-best tax credit policy. Tax credit policy encourages the production and sale of biofuels in the United States. Due to the government support, U.S. has witnessed a rapid growth in ethanol production in the past few years. However, there exists “water” in the subsidy due to the intercept of the ethanol supply curve above the market price of ethanol historically. Because a significant part of the tax credit is redundant, it generates a rectangular deadweight cost, as part of the tax cost of the tax credit, which is not transferrable to any interest group (De Gorter and Just, 2010). A tax credit by itself subsidizes ethanol consumption, but when implemented with a blend mandate, the tax credit actually subsidizes gasoline consumption (De Gorter and Just, 2008). De Gorter and Just (2009a) also develop a framework to analyze the interaction effects of a biofuel tax credit and a price-contingent farm subsidy to analyze the rectangular deadweight costs and the traditional triangular deadweights costs of farm subsidies.

To date, most studies on biofuel policies have ignored the general equilibrium effects, i.e. the impacts of tax credit policy on the general economy through what is called “fiscal interaction effects”. These fiscal interaction effects can be significant. One contribution of my first study is to analyze the interaction effects of the tax credit policy with the fiscal system, which includes tax-interaction effect, subsidy-interaction effect and revenue-recycling effect. I find that considering the fiscal interaction effects, the net welfare change caused by the tax credit policy is negative. The marginal benefits include: environmental welfare gain, subsidy-interaction effect in ethanol market and tax-interaction effect in labor market. The marginal costs include: the own effect of primary cost and subsidy-interaction effect in gasoline market. The second contribution of the paper to the literature is to derive and calibrate a second best tax credit given the pre-

existing tax policies. The second best tax credit is estimated at the level of \$0.22/GEEG (\$0.15/gallon), which is 31% lower than Vedenov's (2008) estimate of \$0.22/gallon, 87% lower than Cui's (2010) estimate of \$1.16/gallon and 67% lower than the current tax exemption of \$0.45/gallon.

The first study runs as follows. First, I construct a general equilibrium model of a closed economy with a representative consumer, four markets and a government. The four markets include ethanol market, gasoline market, corn market and labor market. The general equilibrium model covers profit maximization problems of the competitive firms in gasoline production, corn production and ethanol production, utility maximization problem for the representative consumer, revenue and expenditure balance of the government sector. Next, I analyze the marginal welfare change from the tax credit given the pre-existing government distortions. The results show that the negative marginal costs from the tax credit are higher than the positive marginal benefits, which shows that the tax credit policy is welfare reducing in the second-best setting. Last but not least, we derive the analytical formula of the second best tax credit and estimate the level of it. The second-best tax credit is estimated to be \$0.22/GEEG (\$0.15/gallon), which is 67% lower than the current tax exemption of \$0.475/GEEG (\$0.45/gallon).

1.3 SECOND-BEST MANDATE

This section introduces the second study in this thesis. The second study is an analysis of “quantitative” ethanol mandate from both a positive perspective and a welfare perspective.

In this study, I construct a general equilibrium model of a closed economy and investigate the fiscal interaction effects of “quantitative” ethanol mandate policy given the presence of a fuel tax and labor tax. From a positive perspective, I analyze comparative static effects of fuel tax and ethanol mandate on prices and quantities. From a welfare perspective, given the pre-existing distortions the ethanol mandate is welfare enhancing. Given the current existing RFS level of 13 billion gallon, the net welfare gain caused by the ethanol mandate is

estimated to be \$8.61 billion in the second-best setting while the net welfare loss caused by the tax credit is estimated to be \$26.87 billion. Consistent with previous studies, the estimate results show that the ethanol mandate dominates the tax credit.

Some existing studies suggest that ethanol mandate has better policy achievements than tax credit. De Gorter and Just (2009b) concludes that a mandate has two advantages over a tax credit. First, a mandate doesn't involve taxpayer's costs and the marginal excess burden of taxation associated with it. Second, due to the suboptimal gasoline tax in the United States (Parry and Small 2005), the higher price of gasoline under a mandate at least partially offsets the welfare loss caused by it. If an ethanol mandate is implemented along with a tax credit, the effects of tax credit are reversed, which subsidizes fuel consumption instead of ethanol consumption. A strong policy implication from the study is that it may be more efficient to just apply one policy instrument - ethanol mandate - other than having two biofuel policies or just having tax credit policy.

Thus in the second study, I analyze the economics of a quantitative ethanol mandate and derive the policy implications of the biofuel policies (ranking with tax credit) given the pre-existing distortions. A general equilibrium model is used for both the positive and normative implications of alternative policy instruments, including fuel tax, labor tax and ethanol mandate. From a positive perspective, we replicate the results from some existing studies of the comparative static effects of fuel tax and ethanol mandate on quantities and prices. From a welfare perspective, we show that in the presence of a labor tax and fuel tax, ethanol mandate is welfare enhancing while the tax credit is welfare reducing. Using the estimates we can show that ethanol mandate dominates tax credit.

The study takes the following format. First, I present a general equilibrium model inherited and adapted from the first study, which allows me to perform the positive analysis following some existing studies and also perform welfare analysis in a second-best setting. The model is a closed economy with four commodities (corn, fuel, gasoline and ethanol) and one input (labor). I assume that ethanol, adjusted for energy content, is a perfect substitute for

gasoline. Next, the study provides the partial equilibrium effects of a policy combination of fuel tax and ethanol mandate, following some existing studies (de Gorter and Just, 2009a,b, 2010, Lapan and Moschini 2009). The results are consistent with some existing researches that a fuel tax raises the producer price of fuel and lowers the demand for gasoline and fuel and ethanol mandate raises gasoline price and fuel output in total. Walrasian stability condition supports the unambiguous comparative static effects. Then follows the effects of mandate policy on the general economy through “fiscal interaction effects”. The marginal benefits include: own effects of price difference, environmental welfare gain, subsidy-interaction effects in ethanol market. The marginal costs include: subsidy-interaction effects in gasoline market and tax-interaction effects in labor market. The net welfare change caused by the mandate policy is significantly positive. Last, I compare the estimates of net welfare change caused by either ethanol mandate or tax credit in the same second-best setting, which yields a strong policy implication that ethanol mandate dominates tax credit. The result agrees with previous studies that through the fiscal interaction effects, ethanol mandate has more advantages than tax credit in decreasing CO₂ emissions, enhancing energy security and promoting rural development.

1.4 AD VALOREM TARIFF

This section introduces the third study in the thesis, which uses a modified Bertrand duopoly model of environmentally differentiated products to analyze the effects of an ad valorem tariff on the unit emission levels of production, local and global environment and the total social welfare.

The issue of trade and the environment has appeared in most trade negotiations including WTO. Environmentalists have considered that international trade is a threat to adequate environmental regulation, which has become clear in the discussions surrounding moves towards free trade, like NAFTA. As P.W. Kennedy points out, it has been argued that “freer trade will lead governments to relax their environmental standards in order to gain a competitive edge over

their trading partners’’. In response to the environmentalist, economists generally believe that international trade may be good for the environment (Antweiler et al. 2001; Copeland and Taylor, 2004). At least there is no evidence has proved that trade has detrimental effect on the environment as claimed by “race to bottom” theory (Frankel and Rose, 2001). What’s more, the increased income from trade liberation will generate increased demand for improved environmental quality (Copeland and Taylor, 2004). All in all, there are many puzzles remain unanswered to reveal the real connection between trade and environment.

To analyze the effects of an ad valorem tariff on environment and social welfare for both a developed country and a less developed country, I present a modified Bertrand model of products with environmental characteristics and heterogeneous consumers with various environmental consciousnesses in the green market. Different from previous studies that environmental effluents are produced from manufacturing processes, I consider the environmental effluents are produced through the consumption choice made by the heterogeneous consumers, which are influenced by the trade policies adopted by the importing countries.

The third study is structured as follows. Given the complexity of the connection between trade and the environment, the study starts off reviewing the literature. Next the theoretical model of a modified Bertrand duopoly with heterogeneous consumers and environmentally differentiated products is presented. The model has following features: (1) the environmental effluents created through consumption choices; (2) a continuum of heterogeneous consumers with various preferences for environmental quality; (3) firms choosing the environmental quality level of their products; (4) a clean (dirty) firm producing a clean (dirty) product located in a developed (less developed) country. Then I analyze the effects of an ad valorem tariff imposed by the developed (the less developed country) on the local and global environment and on its social welfare in the imperfect global competition. Our major findings include: in the Bertrand-Nash equilibrium (1) if the developed country has a high environment consciousness, it should restrict imports of the dirty product produced in a dirty firm from the less developed country; (2)

for the less developed country, it should choose a free trade policy for the clean product produced in a clean firm from the developed country.

CHAPTER 2

SECOND-BEST TAX CREDIT

In this chapter, a general equilibrium model of a closed economy is designed to investigate the fiscal interaction effects of the tax credit policy and to derive a second best tax credit given the presence of a fuel tax and a labor tax. Considering the fiscal interaction effects, the tax credit is welfare reducing in the second-best setting. The optimal second-best tax credit is estimated to be \$0.22/GEEG (\$0.15/gallon), which is 67% lower than the current tax exemption of \$0.475/GEEG (\$0.45/gallon). Monte Carlo analysis shows that the probability of tax credit at \$0.22/GEEG or less is 29% and at the current level of \$0.475/GEEG (\$0.45/gallon) or less is 72%.

2.1 INTRODUCTION

In the pursuit of national energy, environmental, and agricultural policy goals, the federal government supports the use of biofuels, produced mainly from renewable plant matter, such as corn. The policy of tax credit encourages the production and sale of biofuels in the United States, effectively lowering the private costs of producing biofuels, such as ethanol or biodiesel, relative to the costs of producing their substitutes—gasoline and diesel fuel. Due to the government support, U.S. has witnessed a rapid growth in ethanol production in the past few years. As the largest world producer of ethanol, U.S. fuel ethanol production has skyrocketed, going from 1.65 billion gallons in 2000 to 10.76 billion gallons in 2009 (RFA 2010). U.S. ethanol production currently benefits from a \$0.45/gallon subsidy as an excise tax credit, a 2.5% out-of-quota ad valorem import tariff and an ethanol import tax of \$0.54/gallon. In addition, the Energy Policy Act of 2005 specified a mandate of specific targets for renewable fuel use, the level of which has been considerably expanded by the Renewable Fuel Standard (RFS2) of the Energy Independence and Security Act of 2007. In 2009, the ethanol production of 10.76 billion gallons exceeds the mandate level by 0.26 billion gallons.

The tax credit provides an incentive for refiners and blenders to bid up the price of ethanol above that of gasoline by the amount of the tax credit. However, there exists “water” in the tax credit due to the fact that the intercept of the ethanol supply curve is above the market price of ethanol historically. Because a significant part of the tax credit is redundant, it generates a rectangular deadweight cost, as part of the tax cost of the tax credit, which is not transferrable to any interest group (de Gorter and Just, 2010). A tax credit by itself subsidizes ethanol consumption, but when implemented with a blend mandate, the tax credit actually subsidizes gasoline consumption (de Gorter and Just, 2008). De Gorter and Just (2009a) also develop a framework to analyze the interaction effects of a biofuel tax credit and a price-contingent farm subsidy to analyze the rectangular deadweight costs and the traditional triangular deadweight costs of farm subsidies.

The removal of the tax credit lowers the ethanol production by 3.75 billion gallon or 30 percent from the baseline forecast and wholesale ethanol prices by \$0.29 per gallon or 17.8 percent from the baseline forecast. Because of the declined ethanol production, the implied retail price of ethanol increases by 12.5 percent (Kruse etc, 2007). The direct effect of cutting government subsidy to ethanol is to lower the government costs. Removing the tax credit saves the taxpayers \$6.5 billion on average (Kruse etc, 2007). FAPRI-UMC Report #17-07 presents the impacts of the cutting of biofuel’s tax credits and the import tariff from 2011 to 2016 period.

The removal of the trade barriers and the federal tax credit for the refiners that blend ethanol with gasoline increases the world ethanol price by 16.51%. Along with a higher world price, the domestic demand for ethanol increases, therefore U.S. net import increases by 136.97%, based on the calibration of 2005 market data and policies (Elobeid and Tokgoz, 2006a). Elobeid and Tokgoz (2008) estimates that the removal of the tax credit and trade distortions will lower the U.S. ethanol consumption by 2.1% and the price of ethanol by 18.4%.

By allowing the endogeneity of world oil and corn prices, the first best policy would include a pollution tax on carbon emissions, an import tax on oil, and an export tax on corn. If policy is constrained, a fuel tax and an ethanol subsidy can be welfare enhancing (Lapan and

Moschini, 2009). Extending the analytical setup of Lapan and Moschini (2009), Cui etc. (2010) establish a general equilibrium model to investigate how the ethanol policies affect the equilibrium (domestic and world) prices of corn, oil, ethanol and gasoline, analyze a number of second best interventions involving various combinations of ethanol mandates, ethanol subsidies and a fuel tax and calculate the optimal values for the second-best policies and the associated welfare gains.

What is missing in all of these analyses is the impact on the general economy through what is called “fiscal interaction effects”. For example, because of the decline in fuel prices caused by biofuel subsidy policies, the real wage increases and shifts the labor supply curve outwards. This increases the fiscal base and so too increases tax revenues, thereby improving social welfare. This is called the “tax-interaction effect.” Another example is the introduction of the tax credit offsets the impacts of the existing fuel tax and lowers the societal welfare loss caused by the fuel tax. This is called “subsidy-interaction effect”. Considering government budgeting, because of the imposition of the ethanol subsidy policies, the government need raise the tax rates in the general economy (e.g., income tax) and the whole society will be worse off. This is called “revenue-recycling effect”.

To date, studies on biofuel policies have ignored such general equilibrium effects. The impact of biofuel policies on tax costs and prices have been studied but only the direct costs and benefits; the indirect, general effects on the economy have not been studied. These fiscal interaction effects can be significant. There is an important literature in environmental economics where the effects of alternative environmental policy instruments can be heavily dependent on their impact on government budget revenues (revenue-recycling) and on the size of the tax base (tax-interaction) (Goulder, Parry and Burtraw 1997; Goulder et al. 1999). So too the possible rankings of a biofuel mandate versus a tax credit can be reversed if fiscal interaction effects are taken into account.

While ignoring fiscal interaction effects, the literature to date has come to several important conclusions regarding the optimal mix of tax credits, mandates, tariffs and fuel taxes.

But one overall conclusion has been that the mandate dominates when there is a suboptimal fuel tax (de Gorter and Just 2010; 2009b; and Lapan and Moschini 2009). The benefits come in the form of reduction in greenhouse gas emissions, externalities associated with miles traveled (local air pollution, traffic congestion and traffic related accidents), and oil dependency. On the other hand, a suboptimal fuel tax makes an ethanol tax credit even more distortionary because the tax credit lowers the fuel price that is already lower than the optimal level because of the suboptimal fuel tax.

But considering the fiscal interaction effects, the impacts of a tax credit and/or a mandate is expected to differ, depending on the scenario. For instance, tax credits and mandates have unique features in terms of revenue-recycling effects. Each will have consequences for tax cost of farm subsidy programs. Even though a mandate does not involve taxpayer expenditures (unlike a tax credit), in theory a mandate can still result in a lower net government budget revenue because of the reduced tax revenues due to the reduced fuel consumption. The final effects will depend on several market parameters, including the level of the fuel tax, the production level of ethanol and gasoline, the desired level of carbon dioxide emission, etc.

In addition to analyzing the interaction effects of the tax credit policy with the fiscal system, another contribution of the paper to the literature is to derive and calibrate a second best tax credit given the pre-existing tax policies. In this paper, we construct a general equilibrium model covering both production sector and consumption sector for ethanol, investigate the fiscal interaction effects of the tax credit policy, and derive a second best tax credit given the presence of a fuel tax and a labor tax. We find that considering the fiscal interaction effects, the net welfare change caused by the tax credit policy is negative. The marginal benefits include: environmental welfare gain, subsidy-interaction effect in ethanol market and tax-interaction effect in labor market. The marginal costs include: the own effect of primary cost and subsidy-interaction effect in gasoline market. We also find that the second best tax credit is estimated at the level of \$0.22/GEEG (\$0.15/gallon), which is 31% lower than Vedenov's (2008) estimate of

\$0.22/gallon, 87% lower than Cui's (2010) estimate of \$1.16/gallon and 67% lower than the current tax exemption of \$0.45/gallon.

2.2 THE ANALYTICAL MODEL

The section develops a general equilibrium model of a closed economy with a representative consumer, four markets and a government. The four markets include ethanol market, gasoline market, corn market and labor market. The general equilibrium model covers profit maximization problems of the competitive firms in gasoline production, corn production and ethanol production, utility maximization problem for the representative consumer, revenue and expenditure balance of the government sector.

Gasoline market: Gasoline production displays constant returns to scale in labor. Labor, as the only input for gasoline production, is normalized to be numeraire. The gasoline production function is

$$(2.1) \quad q_g = \theta_g L_g,$$

where q_g is gasoline output, θ_g is technology parameter of converting labor into gasoline, L_g is labor input for gasoline production. First order condition of profit maximization problem in gasoline production yields the gasoline price:

$$(2.2) \quad P_g = 1/\theta_g,$$

where P_g is the gasoline price and $(1/\theta_g)$ is the marginal cost for gasoline production. Thus the gasoline price is constant and economic profit in gasoline production is zero.

Corn market: Corn production displays constant returns to scale in labor. The corn production function is

$$(2.3) \quad q_c = \theta_c L_c,$$

where q_c is corn output, θ_c is technology parameter of converting labor into corn, L_c is labor input for corn production. First order condition of profit maximization problem in corn production yields the corn price:

$$(2.4) \quad P_c = 1/\theta_c,$$

where P_c is the corn price and $(1/\theta_c)$ is the marginal cost for corn production. Thus the corn price is constant and economic profit in corn production is zero.

Ethanol market: Following de Gorter and Just (2007), we assume that ethanol and gasoline are perfect substitutes in consumption. Ethanol production has a fixed-proportion technology,

$$(2.5) \quad q = \min(\lambda_c c, \lambda_L L_e)$$

where q is ethanol output, c and L_e are the inputs of corn and labor respectively, λ_c and λ_L are technologically determined constants.

The profit maximization problem for ethanol production is posed as:

$$\text{Max } \pi = p_e q - p_c c - L_e$$

subject to the production constraint and price constraints,

$$q = \min(\lambda_c c, \lambda_L L_e),$$

$$p_c = 1/\theta_c,$$

$$\text{and } p_e = \bar{p}_g = 1/\theta_g.$$

The first order condition of the profit maximization yields the relationship between the ethanol price and marginal cost, which is also equal to the fixed gasoline price due to the perfect substitution assumption, that is

$$(2.6) \quad p_e = \frac{1}{\theta_c \lambda_c} + \frac{1}{\lambda_L} \equiv 1/\theta_g$$

Representative consumer: We consider a representative consumer in the economy. The consumer derives utility from the consumptions of goods and leisure and disutility from greenhouse gas pollution caused by burning gasoline. The utility function of the representative consumer is given as:

$$(2.7) \quad U = u(\tau(q_c, q_e + q_g), l) - \varphi(P(.)),$$

where q_c , $q_e + q_g$ and l represent the domestic consumption of corn, fuel (ethanol and gasoline) and leisure respectively and P represents the perceived greenhouse gas pollution due to fuel combustion. The gasoline consumption uses the same denotation as the gasoline output q_g due to the fact that gasoline production displays constant returns to scale and gasoline supply is determined by gasoline demand. The functions $u(\cdot)$ and $\tau(\cdot)$ are quasi-concave reflecting the utility of goods and leisure consumption respectively, whereas the function $\varphi(P(\cdot))$ is quasi-convex reflecting the disutility caused by greenhouse gas pollution.

The perceived greenhouse gas pollution P is the summation of the greenhouse pollution caused by burning gasoline and by burning ethanol:

$$(2.8) \quad P = \epsilon_g q_g + \epsilon_e q_e,$$

where ϵ_g is the CO2 emission rate of gasoline and ϵ_e is the CO2 emission rate of ethanol.

The representative consumer is subject to the time constraint on labor and leisure:

$$(2.9) \quad l + L = \bar{L},$$

where L is total labor and \bar{L} is the time endowment.

The representative consumer consumes corn, ethanol and gasoline, supplies labor and receives a governmental lump-sum transfer and economic profits from ethanol production. The budget constraint is set as:

$$(2.10) \quad p_c q_c + (p_e' + t)q_e + (p_g + t)q_g = (1 - t_L)L + G + \pi,$$

where p_c , p_e' and p_g represent the price received by the consumer for corn, ethanol and gasoline respectively, q_c , q_e and q_g represent the demand for corn, ethanol and gasoline respectively, t is the consumer fuel tax on ethanol and gasoline, t_L is the flat tax rate on labor, G is the lump-sum transfer from government and π is economic profits from ethanol production. The economic profits, π , can be derived from the profit maximization problem in ethanol production by substituting the optimal ethanol production, q^* , into the profits function,

$$(2.11) \quad \pi = p_e q^* - (1/\theta_c * q_c + L_e).$$

As we assumed that ethanol is a perfect substitute for gasoline and gasoline price is a constant, the consumer price for ethanol is equal to the invariable gasoline price in market equilibrium, i.e., $p_e' = \bar{p}_g = 1/\theta_g$, and the producer price for ethanol is equal to the invariable gasoline price plus the tax credit wedge, i.e., $p_e = \bar{p}_g + t_c = 1/\theta_g + t_c$.

Thus, the consumer's utility maximization problem is posed as:

$$Max U = u(\tau(q_c, q_e + q_g), l) - \varphi(P),$$

subject to the constraints,

$$l + L = \bar{L},$$

$$p_c q_c + (p_e' + t)q_e + (p_g + t)q_g = (1 - t_L)L + G + \pi,$$

$$p_c = 1/\theta_c,$$

$$p_e' = \bar{p}_g = 1/\theta_g.$$

Because we assume that ethanol and gasoline are perfect substitutes and gasoline price are invariant to ethanol production, though the tax credit is an ethanol consumption subsidy, the incidence of the subsidy is such that ethanol producers get the full benefit. We denote the consumption fuel tax by t . As consistent with the real world, it is assumed to be lower than the tax credit t_c . We denote $p_{e,ns}$ and $q_{e,ns}$ as the price and quantity of ethanol in absence of tax credit and fuel tax.

Figure 2.1, the supply and demand curve of ethanol is denoted by S^E and D^E . Following de Gorter and Just (2007), we depict the linear supply curve and linear demand curve of ethanol. The tax credit t_c shifts the demand curve outward from D^E to $D^{E'}$. The fuel tax shifts the demand curve inward from $D^{E'}$ to $D^{E''}$. Without the presence of tax credit and fuel tax, ethanol price and quantity are $p_{e,ns}$ and $q_{e,ns}$. The government tax credit creates the wedge of t_c between the producer price and consumer price. Ethanol price faced by the producer raises from $p_{e,ns}$ to p_e and the consumer's price reduces from $p_{e,ns}$ to p_e' and $t_c = p_e - p_e'$. The tax credit raises the demand for ethanol from $q_{e,ns}$ to q_e'' while fuel tax offsets the influence by reducing the consumption from q_e'' to q_e' . In market equilibrium, the consumer price for ethanol $p_e' = \bar{p}_g$ and the producer price for ethanol $p_e = \bar{p}_g + t_c$.

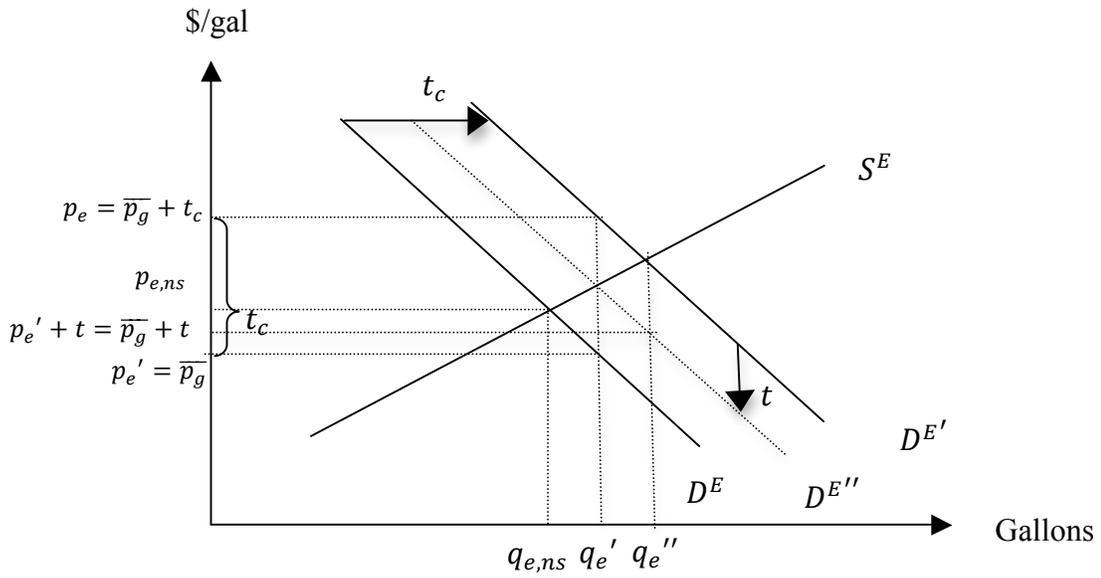


FIGURE 2.1: FIGURE OF ETHANOL MARKET

Labor market: Labor is used in gasoline production (L_g), corn production (L_c) and ethanol production (L_e). Labor supply is L , which is capped by total time endowment \bar{L} less the leisure time l . In market equilibrium, labor market clears satisfying the following condition

$$(2.12) \quad L_g + L_c + L_e = L,$$

where left hand side of the equation is the labor demand in gasoline, corn and ethanol production and right hand side is the total labor supply.

Incorporating the production functions in gasoline, corn and ethanol markets, the labor market clearing condition can be rewritten as

$$(2.13) \quad q_g/\theta_g + q_c/\theta_c + \phi * q_e = L.$$

Government: The government levies a tax on labor, t_L , and a fuel tax, t , on gasoline and ethanol consumption. The tax revenues are spent on a lump-sum transfer, G , to the consumer and a tax

credit, t_c , as ethanol consumption subsidy. Thus we have a balanced government budget constraint and the revenue consequence is neutralized by varying the lump-sum transfer. The government budget constraint is written as,

$$(2.14) \quad G + t_c q_e = t_L L + t(q_e + q_g).$$

2.3 THE WELFARE EFFECTS OF TAX CREDIT POLICY

The marginal welfare change from the tax credit, t_c , is consisting of six components. The marginal welfare effects of the tax credit is solved as in equation (2.25) (see the detailed calculations in Appendix A):

$$(2.15) \quad \underbrace{\frac{1}{\lambda} \frac{dV}{dt_c}}_{\text{Welfare effects of tax credit}} = \underbrace{\frac{\phi'}{\lambda} \frac{dP}{dt_c}}_{\text{Environmental welfare gain}} \underbrace{- t_c \frac{dq_e}{dt_c}}_{\text{Own effects of primary cost}} + \underbrace{t \frac{dq_e}{dt_c}}_{\text{Subsidy-interaction effect in ethanol market}} + \underbrace{t \frac{dq_g}{dt_c}}_{\text{Subsidy-interaction effect in gasoline market}} + \underbrace{t_L \frac{dL}{dt_c}}_{\text{Tax-interaction effect}}$$

(i) Pigouvian welfare gain. The first term in equation (2.15), $-\frac{\phi'}{\lambda} \frac{dP}{dt_c}$, reflects the rectangle environmental welfare gain. The application of a tax credit acting as an ethanol consumption subsidy, t_c , encourages the consumption of ethanol and helps control pollution caused by greenhouse gas emission, which creates a rectangle welfare gain because of the reduced environmental damages. However, the tax credit incurs a triangle primary economic cost, $-t_c \frac{dq_e}{dt_c}$. The Pigouvian welfare gain is the environmental benefits less the primary cost.

In Figure 2.2, we depict the pollution market. The curves of S^P and $S^{P'}$ are the supply curves for pollution before and after the imposition of the tax credit, which reflects the change of carbon dioxide emissions and the consumer's consumption habit for fuel. The curve of D^P is the demand curve for pollution.

Imposing the tax credit reduces pollution supply from P to P' and associated gasoline consumption from q_g to q_g' . The social costs (the price) of the pollution is reduced from C to C' . The tax credit reduces the environmental damages by the area of rectangle $abcd$ and causes economic costs as the primary cost of the policy by the area of triangle acd . The Pigouvian welfare gain is the environmental benefits less the primary costs, reflected by the shaded triangle abd in figure 1. It also equals to the deduction in consumer surplus by the area of trapezoid $P'Pda$ less the deduction in costs by the area of rectangle $P'Pdc$.

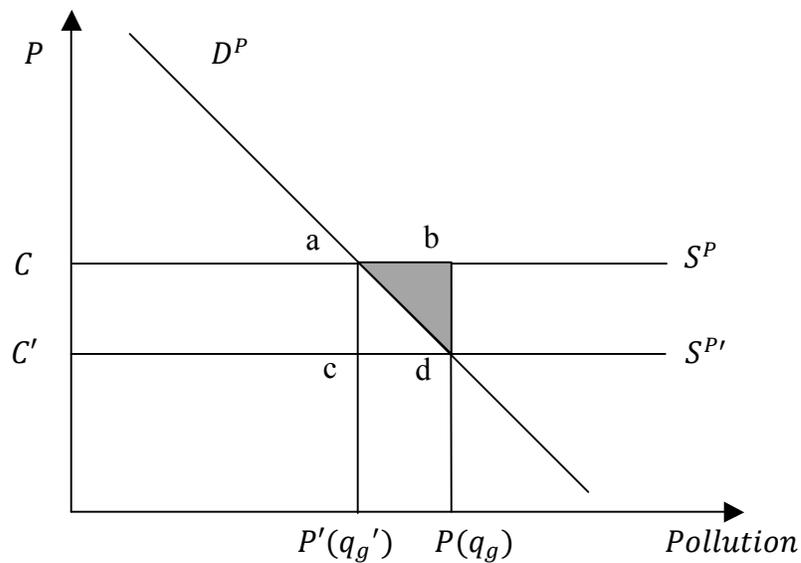


FIGURE 2.2: ENVIRONMENTAL EFFECT IN POLLUTION MARKET

(ii) Subsidy-interaction effect. Fuel tax raises the consumer price for fuel and reduces the consumption of ethanol and gasoline. Tax credit subsidizes the ethanol consumption by creating a wedge between the producer price and the consumer price of ethanol. The subsidy-interaction effect means that for each unit increase in producing ethanol, the social cost caused by the subsidy is increased and consumer benefit is increased as well due to the reduced ethanol price. The net effect is positive because the increase in the consumer benefit surpasses the increase in the social cost.

In the ethanol market, the fuel tax raises the consumer price for ethanol and shifts the demand curve from D^E to $D^{E'}$. The consumer price for ethanol before and after the imposition of the fuel tax is denoted by $p^{C(E)}$ and $p^{C(E)'}$, which is equal to \bar{p}_g and $\bar{p}_g + t$ in equilibrium. The producer price for ethanol shouldn't be affected by the imposition of the consumer fuel tax, which is denoted by $p^{S(E)}$ and equal to $\bar{p}_g + t_c$ in equilibrium. The output of ethanol reduces from q_e to $q_{e'}$. This produces a welfare gain equal to the shaded parallelogram $abcd$. That is, for each unit increase in ethanol consumption, the increase in consumer benefits by the wedge between the producer price and consumer price of the tax credit t_c exceeds the increase in social costs. The subsidy-interaction effect in ethanol market creates the net welfare gain $abcd$.

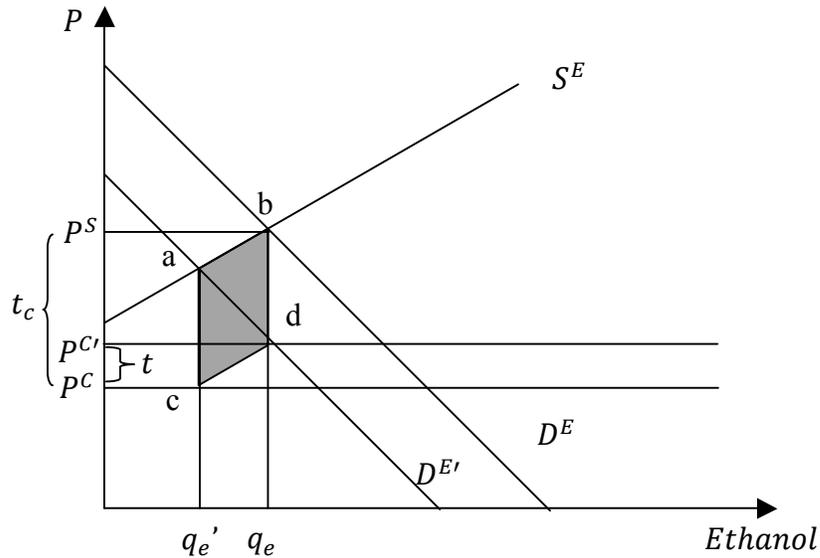


FIGURE 2.3: SUBSIDY INTERACTION EFFECT IN ETHANOL MARKET

In the gasoline market, the imposition of the fuel tax and tax credit moves the demand curve for gasoline inward from D^O to $D^{O'}$. Because we consider gasoline as a perfect substitute for ethanol, the imposition of tax credit will shift the demand curve inward. However, the influence of tax credit on gasoline consumption would be much more complicated if either ethanol is not considered as a perfect substitute for gasoline, or we consider the blended mandate of gasoline and ethanol, which would make it difficult to simply claim that the imposition of tax

credit would shift the gasoline demand curve inward or outward. The gasoline price is a constant number \bar{P}_g and the demand for gasoline declines from q_g to q_g' . The net welfare loss is the shaded triangle abc .

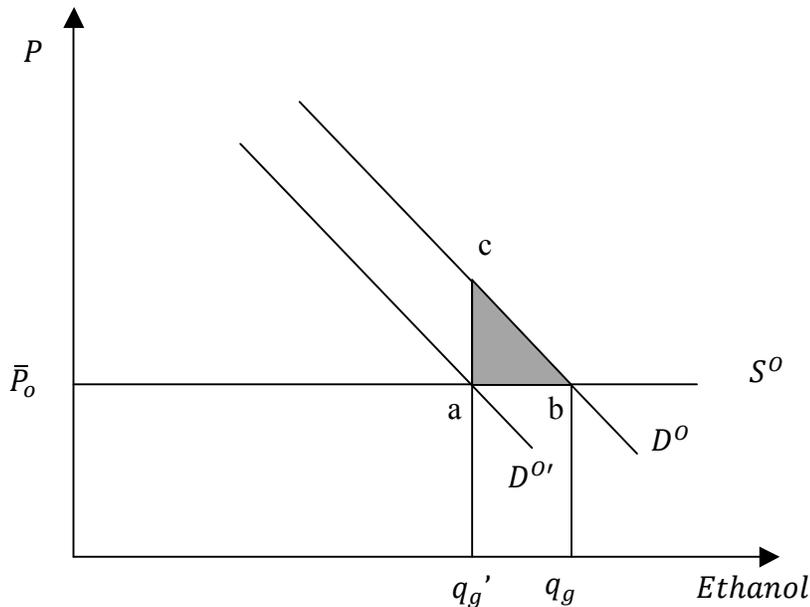


FIGURE 2.4: SUBSIDY INTERACTION EFFECT IN GASOLINE MARKET

(iii) Tax-interaction effect. Tax credit indirectly increases the return to work relative to leisure and causes the labor supply curve to shift outward. This creates a rectangle welfare gain called tax-interaction effect.

Since wage is assumed to be numeraire, net wage is $1 - t_L$ after income tax t_L . The consumption subsidy for ethanol encourages a higher consumption for a given nominal wage and increases the return to work effort relative to leisure. Thus the labor supply curve shifts outward from S^L to $S^{L'}$ and labor supply rises from L to L' . The tax-interaction effect is the welfare gain denoted by the shaded rectangle, which is the product of the wedge between the gross wage (utility) and the net wage $(1 - t_L)$ and the expansion in labor supply $(L' - L)$.

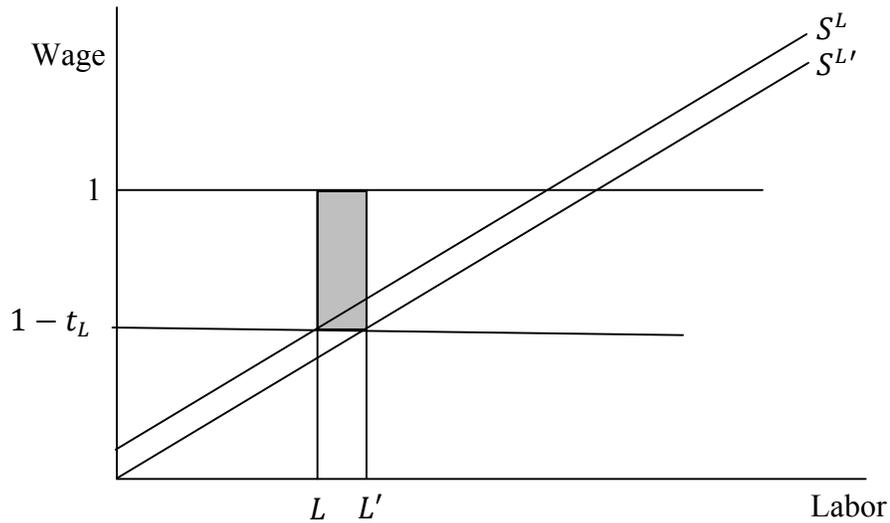


FIGURE 2.5: TAX INTERACTION EFFECT IN LABOR MARKET

(iv) Revenue-recycling effect. Considering the government spending on tax credit will drive up income tax or fuel tax instead of reducing the lump-sum transfer, it will produce two sources of welfare loss. First, this lowers the net-of-tax wage and reduces labor supply. Second, it also slightly reduces the relative subsidy for ethanol consumption and therefore induces a substitution out of ethanol consumption and into gasoline consumption.

2.4 OPTIMAL TAX CREDIT FORMULA

Setting equation (2.15) to zero, after some manipulation, the second-best tax credit is solved analytically in the presence of the existing government policies.

$$(2.16) \quad t_c^* = \frac{CP\eta_P}{q_g - q_e + q_e\eta_e}$$

where C is the social cost (price) of pollution (carbon dioxide emission), P is the amount of pollution (carbon dioxide emission), η_{Pc} is the elasticity of pollution (carbon dioxide emission)

with respect to tax credit (price elasticity of pollution) and η_{ec} is the elasticity of ethanol consumption with respect to tax credit (price elasticity of ethanol).

2.5 PARAMETER VALUES

Benchmark values and parameter ranges used for estimating the welfare effects of ethanol tax credit policy and the optimal tax credit are summarized in Table A. The values of the exogenous parameters and the values of the tax credit policy variables are based on 2009 data from various sources, including Feed Grain Database of the U.S. Department of Agriculture (USDA), U.S. Energy Information Administration (EIA), Renewable Fuels Association (RFA) and Nebraska Energy Office (NEO) websites.

Because ethanol has a lower energy content than gasoline, we convert the units of its price, quantity, subsidy and fuel tax to be expressed per GEEG. Currently, fuel (blended gasoline with ethanol) consumption is subject to the federal tax of \$0.184/gallon plus a state-level tax of \$0.203/gallon on an average level. Thus the tax on gasoline consumption is equal to $\$0.184/\text{gallon} + \$0.203/\text{gallon} = \$0.387/\text{gallon}$. However, considering the lower energy content of ethanol, the tax on ethanol consumption is converted to $\$0.387/.69 = \$0.561/\text{GEEG}$. The tax credit on ethanol of \$0.45/gallon when blended with gasoline is equivalent to a net subsidy of \$0.475/GEEG. The 2009 average rack price of ethanol is \$1.79/gallon, which corresponds to a price of $\$1.79/.69 = \$2.59/\text{GEEG}$. The price of fuel is derive from the price of ethanol plus fuel tax minus the net subsidy, $\$2.59 + \$0.387 - \$0.475 = \$2.50/\text{GEEG}$. The price of unblended gasoline is derived from the price of ethanol minus the net subsidy, $\$2.59 - \$0.475 = \$2.11/\text{GEEG}$.

In 2009, there are 1.93 billion barrels of domestic oil produced and 3.29 billion barrels imported in the U.S. The U.S. ethanol production in 2009 is 10.67 billion gallons corresponding to 7.43 billion GEEG (RFA data). For the finished motor gasoline product, the total fuel consumption in volumetric unites in 2009 is 134.4 billion gallons (EIA data). The unblended

gasoline of 123.6 billion GEEG units is derived from subtracting the ethanol production in volumetric units from the figure of the finished motor gasoline products (Cui et al.2010). Thus the final consumption in fuel, as the sum of gasoline and ethanol consumption, is 131.0 billion GEEG units.

Wang (2007) estimates the carbon emission rate of gasoline measured by carbon dioxide (CO₂), is 11.29 kg/GEEG. The carbon dioxide emission rate of ethanol has a large range due to the discrepancy in measuring feedstock sources and indirect land use. From the life cycle perspective, Farrel et al (2006) estimates the CO₂emission rate of corn ethanol of 8.42 kg/GEEG. Due to the uncertainty on the values, sensitivity analysis will be implemented to measure the environmental impacts of gasoline and ethanol.

As to the social cost of carbon dioxide emissions, Tol (2008) analyzes the 232 published estimates of the marginal damage cost of carbon dioxide and the mean of the estimates is of \$105/tC (metric ton carbon), equivalent to \$28.60/tCO₂, measured in 1995 dollars. The National Highway Traffic Safety Administration (NHTSA) proposed the corporate average fuel economy (CAFE) standard using Tol's survey (2008), which includes 125 estimates of the social carbon dioxide cost in 1995 dollars, which consists of a domestic value (\$2/tCO₂) at the lower end, a global value (\$33/tCO₂) equal to the mean value in Tol (2008), and a global value (\$80/tCO₂) on standard deviation above the aforementioned mean value. Relying on Tol's (2008) survey, the EPA (2008) reports an average value of \$40/tCO₂ with a 3% discount rate and \$68/tCO₂ with a 2% discount rate (measured in 2006 dollars).

"Stern Review" (Stern et al. 2006) applied a lower discount rate to future economic damage and derived a higher estimate of marginal cost of carbon dioxide at approximately \$80/tCO₂. Based on the Stern report with a more conventional discount rate, Hope and Newbery (2008) lowered the carbon cost to the range of \$20-\$24/tCO₂. To account for local and global carbon dioxide costs, the pollution externality cost is measured at the value of \$33/tCO₂, consistent with NHTSA (2009). The range of \$2/tCO₂ - \$100/tCO₂ is applied for sensitivity analysis. The output elasticity of pollution is estimated to be 0.008 (Kalaitzidakis et al, 2008).

The elasticity estimates are obtained from various publications as the econometric evidence. In terms of the price elasticity of demand for gasoline, Hughes et al. (2008) show that the short-run price elasticities of gasoline demand in the U.S. varied from -0.31 to -0.34 in the time period from 1975 to 1980, from -0.034 to -0.077 in the time period from 2001 to 2006, suggesting that the short-run price elasticity of gasoline demand is more inelastic in recent years. Graham and Glaister (2002) estimate the price elasticities of gasoline -0.27 and -0.23 for the short-term, and -0.71 for the long-term. In this paper, we adopted the elasticity estimates from Parry and Small (2005), where the gasoline price elasticity is equal to 0.55 with a range of -0.9 to -0.3.

In contrast, the literature on the price elasticity of ethanol demand is quite limited due to the relatively short period of ethanol availability in the market and consequent data limitations. Rask (1998) estimates the price elasticity of ethanol of -2.82 and -0.37 for two period intervals, 1984 to 1987 and 1988 to 1993. Using a data set consisting of 765 observations cross-sectioned by state from 1988 through 2002, the price elasticity of ethanol was found to be -0.81 (Rask, 2004).

Anderson (2008) shows that the gasoline-price (cross-price) elasticities of ethanol demand in the 2.5 - 3.0 range. With a spatially weighted regression technique, FPTI Research Report Number 5 estimates the gasoline-price elasticity of ethanol demand to be 4.35 for the whole period from 2003 to 2008, ranging from -0.5 to -5.0 reflecting the significant geographic variation. For the prior and post EISA periods, the price elasticity of ethanol is estimated to be 4.67 and 4.36 respectively, suggesting the relatively stable, sensitive ethanol demand-responsiveness to gasoline prices changes throughout the study period.

2.6 RESULTS

Applying the benchmark values from Table A yields the marginal welfare effects of the tax credit policy and an estimated second best tax credit t_c^* . In Table B, the negative marginal

costs caused by the tax credit is higher than the positive marginal benefits, which shows that the tax credit policy is welfare reducing in the second-best setting given the pre-existing fuel tax and labor tax. In the methodology of fiscal policy interaction, the positive effects come in the form of Pigovian welfare gain, subsidy-interaction effect in ethanol market and tax-interaction effect in labor market. The negative effects of the policy are associated with the primary economic cost and subsidy-interaction effect in gasoline market.

The second best tax credit is estimated to be \$0.22/GEEG (\$0.15/gallon), which is 67% lower than the current tax exemption of \$0.475/GEEG (\$0.45/gallon). Vedenov and Wetzstein (2006) and Cui et al (2010) estimate the optimal ethanol subsidy of \$0.22/gallon and \$1.16/gallon respectively, which is 32% and 87% higher than our estimate.

There are three major reasons to explain the smaller estimate in our paper: First, the previous publications didn't consider the presence of other existing policies. The tax credit policy is the only source of government income. The larger role of tax credit policy playing in government budgeting yields a higher estimate of the subsidy in Vedenov and Wetzstein (2006)'s and Cui et al (2010)'s. Second, considering fiscal interaction effects, I have the two additional tax distortion wedges in our study, which increases the marginal costs of the tax credit policy. Thus the estimated optimal tax credit policy is lower than previous studies. Third, I didn't consider biofuel mandate in our model, which simplify the subsidizing effect of tax credit on ethanol rather than on the blended fuel or even unblended gasoline. Because the "optimal" tax credit focus solely on subsidizing ethanol consumption, the rate of it is not "watered".

Individual parameter variation was implemented to analyze the sensitivity of the second best tax credit t_c^* to the ranges of three parameters, including the cost of carbon dioxide emission, the price elasticity of ethanol and the price elasticity of gasoline. Figure A and B indicate the tax credit is positively related to the cost of carbon dioxide emission and the price elasticity of gasoline. Figure C indicates that the tax credit is negatively related to the price elasticity of ethanol. Those figures show that the optimal tax credit is very sensitive to the

parameters values. With a narrowed range of those parameters, a more precious estimate of the tax credit can be derived.

A Monte Carlo analysis is also implemented for the sensitivity analysis. In table 2.3, the probabilities of the second best tax credit are listed below some specific thresholds. With Monte Carlo simulation, 10,000 random draws of the parameters were generated using normal distributions over respective ranges of those values. The random draws were then applied to solve for the second best tax credit and create an empirical CDF for it. As indicated in table F.3, the probability of the second best tax credit being nonnegative is over 94%. The probability of it at the optimal level of \$0.22/GEEG (\$0.15/gallon) or less is 29%. The probability of it at the current existing level of \$0.475/GEEG (\$0.45/gallon) or less is 72%. The probability of it being less than \$1/GEEG (\$0.69/gallon) is 100%.

CHAPTER 3

SECOND-BEST MANDATE

In this chapter, a general equilibrium model of a closed economy is used to investigate the fiscal interaction effects of “quantitative” ethanol mandate policy given the presence of a fuel tax and labor tax. From a positive perspective, I analyze comparative static effects of fuel tax and ethanol mandate on prices and quantities. From a welfare perspective, given the pre-existing distortions ethanol mandate is welfare enhancing while tax credit is welfare reducing. Consistent with previous studies, our estimates show that the ethanol mandate dominates the tax credit.

3.1 INTRODUCTION

A combination of mandates, tax credits, and biofuel production subsidies are employed in the US to encourage biofuel production and consumption. A central element of the U.S. biofuels policy concerns the use of quantitative “mandates” on the amount of biofuels production. Energy Independence and Security Act (EISA 2007) established a new renewable fuel standard (RFS) that mandates the domestic biofuel use of 36 billion gallons annually by 2022, of which 15 billion gallons must be corn-based ethanol. It suggests a production rate nearly three times the roughly 13 billion gallons produced in 2010. The RFS is enforced through a trading credit scheme administered by the U.S. Environmental Protection Agency (EPA). Renewable identification numbers (RINs) are generated with each gallon of biofuel by biofuel producers and importers, then they are transferred to blenders or refiners. The excess RIN credits can be sold to other obligated parties who blend biofuels at a rate below the RFS (EPA2008). The RFS blending requirement is set every year based on government’s expectation of total U.S. fuel consumption after corroborating the correct number of RINs.

Such mandates could be implemented in several different ways: a mandated level of consumption or as a mandated proportion of total consumption. De Gorter and Just (2009b) and Holland, Hughes and Knittel (2009) consider a biofuel blend mandate, which is the ratio of ethanol to total fuel consumption that each fuel-producing firm must meet. Whereas it is true that EPA implements the blend mandate through the system of RINs for the obligated parties, it is also true that EISA set the chosen standard to meet the specific overall quantitative target at an expected total consumption level. Hence, in this paper, I focus on mandated quantity of ethanol as specifying a minimum level of consumption.

Previous studies analyze that the biofuel mandates will cause a drastic increase in food prices globally, due to the fact that the aggressive growth in ethanol and biodiesel supply doesn't come along with the required increase in crop productivity (Msangi 2006, OECD 2006 and IEA 2006). OECD and FAO developed a dynamic partial equilibrium model to project a medium-term supply, demand, trade and prices. The model predicts crop prices in 2014 could increase by 2% in the case of oilseeds and almost 60% in the case of sugar.

Food and Agricultural Policy Research Institute (FAPRI) develops a stochastic model of the U. S. agricultural sector and indicates that additional ethanol production because of the mandates results in an increase in corn prices but reduced prices for ethanol, corn byproducts, and soybean meal. Corn and corn byproducts production increases, while corn exports, feed consumption, and stocks decline. The taxpayer cost of farm programs is reduced by an average of \$1.0 billion per year between 2011 and 2015. The increases in ethanol consumption could reduce tax revenue, considering the differences in tax policies of ethanol and gasoline. Net farm income exceeds baseline levels by an average of \$298 million per year over 2011-2015.

OECD (2006) predicts the commodity prices in the ethanol mandate of 86 billion gallons in the United States by the year 2025 under certain assumption of yield for major food crops. It predicts an increase of 13%, 6%, and 30% in the price of corn, wheat, and soybeans, respectively, in the year 2025. Major acreage changes include conversion of 33 million acres in pastureland and 15 million acres of CRP land into cropland.

However, most of existing studies suggest that ethanol mandate has better policy achievements than tax credit. De Gorter and Just (2009b) concludes that a mandate has two advantages over a tax credit. First, a mandate doesn't involve taxpayer's costs and the marginal excess burden of taxation associated with it. Second, due to the suboptimal gasoline tax in the United States (Parry and Small 2005), the higher price of gasoline under a mandate at least partially offsets the welfare loss caused by it. If an ethanol mandate is implemented along with a tax credit, the effects of tax credit are reversed, which subsidizes fuel consumption instead of ethanol consumption. A policy implication is that it may be more desirable to have only one policy instrument, ethanol mandate, than to have the two policies working at the same time or just have tax credit policy.

The purpose of this paper is to analyze the economics of a quantitative ethanol mandate and derive the policy implications of the ethanol policies (tax credit and ethanol mandate) given the pre-existing distortions. I construct a general equilibrium model to analyze government intervention in the second-best setting. The model is used both the positive and normative implications of alternative policy instruments, including fuel tax, labor tax and ethanol mandate. From a positive perspective, I replicate the results from some existing studies of the comparative static effects of fuel tax and ethanol mandate on quantities and prices. From a welfare perspective, in the presence of lab tax and fuel tax policies, ethanol mandate is welfare enhancing. Therefore the results agree with previous researches that ethanol mandate dominates tax credit.

There are three major contributions of the paper to the literature. First, I carry out a comparative static analysis on ethanol mandate and fuel tax. Our results are consistent with some existing researches that a fuel tax raises the producer price of fuel and lowers the demand for gasoline and fuel. Consequently, the fuel tax would reduce the total greenhouse pollution. The comparative static results also show that ethanol mandate raises gasoline price and fuel output in total. Walrasian stability condition supports the unambiguous comparative static effects.

Second, I analyze the impact of the ethanol mandate on the general economy through “fiscal interaction effects” with fuel tax and labor tax. For example, ethanol mandate leads to a higher ethanol price and thus a higher corn price and fuel price (I consider exogenous gasoline price in the paper), so that real wage decreases and labor supply reduces. This reduces the fiscal base and so too decreases tax revenues, thereby resulting in a lower social welfare. This is called the “tax-interaction effect.” Another example is ethanol mandate offsets the social costs caused by the existing fuel tax. The imposition of ethanol mandate raises ethanol price and fuel price (gasoline price is exogenous), which offsets the suboptimal fuel tax in the United States (Parry and Small, 2005). This is called “subsidy-interaction effect”. Compared to the imposition of tax credit policy, the government doesn’t need raise the tax rates (e.g., income tax) in the general economy to support the mandate, there is no “revenue-recycling effect” involved with the imposition of ethanol mandate.

The general equilibrium welfare analysis estimates the marginal benefits and marginal costs caused by the interaction of ethanol mandate and the general economy. The marginal benefits include: own effects of price difference - mandate on ethanol increases the total consumption and production of ethanol and raises the price received by the producers. Hence, ethanol mandate creates a positive welfare to producers. Environmental welfare gain – ethanol mandate reduces the total fuel consumption and the associated carbon dioxide emissions. Thus it creates a positive welfare gain due to the reduced environmental pollution. Subsidy-interaction effects in ethanol market – because ethanol mandate drives up the ethanol consumption and production, it offsets the social costs caused by the fuel tax. The pre-existing fuel tax lowers ethanol consumption and decreases consumer surplus. Ethanol mandate creates a positive welfare gain by offsetting the social costs created by the fuel tax and it is called subsidy-interaction effects in the ethanol market. The marginal costs include: subsidy-interaction effects in gasoline market – ethanol mandate shifts the gasoline demand curve inward by lowering the share of gasoline in fuel blends relative to the share of ethanol. Given the pre-existing fuel tax, ethanol mandate further reduces the gasoline consumption and consumer surplus. Tax-interaction

effects – ethanol mandate raises the prices of corn and fuel, indirectly decreases the return to work relative to leisure and shifts the labor supply curve inward. It creates a welfare loss in the labor market. The net welfare change caused by the mandate policy is significantly positive.

Third, my estimates of welfare change caused by either mandate or tax credit, given the two pre-existing government policies – labor tax and fuel tax – yield a strong policy implication, which agrees with previous studies that given pre-existing distortions of government intervention ethanol mandate dominates tax credit. Through the fiscal interaction effects, ethanol mandate has more advantages than tax credit in decreasing CO₂ emissions, enhancing energy security and promoting rural development.

3.2 THE MODEL

I inherit and adapt the general equilibrium model developed in my previous studies, which allows me to perform the positive analysis following some existing studies and also perform welfare analysis in a second-best setting. The model is a closed economy with four commodities (corn, fuel, gasoline and ethanol) and one input (labor). I assume that ethanol, adjusted for energy content, is a perfect substitute for gasoline. There exists four industries: ethanol industry that converts corn and labor into ethanol, which then blended with gasoline to create fuel used by households; corn and gasoline industries which produces corn and gasoline in the fashion of constant returns to scale in labor; fuel industry which produces fuel by blending ethanol and gasoline. I consider a domestic population of consumers that have quasi-linear preferences. The utility of the consumers is positively affected by consuming two goods, corn and fuel, and spending leisure time and negatively affected by the pollution associated with the consumption of fuel. I assume a government sector. The government levies a unit tax on labor and a unit tax on fuel consumption.

3.2.1 PRODUCTION

Following the previous chapter, I assume the constant returns to scale (CRTS) in labor (L) in corn production (q_c^S) and gasoline production (q_g^S). Consequently, I can obtain the market clearing condition for both goods by imposing the CRTS production assumption directly.

Ethanol production is assumed to be a fixed-proportion technology,

$$(3.1) \quad q_e^S = \min(\rho C, L_e),$$

where q_e^S is ethanol output measured in gasoline energy equivalent gallons (GEEG), C and L_e are the inputs of corn and labor respectively, ρ is a production coefficient. Because the energy content of ethanol is much lower than that of gasoline, and consumers ultimately care about the miles travelled with any amount of fuel (de Gorter and Just 2010), it is important to keep track of this fact to handle the blending of ethanol and gasoline (into fuel) in a consistent fashion. Thus, for the rest of the paper, ethanol amount is consistent measured in “gasoline-energy-equivalent gallon” (GEEG) units. (See Appendix C for detailed derivation of ethanol production function and inverse supply curve of ethanol)

Fuel is assumed to be consisted of two products, ethanol and gasoline, which are perfectly substitutable. Labor input L_f is used to blend ethanol and gasoline. Fuel output can be solved as $q_f^S = q_e^D + q_g^D$, where q_f^S is the fuel supply, q_e^D and q_g^D are the ethanol and gasoline demand by blenders.

3.2.2 CONSUMPTION

I assume that consumers in the closed economy have quasi-linear preferences, which allows for an internally consistent welfare analysis. The preferences can be aggregated up to a single representative agent’s utility. The utility function is assumed to be:

$$(3.2) \quad U = u(\tau(q_c, q_f), l) - \varphi(P(.)),$$

where q_c , q_f and l represent the domestic consumption of corn, fuel and leisure respectively and P represents the perceived greenhouse gas pollution due to fuel combustion. The functions $u(\cdot)$ and $\tau(\cdot)$ are quasi-concave reflecting the positive utility of goods and leisure consumption, whereas the function $\varphi(P(\cdot))$ is quasi-convex showing the negative disutility due to the greenhouse gas pollution.

The perceived greenhouse gas pollution P is the greenhouse pollution caused by fuel combustion:

$$(3.3) \quad P = \epsilon_f q_f,$$

where ϵ_f is the CO2 emission rate of fuel.

The representative consumer is subject to the time constraint on labor and leisure:

$$(3.4) \quad l + L = \bar{L},$$

where L is total labor and \bar{L} is the time endowment.

3.2.3 GOVERNMENT POLICY

In the second-best framework, I analyze the second-best ethanol mandate in the presence of two pre-existing policies: labor tax (t_L) and fuel tax (t). The tax revenues are neutralized by varying a government lump-sum transfer (G) to the households. In equilibrium, the government budget constraint is balanced.

3.2.4 EQUILIBRIUM CONDITIONS

I specify the equilibrium conditions which must hold in the model, account for the set of policy instruments. For the purpose of policy analysis, I consider labor tax, fuel tax and ethanol mandate in our model. Given all that, the equilibrium conditions include:

Gasoline Market Equilibrium:

$$(3.5) \quad q_g^S \equiv q_g^D = q_g,$$

where q_g^S is gasoline supply, q_g^D is gasoline demand for blending fuel, q_g is the equilibrium amount. I assume that gasoline production is constant returns to scale in labor, where L_g is labor input for gasoline production.

Corn Market Equilibrium:

$$(3.6) \quad q_c^S \equiv q_c + C,$$

where q_c^S is corn supply, q_c is the corn demand by households, C is corn input for ethanol production. Given CRTS of corn production assumption, market clearing condition is satisfied. The labor input for corn production is denoted by L_c .

Ethanol Market Equilibrium:

$$(3.7) \quad q_e^S \equiv q_e^D = q_e, q_e = \bar{M},$$

where q_e^S , q_e^D are ethanol supply and ethanol demand, q_e is the equilibrium amount of ethanol, \bar{M} is the binding ethanol mandate. With a binding mandate, ethanol price is strictly determined by the mandate, denoted by $p_e(\bar{M})$. Ethanol mandate drives up ethanol price compared to the equilibrium without mandate, causing the market prices for ethanol and gasoline to diverge. In equilibrium, consumers must pay the marginal cost to the blender of producing a unit of fuel mixture. This marginal cost is given by the weighted average price of ethanol and gasoline where

the weights are formed by the required share of ethanol under the mandate (de Gorter and Just, 2009).

Fuel Market Equilibrium:

$$(3.8) \quad q_f^S = q_g^D + q_e^D = q_f$$

where q_f^S is fuel supply, q_g^D and q_e^D are gasoline input and ethanol input for fuel blends, q_f is the fuel demand by households. Given the market clearing condition in both ethanol and gasoline markets, that is $q_e^S \equiv q_e^D = q_e$ and $q_g^S \equiv q_g^D = q_g$. Fuel supply function becomes: $q_f^S = q_e + q_g$.

The fuel equilibrium condition becomes:

$$(3.9) \quad q_f^S = q_e + q_g = q_f.$$

Consider the quantitative mandate in ethanol (\bar{M}), that is $q_e = \bar{M}$, the function becomes:

$$(3.10) \quad q_f^S = \bar{M} + q_g = q_f.$$

Zero Profit Function Fuel Industry:

$$(3.11) \quad P_f(q_f)q_f - P_g(q_g)q_g - p_e(q_e)q_e = 0$$

where $P_f(\cdot)$, $P_g(\cdot)$ and $P_e(\cdot)$ are the price of fuel, gasoline and ethanol respectively.

Considering policy instruments, I use the binding mandate condition and fuel tax in the function, the zero profit condition in fuel production becomes:

$$(3.12) \quad [P_f(q_g + \bar{M}) - t](q_g + \bar{M}) - P_g(q_g)q_g - p_e(\bar{M})\bar{M} = 0$$

Where $p_e(\bar{M}) \geq P_f(q_g + \bar{M}) \geq P_g(q_g)$, the strict inequality holds if the mandate is binding and the fuel price is a weighted average of gasoline price and ethanol price.

Labor Market Equilibrium:

$$(3.13) \quad L = L_c + L_g + L_e + L_f,$$

where L is total labor supply and (L_c, L_g, L_e, L_f) are labor demand in corn, gasoline, ethanol and fuel industries.

Government Budget Balance:

$$(3.14) \quad G = t_L L + t q_f,$$

where the left hand side stands for government expenditure on a lump-sum transfer (G) and the right hand side represents the government revenue from a labor tax ($t_L * L$) and a fuel tax ($t * q_f$).

3.3 PARTIAL EQUILIBRIUM WITH ETHANOL MANDATE AND FUEL TAX

In this section, I analyze the partial equilibrium effects of a policy combination of fuel tax and ethanol mandate, following some existing studies (de Gorter and Just, 2009a,b, 2010, Lapan and Moschini 2009). The equilibrium in the energy market can be written in terms of arbitrage conditions, which account for the policy instruments of interest. We denote t as unit tax on fuel and \bar{M} as quantitative ethanol mandate. In equilibrium, the arbitrage functions in energy market are written as:

$$(3.15) \quad \begin{cases} P_g^S(q_g) = P_f(q_f) - t \\ P_e^S(\bar{M}) = P_f(q_f) - t \end{cases}$$

where $P_f(\cdot)$ is the inverse demand for fuel, $q_f \equiv q_g + \bar{M}$, $P_g^S(\cdot)$ is the inverse supply of gasoline,

P_e^S is the inverse supply of ethanol. We assume that $\frac{\partial P_f}{\partial q_f} = \frac{1}{D'_f} < 0$, $\frac{\partial P_g}{\partial q_g} = \frac{1}{S'_g} > 0$ and $\frac{\partial P_e}{\partial q_e} =$

$\frac{1}{\rho^2 C'} > 0$, where D'_f is the slope of fuel demand curve, S'_g is the slope of gasoline supply curve, ρ

is a production coefficient and $\rho > 0$, $C(\cdot)$ is the residue supply function of corn to ethanol production and $C'(\cdot) > 0$. Totally differentiating the above arbitrage functions and using the above assumptions, the comparative static effects of fuel tax and ethanol mandate on prices and quantities are derived as (details see Appendix D):

$$\frac{dP_g}{dt} = \frac{D'_f}{2(-D'_f + \rho^2 C' + S'_g)} < 0, \quad \frac{dq_g}{dt} = \frac{D'_f S'_g}{2(-D'_f + \rho^2 C' + S'_g)} < 0, \quad \frac{dP_f}{dt} = \frac{\rho^2 C' + S'_g}{2(-D'_f + \rho^2 C' + S'_g)} > 0, \quad \frac{dq_f}{dt} = \frac{(\rho^2 C' + S'_g) D'_f}{2(-D'_f + \rho^2 C' + S'_g)} < 0, \quad \frac{dP_g}{d\bar{M}} = \frac{1}{\rho^2 C'} > 0, \quad \frac{dq_g}{d\bar{M}} = \frac{S'_g}{\rho^2 C'} > 0, \quad \frac{dP_f}{d\bar{M}} = \frac{\rho^2 C' + S'_g}{\rho^2 C' D'_f} < 0, \quad \frac{dq_f}{d\bar{M}} = \frac{\rho^2 C' + S'_g}{\rho^2 C'} > 0.$$

As expected, a fuel tax raises the producer price of fuel and lowers the demand for gasoline and fuel and consequently reduces the total greenhouse pollution. Because I consider ethanol and gasoline are perfect substitutes, ethanol mandate raises the gasoline price and fuel output in total. Under the assumptions of the simplified model, fuel price declines with ethanol mandate. However, if I loose assumptions of the model and consider the complexity of energy market, the direction of the change in fuel price due to ethanol mandate is uncertain.

3.4 WALRASIAN STABILITY CONDITIONS IN PARTIAL EQUILIBRIUM

Unambiguous comparative statics rely on stability conditions. To derive Walrasian stability condition of the fuel market, I first differentiate the zero profit function in fuel production and rearrange the terms:

$$(3.16) \quad (MR_f - MC_g) dq_g = (MC_e - MR_f) d\bar{M}$$

where MR_f is the marginal revenue for fuel production and

$$(3.17) \quad MR_f \equiv p_f + q_f * \left(\frac{dp_f}{dq_f} \right) = p_f + \frac{q_f}{D'_f},$$

MC_g is the marginal cost for gasoline production and

$$(3.18) \quad MC_g \equiv p_g + q_g * \left(\frac{dp_g}{dq_g} \right) = p_g + \frac{q_g}{S'_g},$$

MC_e is the marginal cost for ethanol production and

$$(3.19) \quad MC_e \equiv p_e + q_e * \left(\frac{dp_e}{dq_e} \right) = p_e + \frac{\bar{M}}{\rho^2 C'}.$$

Substituting the marginal revenue and marginal cost functions into equation (16), the zero profit function becomes:

$$(3.20) \quad \left[(p_f - p_g) + \frac{q_g + \bar{M}}{D'_f} - \frac{q_g}{S'_g} \right] dq_g = \left[-\frac{q_g + \bar{M}}{q'_f} + \frac{\bar{M}}{\rho^2 C'} + p_e - p_f \right] d\bar{M}$$

I define the excess demand function in energy market:

$$(3.21) \quad E(p_g) = D_f(P_f) - q_g - \bar{M} = 0,$$

where $E(.)$ is the excess demand function hinging on the price of gasoline. Walrasian stability condition requires $\frac{dE}{dp_g} = D'_f \left(\frac{dP_f}{dp_g} \right) - S'_g \leq 0$. Using the functions of marginal revenue in fuel industry and marginal cost in gasoline industry, the stability condition is rewritten as:

$$(3.22) \quad \frac{dE}{dp_g} = \left(-\frac{S'_g D'_f}{q_f} \right) (MR_f - MC_g) \leq 0$$

Given the equilibrium condition of the zero profit function in fuel industry, Walrasian stability condition holds and we have unambiguous comparative statistics results.

3.5 GENERAL EQUILIBRIUM

The utility function of the representative consumer is given in equation (3.2): $U = u(\tau(q_c, q_f), l) - \varphi(P(.))$. The budget constraint is set as:

$$(3.23) \quad p_c q_c + (p_f + t)q_f = (1 - t_L)L + G + \pi,$$

where p_c, p_f represent the consumer price for corn and fuel, q_c, q_f represent the demand for corn and fuel, t is the consumer fuel tax on fuel, t_L is the flat tax rate on labor, G is the lump-sum transfer from government and π is economic profits from ethanol production. The assumptions we imposed on corn, gasoline and fuel industries ensure that in the long run the economic profits in those industries are zero. The non-negative economic profits that consumers receive only come from ethanol industry. The economic profits, π , can be derived from the profit maximization problem in ethanol production.

The representative consumer is subject to the time constraint on labor and leisure:

$$(3.24) \quad l + L = \bar{L},$$

where L is total labor supply and \bar{L} is the time endowment.

3.6 THE WELFARE EFFECTS OF ETHANOL MANDATE POLICY

The marginal welfare change from the ethanol mandate, \bar{M} , is consisting of five components. The marginal welfare effects of ethanol mandate is solved as in equation (25) (see the detailed calculations in Appendix E):

$$(3.25) \quad \underbrace{\frac{1}{\lambda} \frac{dV}{d\bar{M}}}_{\text{Welfare effects of mandate}} = \underbrace{\left(p_e - \frac{p_c}{\rho} - 1 \right)}_{\text{Own effects of price difference}} + \underbrace{\left(-\frac{\phi'}{\lambda} \frac{dP}{d\bar{M}} \right)}_{\text{Environmental welfare gain}} + \underbrace{t \frac{dq_e}{d\bar{M}}}_{\text{Subsidy-interaction effect in ethanol market}} + \underbrace{t \frac{dq_g}{d\bar{M}}}_{\text{Subsidy-interaction effect in gasoline market}} + \underbrace{t_L \frac{dL}{d\bar{M}}}_{\text{Tax-interaction effect}}$$

(i) Environmental welfare gain. The first term in equation (25), $-\frac{\phi'}{\lambda} \frac{dP}{d\bar{M}}$, reflects the rectangle environmental welfare gain. The application of an ethanol mandate sets a minimal consumption level for ethanol and helps control pollution caused by greenhouse gas emission, which creates a rectangle welfare gain. Unlike tax credit policy, ethanol mandate policy doesn't incur a triangle primary economic cost.

Figure 3.1 depicts the pollution market. The curves of S^P and $S^{P'}$ are the supply curves for pollution before and after the application of the ethanol mandate, which reflects the change of carbon dioxide emissions and the fuel consumption. The curve of D^P is the demand curve for pollution. Ethanol mandate reduces pollution supply from P to P' and associated fuel consumption from q_f to q_f' . The social costs (the price) of the pollution is reduced from τ to τ' . The ethanol mandate reduces the environmental damages by the area of rectangle $abcd$.

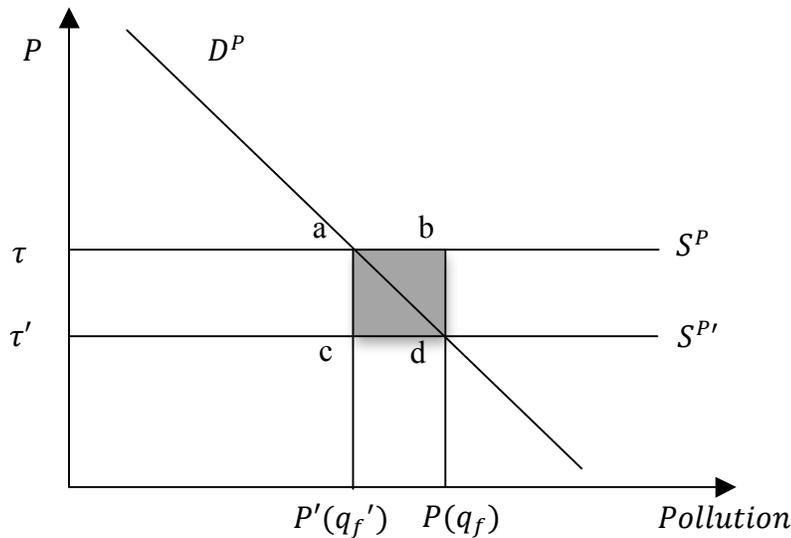


FIGURE 3.1: ENVIRONMENTAL EFFECT IN POLLUTION MARKET

(ii) Subsidy-interaction effects in ethanol market. In the ethanol market, the fuel tax shifts the ethanol demand curve inward from D^E to $D^{E'}$, lowers the consumer price for ethanol from p_e to p_e' and decreases the ethanol demand from q_e to q_e' . I consider a minimal share of ethanol is required in all fuel sold, so that $D^E = \alpha D^F$, $\alpha \in (0,1)$, where D^F is the fuel demand. Imposing a quantitative mandate \bar{M} on ethanol (for simplicity, I consider the mandate \bar{M} is set at the laissez-faire ethanol demand q_e), ethanol price is restored at the level of p_e , consumer surplus increases by the shaded area $q_e'q_eba$ and producer surplus increases by the shaded area $abcd$. Consequently, it produces a total welfare gain equal to the shaded rectangle $q_e'q_e cd$. That is, ethanol mandate drives up ethanol consumption (by blenders) and production, which offsets the social costs caused by fuel tax.

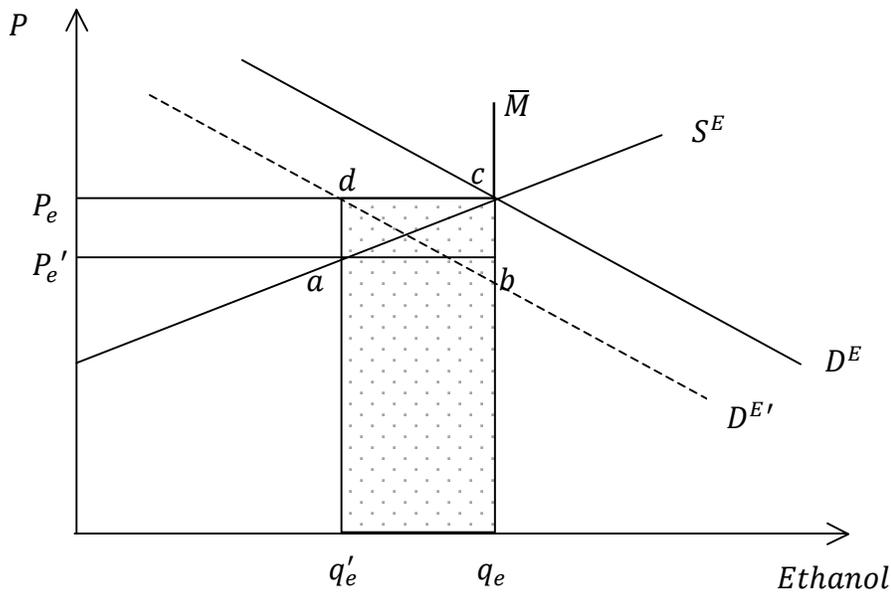


FIGURE 3.2: SUBSIDY INTERACTION EFFECT IN ETHANOL MARKET

(iii) Subsidy-interaction effect in gasoline market. In the gasoline market, we have gasoline demand curve D^G , where $D^G = (1 - \alpha)D^F$ and $\alpha \in (0,1)$, and the completely inelastic supply curve S^G for gasoline following the assumption of CRTS in gasoline production. Fuel tax

raises the gasoline price from p_g to p_g' and lowers gasoline consumption from q_g to q_g' . (The extent of fuel tax affecting gasoline price and demand depends on the elasticity of fuel demand curve and the share of gasoline in fuel blends.) Gasoline consumers suffer from a welfare loss of the shaded area $p_g a b p_g'$. The imposition of ethanol mandate lowers the share of gasoline in fuel blends relative to the share of ethanol. Gasoline consumption reduces further from q_g' to q_g'' . So that ethanol mandate shifts the gasoline demand curve inward from D^G to $D^{G'}$, where $D^{G'} = (1 - \alpha')D^F$ and $0 < \alpha < \alpha' < 1$. Consumer surplus is further reduced by the shaded triangle area $b c p_o$.

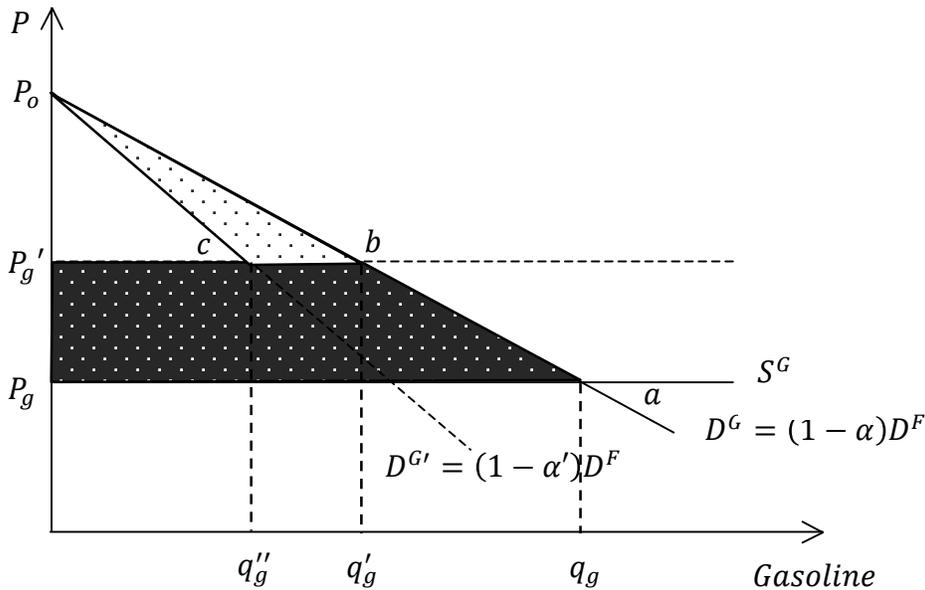


FIGURE 3.3: SUBSIDY INTERACTION EFFECT IN GASOLINE MARKET

(iv) Tax-interaction effects. Ethanol mandate increases the consumer price for corn and fuel, indirectly decreases the return to work relative to leisure and causes the labor supply curve to shift inward. This creates a rectangle welfare loss called tax-interaction effect.

I normalize the price of labor (wage) to one and the net wage is $(1 - t_L)$ after income tax t_L . Because ethanol mandate drives up ethanol price and leads to a higher demand for corn, as

corn is the major input for ethanol production, corn price is increased with ethanol mandate. With exogenous gasoline price in the model, ethanol mandate raises fuel price as the average of gasoline price and ethanol price. Therefore ethanol mandate discourages the household consumption for corn and fuel at a given nominal wage.

In Figure 3.4, labor supply curve shifts inward from S^L to $S^{L'}$ and labor supply reduces from L to L' . The tax-interaction effect is the welfare loss denoted by the shaded rectangle $abcd$, which is the product of the wedge between the gross wage (1) and the net wage ($1 - t_L$) and the reduction in labor supply ($L - L'$).

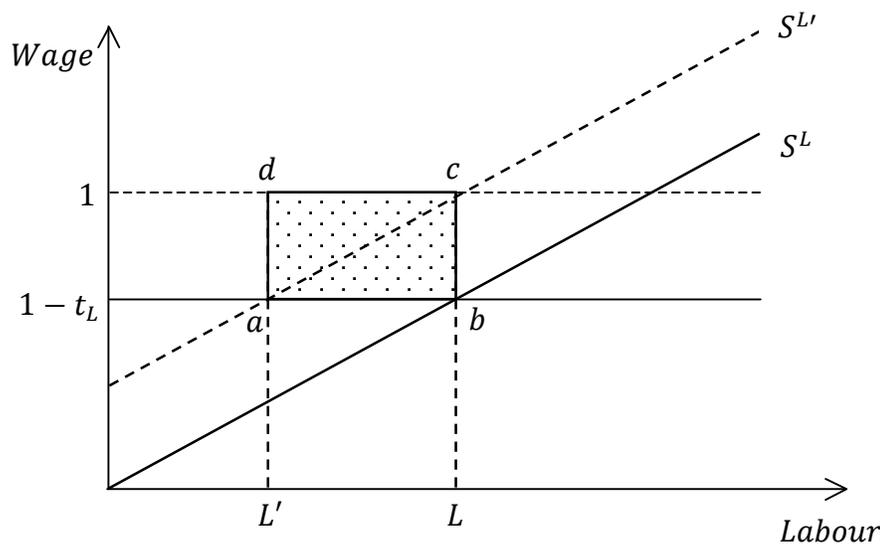


FIGURE 3.4 TAX INTERACTION EFFECT

3.7 MODEL CALIBRATION

Benchmark values and parameter ranges used for estimating the welfare effects of ethanol mandate policy are summarized in table 3.1. The values of the exogenous parameters and the values of the mandate policy variables are based on 2009 data from various sources, including Feed Grain Database of the U.S. Department of Agriculture (USDA), U.S. Energy Information

Administration (EIA), Renewable Fuels Association (RFA) and Nebraska Energy Office (NEO) websites.

As I defined in previous section, ethanol production function is assumed to be: $q_e = \min(\rho c, L_e)$, where $\rho = \alpha \lambda_c / (1 - \sigma_1 \sigma_2)$. The introduction of α shows that ethanol is measured in gasoline energy equivalent units, where $\alpha \approx 0.69$. Accord to Eidman (2007), one bushel of corn produces approximately 2.80 gallons of ethanol, thus $\lambda_c = 2.8$. We also assume that in the function, one unit of corn produces σ_1 units of byproduct, where $\sigma_1 = 0.303$ (RFA), the proportion of byproduct price to corn price is σ_2 , where $\sigma_2 = 0.776$ (Cui *et al*, 2010). Hence the value of parameter ρ is solved to be 2.20. The 2009 average rack price of ethanol is \$1.79/gallon, which can be converted to a per GEEG price of $\$1.79/.69 = \$2.59/\text{GEEG}$. Using the average farm price, the corn price is \$3.74/bushel, which is equivalent to \$0.4/gallon. The 2009 average rack price of ethanol is \$1.79/gallon, which corresponds to a price of $\$1.79/.69 = \$2.59/\text{GEEG}$. Therefore, I am able to solve for the welfare change due to the own effects in price difference. In the first component of marginal welfare effect function, increase one gallon of mandate, welfare will increase by $p_e - \frac{p_c}{\rho} - 1 = \$0.61/\text{gal}$.

To be consistent with previous studies, I pick the social cost of carbon dioxide emissions at the mean level of \$32/tCO₂, ranging from \$2/tCO₂ to \$100/tCO₂. From the life cycle perspective, the estimate of CO₂emission rate of corn ethanol is 8.42 kg/GEEG, equivalent to \$5.81 kg/gal (Farrel *et al*, 2006). In the second component of marginal welfare effect function, by each gallon of ethanol mandate, the mean level of social costs due to the reduction in carbon dioxide pollution will decrease by \$0.186/gal, ranging from \$0.012/gal to \$0.581/gal.

Currently, fuel consumption is subject to the federal tax of \$0.184/gallon plus a state-level tax of \$0.203/gallon on an average level. Thus the average fuel tax is solved as $\$0.184/\text{gallon} + \$0.203/\text{gallon} = \$0.387/\text{gallon}$. Therefore, the third component of marginal welfare change reflected the subsidy-interaction effects in ethanol market, is \$0.387/gallon for each gallon increase in the level of ethanol mandate.

The fourth component in the marginal welfare change function reflects the subsidy-

interaction effect in gasoline market. To calibrate the effects, I rewrite the fourth component as $t \frac{dq_g}{d\bar{M}} = t \frac{\eta_g^D}{\eta_{e,g}} \frac{q_g}{\bar{M}}$, where η_g^D is the elasticity of gasoline demand, $\eta_{e,g}$ is gasoline-price (cross-price) elasticity of ethanol demand. I adopt the estimates of gasoline demand elasticity from Parry and Small (2005), the mean level is at -0.55 with a range of -0.9 to -0.3. Anderson (2008) shows that the gasoline-price (cross-price) elasticities of ethanol demand in the 2.5 - 3.0 range. In 2009, the total fuel consumption in volumetric units is 134.4 billion gallons (EIA data). The unblended gasoline of 123.6 billion GEEG units (approximately 85.28 billion gallons) is derived from subtracting the ethanol production in volumetric units from the figure of the finished motor gasoline products (Cui *et al.* 2010). I adopt the current existing RFS level of 13 billion gallon to estimate \bar{M} . Thus, the marginal effects is estimated to be $t \frac{\eta_g^D}{\eta_{e,g}} \frac{q_g}{\bar{M}} = -\$0.52/gal$.

The fifth component in the marginal welfare change function reflects the tax-interaction in the labor market. To calibrate the effect, I rewrite the term $t_L \frac{dL}{d\bar{M}} = t_L \eta_L^S \eta_e^D \frac{L}{\bar{M}}$, where η_L^S is labor supply elasticity, η_e^D is ethanol demand elasticity. Following Parry and Small (2005), labor supply elasticity is estimated to be 0.2, ranging from 0.1 to 0.3. We adopt the estimate of ethanol demand elasticity at the mean level of -0.81, varying from -2.82 and -0.37 (Rask, 2004). Using 2007 ethanol production data, U.S. needs the equivalent of 142 ethanol plants and 6,594 workers with the capacity to convert 3.23 billion bushels of corn into 8.9 billion gallons of ethanol by the end of 2007 (Swenson, 2007). Consistent with previous studies, the estimate of labor tax is assumed to be \$0.39/labor. Therefore, the marginal tax-interaction effect in the labor market is estimated to be $-\$4.7 * 10^{-7}/gal$. Compared to other effects, the welfare impacts of ethanol mandate on labor market are too trivial to be significant.

Therefore, the positive marginal benefits from the mandate is \$4.163/gal and the negative marginal costs is $-\$0.52/gal$, which shows that in the second-best setting the ethanol mandate policy does yield net positive effects and is plausible in the areas of reducing greenhouse gases and enhancing energy security.

3.8 RESULTS

Based on the figurative analysis and calibration, in the methodology of fiscal policy interaction, the positive effects of ethanol mandate come in the form of environmental welfare gain and subsidy-interaction effect in ethanol market. The negative effects of the policy are associated with subsidy-interaction effect in gasoline market and tax-interaction effect in labor market. The positive marginal benefits are significantly higher than the negative marginal costs, which show that ethanol mandate is welfare enhancing given the pre-existing policies (labor tax and fuel tax). However, given the pre-existing fuel tax and labor tax, tax credit is welfare reducing in the same second-best setting. Therefore, considering the fiscal-interaction effects ethanol mandate dominates tax credit.

Using the parameter values from Table D, I derive the estimates of welfare change in the second-best setting caused by ethanol mandate and tax credit, the results of the marginal welfare effects caused by the ethanol mandate is summarized in Table E. If we consider the constant slope in relationship between welfare and mandate/tax credit, we can compare the net welfare change caused by the two policies. I apply the current existing RFS level of 13 billion gallon and the current tax credit level of \$0.475/GEEG to estimate the net welfare change, the results of which is summarized in Table F.

The own effects of primary costs caused by the tax credit is estimated to be 2.86 billion dollars while the own effects of price differences caused by ethanol mandate is estimated to be 7.93 billion dollars. Environmental welfare gain created by ethanol mandate and tax credit are estimated to be 2.418 and 0.38 billion dollars respectively. Subsidy-interaction effect in ethanol market created by ethanol mandate and tax credit are estimated to be 5.031 and 3.38 billion dollars respectively. Subsidy-interaction effect in gasoline market created by ethanol mandate and tax credit are estimated to be -6.76 and -27.77 billion dollars respectively. Tax-interaction effect caused by ethanol mandate and tax credit are estimated to be -0.005291 and 0.000543 million dollars respectively, the results of which compared to other effects are too small to be

significant. Adding up all the effects, the estimates of the welfare change due to the ethanol mandate and the tax credit in presence of existing government distortions are calibrated to be \$8.61 billion and -\$26.87 billion. Therefore the estimate results corresponds to previous studies that ethanol mandate dominates tax credit.

The existing literature suggests a number of reasons explaining the dominance of ethanol mandate over tax credit. First of all, ethanol mandate doesn't involve taxpayer's costs and the marginal excess burden of taxation associated with it. As in our figure 1, ethanol mandate doesn't incur the triangle primary economic costs as tax credit does. Second, ethanol mandate tends to raise the gasoline price, which partially offsets the welfare loss due to the suboptimal gasoline tax in the United States (de Gorter and Just, 2009b).

CHAPTER 4

AD VALOREM TARIFF

In the chapter, we design and analyze a modified Bertrand duopoly model with environmentally differentiated products. We consider the trade barrier of an ad valorem tariff levied by a developed country and a less developed country. In the Bertrand-Nash equilibrium, the effects of the tariff on social welfare and on local and global environment are analyzed.

4.1 INTRODUCTION

Over the last twenty years environmentalists and the trade policy community have engaged in a debate over liberalized trade. Two important questions arise from the debate: what is the connection between trade and the environment? How does the connection affect international trade or the global environment?

Most studies agree that international trade affects the pattern and extent of the production and consumption in trading countries. If these activities of consumption and production have impacts on the environment of the trading countries, we can claim that international trade will affect the environment. Equally, government policies applied to improve the environment by adjusting the activities of production and consumption in various countries shall impact the pattern and magnitude of international trade.

Some fundamentalist environmentalists insist that trade liberalization is harmful to the environment and that governments should impose trade restrictions to protect the environment (Barrett 1994; Rauscher 1997; Ulph 1999, 2001; Copeland and Taylor 2003). However, economists focus on analyzing how to use government intervention to regulate international trade and thus protect the environment (Antweiler et al. 2001; Copeland and Taylor, 2004; Smarzynska and Wei, 2001). There are two major directions of those economists' studies: one addresses the question that how trade policies affect environment and social welfare; the other

one investigates how environmental policies, such as green taxes, emission standards, and eco-labels etc, affect international trade, factor mobility and geographic allocations of firms.

Previous studies emphasize on the polluting environmental effluents that are produced from manufacturing processes. In this paper, however, I introduce products with environmental characteristics and heterogeneous consumers with various environmental concerns. The environmental effluents are produced through the consumption choice made by the heterogeneous consumers, which are influenced by trade policies of the importing country. Considering the fact that consumers differ in the degree of environmental consciousness, I analyze the effects of an *ad valorem* tariff on environment and social welfare in a Bertrand duopoly of a developed country and a less developed country.

Although few studies have directly analyzed the subject in this paper, some previous research analyzes how a tariff policy affect quality choice of firms and social welfare. Some works use a model of an international oligopoly with vertically differentiated products to estimate the impacts of a tariff (Polavarapu and Vaidya, 1996; Herguera et al. 2002; Morga-Gonzalez and Viaene 2005). Herguera *et al.* (2002) compare the effects of the optimal ex-ante and ex-post tariffs on social welfare. Optimal ex-post tariffs are positive and ensure that the domestic firm always produces the high quality goods. The optimal ex-ante tariff is prohibitive and welfare under domestic monopoly is lower than under ex-post tariffs, unless firms compete in prices and the domestic firm is high quality. Morga-Gonzalez and Viaene (2005) analyze the policy mix of a tariff-cum-subsidy in both cases of Bertrand and Cournot duopoly.

The remainder of the paper is structured as follows. Section 2 reviews the literature on the connection between trade and environmental policies. Section 3 presents our theoretical model of Bertrand duopoly with heterogeneous consumers and environmentally differentiated products. Section 3 estimates the effects of an *ad valorem* tariff on local and global environment and social welfare of both the developed country and the less developed country. The last section summarizes the results and outlines directions of future research.

4.2 LITERATURE REVIEW

Recently the debate over the relationship between trade and the environment has become considerably heated in the academic world. The economic literature on the issue came in two waves. The earlier literature in the 1970s was normative, with a focus on issues such as welfare gains from trade or environmental policies. Recent works, stimulated by the policy debates of the past decade, focus more on positive policy analysis. In the later wave of literature, a lot of work concentrates on generating and testing hypotheses regarding how trade affects environmental outcomes.

There are three factors that create a link between trade and environment (Ulph, 1997; Sheldon 2005). First, environmental policies targeting production and consumption activities affect the pattern of trade. Trade also has impacts on the environment by affecting the structures of production and consumption activities. Therefore, trade and the environment are linked by production and consumption activities. Second, trade policy may be used as punishment by the home country if international trade potentially results in negative global environmental effects from dirty production and consumption. Third, the sanction trade policies help to enforce international environmental agreements.

Environmentalists believe that trade will cause more consumption and production, which results in more environmental damage. The pollution haven hypothesis (PHH) suggests that, under free trade, the production of the pollution-intensive goods are relocated from developed countries to less developed countries by taking advantage of the low environmental monitoring in the less developed countries. Over time, the less developed countries will develop a comparative advantage in pollution-intensive industries and become “havens” for the polluting industries. On the contrary, the factor endowment hypothesis (FEH) predicts that the capital abundant countries exports the capital-intensive (dirty) goods and thus raise pollution in the capital abundant country, while pollution declines in the capital-scarce countries due to the

contraction in pollution-intensive goods production. Both hypotheses predict that free trade alters the composition of national outputs depending on the comparative advantages of the country.

Counter to the belief widely held by environmentalists, economists tend to believe that international trade may be good for the environment (Antweiler et al. 2001; Copeland and Taylor, 2004). At least no evidence has proven that trade has detrimental effects on the environment as claimed by the “race to bottom” theory (Frankel and Rose, 2001). The overall evidence supporting PHH is relatively weak and does not survive numerous checks (Smarzynska and Wei, 2005). In addition, increased income from trade liberalization could generate increased demand for improved environmental quality. Copeland and Taylor (2004) provided evidence that there is an income effect that raises environmental quality. World Bank (2000) claims that trade can provide developing countries with both an incentive and access to advanced technology which is cleaner than old technologies.

Given the environmental externalities in this setting, some economists designed trade restrictiveness indicators to evaluate the efficient effects of trade policies. Chau, Fare and Grosskopf (2011) use modified indicators (account for differences rather than ratios) to evaluate efficiency changes in the face of simultaneous and multi-dimensional trade and environmental policy reforms. Two issues are addressed in the literature: how do the existing trade and environmental policies influence the division of efficiency gains between producers and consumers subsequent to a welfare improving trade policy reform in general equilibrium? How do the same existing policy configurations affect the division of gains between producers and consumers subsequent to a welfare improving environmental policy reform?

Controversy also remains on the issues of “regulatory chill” – the idea that the obligation to pay compensation for regulatory change may make it more difficult for host states to regulate in “socially desirable” areas such as human rights or environment protection – and “a race to the bottom” – as an outcome of regulatory competition, progressive taxation policies and social welfare spending, when competition becomes fierce between nations over a particular area of trade and production, countries are given increased incentive to dismantle currently existing

regulatory standards – in environmental standards and policies. Copeland and Taylor (2004) argue that under the pressures of global competitiveness, the domestic industries of the developed countries may get hurt by losing market share to less developed countries with weaker environmental standards or may be forced to move industries to those countries (PHH). Moreover, under the auspices of the GATT/WTO, the governments may not be able to set the optimal environmental policies because of the constrained use of trade tools (Hudec 1996; Sheldon, 2006). Thus developed countries will either resist implementing stringent environmental policies in “regulatory chill” (Bagwell and Staiger, 2001a) or relaxing the existing environmental standards in a “race to bottom”(Bhagwati and Srinivasan, 1996; Bagwell and Staiger, 2001a). Therefore, as many critics argued, trade and investment competition could lead to lowering of environmental standards and regulations (World Bank 2000).

Nonetheless, some studies believe that “they should be no conflict between an open trade policy and a good environmental policy. A liberal trade policy should not prevent the adoption and implementation of good environmental policy and vice versa” (Medalla and Lazaro, 2005). They are numerous studies finding little or no evidence in linking trade to environmental regulations (Low and Yeats, 1992; Van Beers and Van den Bergh, 1997; Grether and De Melo, 2003). Environmental standards are not necessarily harmonized across nations because of different valuations of environmental resources (World Bank 2000). A lower environmental standard adopted by developing countries could simply be a reflection of absorptive capacity and not necessarily evidence of a “race to bottom” or “pollution haven”. Indeed many low-income developing countries are becoming more environmental aware and able to achieve high levels of environmental performance before they reach the income levels of the developed countries (World Bank 2000).

All in all, many puzzles remain unsolved in explaining the real connection between trade and environment.

4.3 THE MODEL

In the section, I present a modified Bertrand duopoly model of environmentally differentiated products. There exist two economies in the model: one developed country with a clean firm that produces clean products and one less developed country with a dirty firm that produces dirty products. The firms incur a production cost associated with the unit emission level of an environmentally differentiated product. I consider heterogeneous consumers with differentiated environmental preferences in the green market. In the model, I analyze two cases of government intervention in the Bertrand duopoly: an *ad valorem* tariff imposed by the developed country on the dirty products produced in the less developed country and an *ad valorem* tariff imposed by the less developed country on the clean products produced in the developed country.

4.3.1 FIRMS

I assume that a firm that produces a clean product with a low unit level of polluting emission is a clean firm, which is located in a developed country, while a firm associated with a high unit level of polluting emission is a dirty firm, which is located in a less developed country. I denote e as the observable per unit level of polluting emissions from producing the product, where e varies from zero to infinity. Without loss of generality, firm 1 is assumed to be a dirty firm that supplies a product with unit emission level e_1 at price p_1 and firm 2 is assumed to be a clean firm that supplies a product with unit emission level e_2 at price p_2 , where $e_1 > e_2 \geq 0$.

I assume that the production function exhibits constant returns to scale and the cost function exhibit costs that are linear in the level of output. Because firms must build a product line with a certain level of emission in advance of production, I assume that the average costs associated with the unit emission level are given by: for $i = 1, 2$, $C_i = C_i(e_i)$, meaning that the

average cost function of both firms are determined by the unit emission level, $C_i' = \partial C_i / \partial e_i < 0$, meaning that producing cleaner products with lower unit emissions requests higher costs, $C_i'' = \partial^2 C_i / \partial e_i^2 > 0$, showing that as the emissions decreases the costs to further reduce one unit of emissions increases. Following Moraga Gonzalez and Pandron-Fumero (2002), I assume that the average cost function is a homogenous function of degree ε :

$$(4.1) \quad C_1 = a e_1^{-\varepsilon},$$

$$(4.2) \quad C_2 = e_2^{-\varepsilon},$$

where $a > 1$, $\varepsilon \geq 2$. In order to avoid multiple equilibria in the decision game, I consider the asymmetry of costs function between the two firms, denoted by $a > 1$. The total cost function of both firms are given by:

$$(4.3) \quad TC_1 = C_1 * q_1 = a e_1^{-\varepsilon} q_1,$$

$$(4.4) \quad TC_2 = C_2 * q_2 = e_2^{-\varepsilon} q_2$$

where TC_i , $i = 1, 2$, represent the total costs of firm i and q_i is the output level of product i . The dirty firm from the less developed country can't choose to produce the clean product due to the inefficient cost performance. Because of environmental regulation in the developed country, although the clean firm has the capacity of producing dirty products, it is not allowed to do so.

4.3.2 CONSUMERS

I assume a continuum of heterogeneous consumers who differ in their marginal valuation θ of the green feature of the product: $\theta \in [0, 1]$, the value of which is uniformly distributed in the market. The two extreme cases of value θ equal to zero or one means that the consumer is completely unconscious or conscious of the environment.

Consumers can purchase either zero unit or, at most, one unit of the product. The net

surplus of consumer θ is assumed to be:

$$(4.5) \quad u(\theta, e) = v - e\theta - p$$

where v is the utility obtained from consuming a single unit of the product regardless of the unit emission level, p is price of the product. I assume that $v \geq \frac{e_1 p_2 - e_2 p_1}{e_1 - e_2}$ to ensure the demands for both products are positive. Note that the net surplus is assumed to be zero if a consumer does not purchase any product in the market.

4.3.3 DEMAND FUNCTIONS

I first solve for two indexes of marginal valuation at which consumer is indifferent between purchasing the dirty product or clean product and at which consumer is indifferent between purchasing the clean product or not purchasing any product. The first index $\theta_1 = \frac{p_2 - p_1}{e_1 - e_2}$ is solved from the equation $v - e_1 \theta_1 - p_1 = v - e_2 \theta_1 - p_2$, meaning that consumer with marginal valuation θ_1 is indifferent between purchasing the dirty product or clean product. The second index $\theta_2 = \frac{v - p_2}{e_2}$ is solved from the equation $v - e_2 \theta_2 - p_2 = 0$, showing that consumer with marginal valuation θ_2 is indifferent between purchasing the clean product or not purchasing at all. In summary,

$$\text{consumer } \theta = \begin{cases} \theta_1 = \frac{p_2 - p_1}{e_1 - e_2}, \text{ indifferent between clean or dirty product} \\ \theta_2 = \frac{v - p_2}{e_2}, \text{ indifferent between clean product or no product} \end{cases}$$

Based on our assumption on v , it is obvious to see that $\theta_2 \geq \theta_1$. For consumers θ falling in the range of $0 \leq \theta \leq \theta_1$, they purchase dirty product. For consumers θ falling in the range of $\theta_1 < \theta < \theta_2$, they purchase clean product. For consumers θ falling in the range of $\theta_2 < \theta \leq 1$, they don't purchase any product. So that, the demand function is written as:

$$\text{Demand of consumer } \theta = \begin{cases} \text{Dirty product,} & \text{if } 0 \leq \theta \leq \theta_1 \\ \text{Clean product,} & \text{if } \theta_1 < \theta < \theta_2 \\ \text{No product,} & \text{if } \theta_2 < \theta \leq 1 \end{cases}$$

Given the assumption of uniform distribution of θ , the demand for clean and dirty products are solved as:

$$(4.6) \quad q_1 = \theta_1 = \frac{p_2 - p_1}{e_1 - e_2},$$

$$(4.7) \quad q_2 = \theta_2 - \theta_1 = \frac{e_1(v - p_2) - e_2(v - p_1)}{e_2(e_1 - e_2)}.$$

where q_1 is the demand for dirty product and q_2 is the demand for clean product. Rearrange the above equations, the corresponding inverse demand functions are derived as:

$$(4.8) \quad p_1 = v - e_1 q_1 - e_2 q_2,$$

$$(4.9) \quad p_2 = v - e_2 q_1 - e_2 q_2,$$

where $p_2 > p_1$, p_1 is the price for dirty product and p_2 is the price for clean product.

4.3.4 GOVERNMENT

The government of the importing country imposes an *ad valorem* tariff on imported products. Specifically, when the developed country imports the dirty products from the less developed country, it imposes tariff t_1 on them; when the less developed country imports the clean products from the developed country, it imposes tariff t_2 on them.

The revenue function of firm i ($i = 1, 2$) is expressed as:

$$(4.10) \quad R_i = p_i q_i, \quad i = 1, 2$$

where R_i is the revenue received by firm i . The profit function of firm i ($i = 1, 2$) is expressed as:

$$(4.11) \quad \pi_i = (1 - t_i)p_i q_i - TC_i = [(1 - t_i)p_i - C_i(e_i)]q_i, \quad i = 1, 2$$

where π_i is the profit received by firm i , $t_i < 1$ is an *ad valorem* tariff levied by the importing country. Tax revenues of the importing country are collected from firm i under the *ad valorem* taxation. It is reasonable to assume that the tariff is ex ante committed by a credible tariff policy so that the domestic firms won't be able to monopolize the market in the importing country.

4.3.5 WELFARE

The social welfare of country i is given by:

$$(4.12) \quad W_i = CS_i + \pi_i + TR_i - \mu E_i, \quad i = 1, 2,$$

where W_i is the net social welfare of country i , $CS_i = N_{1i} \int_0^{\theta_1} (v - e_1 \theta - p_1) d\theta + N_{2i} \int_{\theta_1}^{\theta_2} (v - e_2 \theta - p_2) d\theta = N_{1i} \theta_1 \left(v - p_1 - \frac{e_1 \theta_1}{2} \right) + N_{2i} (\theta_2 - \theta_1) \left(v - p_2 - \frac{e_2 (\theta_2 + \theta_1)}{2} \right)$ is consumer surplus of country i , of which N_{1i} and N_{2i} are the population of consumers purchasing dirty products and clean products in country i , $\pi_i = (1 - t_i) p_i q_i - TC_i$ is the profits received by firm i (producer surplus of country i), $TR_i = t_j p_j q_j (i \neq j, j = 1, 2)$ is the tariff revenue of country i , μE_i ($\mu \geq 0$) is the social costs caused by polluting emissions, μ is the marginal social costs due to the emissions and $E_i = e_i q_i$ is the aggregate emissions in country i .

4.4 DEVELOPMENT OF THE GAME

In the paper, I present a three-stage game. In the first stage, the importing countries decide the level of an *ad valorem* tariff (t_i) on importing goods. In the second stage, firms simultaneously choose the unit emission level (e_i), which determines the production costs (C_i), before the production process start. Conditional on that, firms decide the prices of products (p_i) to compete in the Bertrand duopoly in the final stage. The following section is devoted to

analyzing the backwards induction steps in the development of Nash-equilibrium outcome.

4.4.1 PRICE GAME

In the final stage of the Bertrand game, the two firms are competing with prices given the tariff (t_i) and the unit emission level (e_i). Applying the process of iterated elimination of strictly dominated strategies, it yields a unique Nash equilibrium solution. The complete process requires an infinite number of steps to eliminate a fraction of prices remaining in each firm's strategy space. To find the Nash equilibrium of the Bertrand game, I solve the profit maximization problems for firm i ($i = 1,2$) with the price choices as the strategy. I substitute equation (4.6) and equation (4.7) into the equation (4.11) to solve the profit maximization problems for both firms with prices as the choices. Thus the Bertrand-Nash equilibrium price pair is given by:

$$(4.13) \quad (p_1^*, p_2^*) = \left(\frac{(1-t_1)e_1C_2(e_2)}{(4e_1-e_2)(1-t_2)} + \frac{2e_1C_1(e_1)+e_1(1-t_1)v-e_2(1-t_1)v}{4e_1-e_2}, \frac{2(1-t_1)e_1C_2(e_2)}{(4e_1-e_2)(1-t_2)} + \frac{C_1(e_1)(e_2-4e_1t_1)}{(4e_1-e_2)(1-t_1)} + \frac{2e_1(1-t_1)v-2e_2(1-t_1)v}{4e_1-e_2} \right).$$

We differentiate the Bertrand-Nash equilibrium prices with respect to the unit emission levels, the comparative statistic results are given by:

$$(4.14) \quad \frac{\partial p_1^*}{\partial e_1} > 0, \frac{\partial p_1^*}{\partial e_2} < 0, \frac{\partial p_2^*}{\partial e_1} > 0, \frac{\partial p_2^*}{\partial e_2} < 0.$$

The comparative static results show that the price of dirty products is positively relative to the unit emission of the dirty products while negatively relative to the unit emission of the clean products and the price of clean products is positively relative to the unit emission of the dirty products while negatively relative to the unit emission of the clean products.

4.4.2 EMISSION GAME

As the second stage of the Bertrand game, firms determine the unit emission levels taking the tariffs as given. As discussed in the setting of the model, firm 1 is assumed to be a dirty firm with unit emission level e_1 and firm 2 is assumed to be a clean firm with unit emission level e_2 , where $e_1 > e_2 \geq 0$.

The aggregate local emissions in country i ($i = 1,2$) and the total global emissions are solved by:

$$(4.15) \quad E_1 = e_1 q_1^* = e_1 * \frac{p_2^* - p_1^*}{e_1 - e_2},$$

$$(4.16) \quad E_2 = e_2 q_2^* = e_2 * \frac{e_1(v - p_2^*) - e_2(v - p_1^*)}{e_2(e_1 - e_2)},$$

$$(4.17) \quad E = E_1 + E_2 = \frac{e_1(v - p_2^* + e_2 p_2^*) - e_2(v - p_1^* + e_1 p_1^*)}{e_2(e_1 - e_2)},$$

where $\frac{\partial E_1}{\partial e_1} < 0$, $\frac{\partial E_1}{\partial e_2} > 0$, $\frac{\partial E_2}{\partial e_1} < 0$, $\frac{\partial E_2}{\partial e_2} > 0$, $\frac{\partial E}{\partial e_1} < 0$, $\frac{\partial E}{\partial e_2} > 0$. It shows that an increase in the unit emission level of the dirty product reduces the aggregate emissions for both countries and the total global emissions and an increase in the unit emission level of the clean product raises the aggregate emissions in both countries and the total global emissions. The results of comparative statics may seem counter-intuitive, however because the Bertrand-Nash equilibrium quantity of clean products is twice that of dirty products and clean products account for a larger share of emissions than the emissions from the dirty products, the increase in the unit emission of clean products raises polluting emissions while the opposite result applies to dirty products.

4.4.3 TARIFF GAME

In the first stage of the game, the government of the importing country chooses the tariff

level. The credible tariff policy is determined ex ante so that the firms are able to make production decisions in terms of the unit emissions and price choices based on the committed tariff level. I assume that the government has perfect information to implement the tariff game. The asymmetry of the cost functions for both firms impact the tariff outcomes by the governments and engage the two countries in the tariff game. Given the dirty firm in the less developed country produces with a higher cost function ($a > 1$), the government has the incentive to protect the domestic industry by levying a tariff on the competitive product with lower production costs. The developed country with a higher environmental standard has an incentive of tariffing on the imported dirty products to “punish” the pollution and to revenge on the tariff levied on its clean products.

In the first stage of tariff setting, I consider the policy maker of country i maximizes the tax revenue $TR_i = t_j p_j q_j$ by choosing t_j , while treating t_i as given ($i, j = 1, 2, i \neq j$). I calculate the first order condition and rearrange it to obtain a best reply function for the revenue maximizing policy maker:

$$\begin{aligned}
(18) \quad TR_1 &= t_2 p_2^* q_2^* = t_2 p_2^* \frac{e_1(v-p_2^*)-e_2(v-p_1^*)}{e_2(e_1-e_2)} = \frac{t_2}{e_2(e_1-e_2)} * \left[\frac{2(1-t_1)e_1C_2(e_2)}{(4e_1-e_2)(1-t_2)} + \right. \\
&\left. \frac{C_1(e_1)(e_2-4e_1t_1)}{(4e_1-e_2)(1-t_1)} + \frac{2e_1(1-t_1)v-2e_2(1-t_1)v}{4e_1-e_2} \right] * \\
&\left[e_1 \left(v - \frac{2(1-t_1)e_1C_2(e_2)}{(4e_1-e_2)(1-t_2)} - \frac{C_1(e_1)(e_2-4e_1t_1)}{(4e_1-e_2)(1-t_1)} - \frac{2e_1(1-t_1)v-2e_2(1-t_1)v}{4e_1-e_2} \right) - e_2 \left(v - \frac{(1-t_1)e_1C_2(e_2)}{(4e_1-e_2)(1-t_2)} - \right. \right. \\
&\left. \left. \frac{2e_1C_1(e_1)+e_1(1-t_1)v-e_2(1-t_1)v}{4e_1-e_2} \right) \right] \\
(19) \quad TR_2 &= t_1 p_1^* q_1^* = t_1 p_1^* \frac{p_2^*-p_1^*}{e_1-e_2} = \\
&\frac{t_1}{e_1-e_2} * \left[\frac{(1-t_1)e_1C_2(e_2)}{(4e_1-e_2)(1-t_2)} + \frac{2e_1C_1(e_1)+e_1(1-t_1)v-e_2(1-t_1)v}{4e_1-e_2} \right] * \left[\frac{(1-t_1)e_1C_2(e_2)}{(4e_1-e_2)(1-t_2)} + \frac{C_1(e_1)(e_2-4e_1t_1)}{(4e_1-e_2)(1-t_1)} + \right. \\
&\left. \frac{e_1(1-t_1)v-2e_1C_1(e_1)-e_2(1-t_1)v}{4e_1-e_2} \right]
\end{aligned}$$

Differentiating the above tax revenue function with respect to its tariff, we can derive the best response function for each country: $t_1^*(t_1, t_2)$ and $t_2^*(t_1, t_2)$.

I can also assume the policy maker of country i maximizes the welfare W_i ($i = 1, 2$). Differentiating the social welfare function with respect to its tariff level, we can derive the welfare-maximizing tariff level given the tariff used by the other country. In later chapter of welfare effects of strategic tariff (equation 4.29), I will show the existence of the strategic tariff by applying Lagrange mean value theorem.

4.5 EFFECTS OF TARIFF IMPOSED BY THE DEVELOPED COUNTRY

In this section, I analyze the effects of an *ad valorem* tariff imposed by the developed country on its local environment, social welfare and global environment.

4.5.1 ENVIRONMENTAL EFFECTS

Differentiating the local emissions in the developed country E_2 with respect to the tariff t_1 , we obtain:

$$(4.18) \quad \frac{dE_2}{dt_1} = \frac{\partial E_2}{\partial e_1} \frac{\partial e_1}{\partial t_1} + \frac{\partial E_2}{\partial e_2} \frac{\partial e_2}{\partial t_1} = \frac{2v}{(4e_1 - e_2)^2} \left[e_1 \frac{\partial e_2}{\partial t_1} - e_2 \frac{\partial e_1}{\partial t_1} \right]$$

Then I derive the effects of a tariff on the unit emission levels. I start with the first-order conditions of both firms' decision problems:

$$(4.19) \quad \frac{\partial}{\partial p_1} \left\{ \frac{(p_2 - p_1)[(1 - t_1)p_1 - c_1(e_1)]}{e_1 - e_2} \right\} = 0,$$

$$(4.20) \quad \frac{\partial}{\partial p_2} \left\{ \frac{[e_1(v - p_2) - e_2(v - p_1)][(1 - t_2)p_2 - c_2(e_2)]}{e_2(e_1 - e_2)} \right\} = 0.$$

Totally differentiating the first-order conditions of both firms' decision problems, the derivative of unit emissions with respect to the tariffs are given by (Moraga Gonzalez and Pandron-Fumero,

2002):

$$(4.21) \quad \frac{de_i}{dt_i} = \frac{c'_i(e_1) \partial^2 \pi_j}{\Delta \partial e_j^2} > 0, i, j = 1, 2, i \neq j,$$

$$(4.22) \quad \frac{de_i}{dt_j} = -\frac{c'_j(e_j) \partial^2 \pi_i}{\Delta \partial e_i \partial e_j} > 0, i, j = 1, 2, i \neq j.$$

where $\Delta > 0$. The partial derivatives show that in the Bertrand duopoly case the tariff raises the unit emission levels for both products compared to the free trade case (details see Appendix A).

Using equations (22) and (23) in equation (19), the sign of $\frac{dE_2}{dt_1}$ is equivalent to the sign of

$(2 - \epsilon_i)$, where $\epsilon_i \equiv \frac{e_i c''_i}{(-c'_i)}$ ($i = 1, 2$). Clearly, $2 - \epsilon_i < 0$ due to the assumptions of the cost

functions (equation 1 and 2) so that we have $\frac{dE_2}{dt_1} < 0$.

Similarly, I differentiate the total global emissions $E = E_1 + E_2$ with respect to the tariff t_1 :

$$(4.23) \quad \frac{dE}{dt_1} = \frac{\partial E}{\partial e_1} \frac{\partial e_1}{\partial t_1} + \frac{\partial E}{\partial e_2} \frac{\partial e_2}{\partial t_1} = \frac{3v}{(4e_1 - e_2)^2} \left[e_1 \frac{\partial e_2}{\partial t_1} - e_2 \frac{\partial e_1}{\partial t_1} \right] < 0$$

Hence the tariff reduces the pollution level in the developed country and the total global pollution level, compared to the free trade case. Although the tariff increases unit emission level of both products, the increase in the output of clean/dirty product raises/lowers the aggregate emissions. In the Bertrand duopoly case of tariff imposed by developed country, the magnitude of an increase in clean product is sufficiently smaller than that of the dirty product. Hence, the local and global environmental damages decline compared to the free trade scenario.

The results agree with the pollution haven hypothesis, or pollution haven effect, that free trade will encourage polluting industries relocating from developed areas with more stringent environmental regulations to less stringent locales. The premise is intuitive: applying clean technology and running a less or no polluting manufacture raise the total costs of production,

thus reduce the comparative advantages in the “dirty” industry majorly located in less developed areas.

4.5.2 WELFARE EFFECTS

In order to analyze the welfare effects of the tariff, I differentiate the social welfare function of the developed country with respect to the tariff. The result yields:

$$(4.24) \quad \frac{dW_2}{dt_1} = \underbrace{\left[\frac{\partial CS_2}{\partial e_1} + \frac{\partial R_2}{\partial e_1} \right]}_{-} \underbrace{\frac{\partial e_1}{\partial t_1}}_{+} + \underbrace{\frac{\partial CS_2}{\partial e_2}}_{-} \underbrace{\frac{\partial e_2}{\partial t_1}}_{+} + \underbrace{\frac{\partial CS_2}{\partial p_1}}_{-} \underbrace{\frac{\partial p_1}{\partial t_1}}_{-} + \underbrace{\frac{\partial CS_2}{\partial p_1}}_{-} \underbrace{\frac{\partial p_1}{\partial t_2}}_{+} + \underbrace{\frac{\partial CS_2}{\partial p_2}}_{-} \underbrace{\frac{\partial p_2}{\partial t_1}}_{-} + \underbrace{\frac{\partial CS_2}{\partial p_2}}_{-} \underbrace{\frac{\partial p_2}{\partial t_2}}_{+} +$$

$$\underbrace{\left(1 - \frac{1}{t_1}\right)}_{+} \underbrace{\left[\frac{\partial R_1}{\partial e_1} \frac{\partial e_1}{\partial t_1} + \frac{\partial R_1}{\partial e_2} \frac{\partial e_2}{\partial t_1} \right]}_{-} + \underbrace{\frac{1}{t_1^2} R_1}_{+}$$

where R_1 and R_2 are the Bertrand-Nash equilibrium revenue functions of dirty and clean firms.

I consider $\frac{\partial CS_2}{\partial e_1} < 0$, $\frac{\partial CS_2}{\partial e_2} < 0$, $\frac{\partial CS_2}{\partial p_2} < 0$ and $\frac{\partial CS_2}{\partial p_2} < 0$, showing that the consumer surplus of the developed country is negatively related to the unit emission level of both products. It is easy to show that $\frac{\partial R_1}{\partial e_1} < 0$, $\frac{\partial R_1}{\partial e_2} < 0$ and $\frac{\partial R_2}{\partial e_1} < 0$, suggesting that the Bertrand-Nash equilibrium revenue of dirty firm is negatively related to unit emission of both products and the Bertrand-Nash equilibrium revenue of clean firm is negatively related to unit emission of dirty product. Thus, the signs of the first, second and third terms of the welfare effect function are negative while the fourth term is positive. Unless the fourth term (tariff revenue) is sufficiently large, we consider that the tariff reduces the social welfare of the developed country.

Thus the trade restriction has caused a welfare loss in the importing country. In the literature of applied welfare economics, the welfare costs of exogenously given tariffs are assessed by calculating the areas of the “little triangles” of consumers’ and producers’ surplus lying beneath the demand and supply curves for the commodities on which these restrictions are

placed. In the Bertrand duopoly case, the tariff policy imposed by the developed country improves its local and global environment while reduces the social welfare. If the developed country has a high environmental standard, even if the tariff might reduce the consumer surplus and producer surplus, the country should restrict its imports of the dirty product from the less developed country. Otherwise, it should adopt a free-trade policy.

4.6 EFFECTS OF TARIFF IMPOSED BY THE LESS DEVELOPED COUNTRY

Following the previous section, I analyze the effects of an *ad valorem* tariff imposed by the less developed country on its local and global environment and social welfare.

4.6.1 ENVIRONMENTAL EFFECTS

In order to analyze the environmental effects of the tariff on the less developed country, I differentiate the local emissions in the less developed country E_1 and global emissions E with respect to the tariff t_2 . The total emissions in the Bertrand-Nash equilibrium is given by equation (4.12) and the first derivative to the tariff is derived as:

$$(4.25) \quad \frac{dE_1}{dt_2} = \frac{\partial E_1}{\partial e_1} \frac{\partial e_1}{\partial t_2} + \frac{\partial E_1}{\partial e_2} \frac{\partial e_2}{\partial t_2} = \frac{v}{(4e_1 - e_2)^2} \left[e_1 \frac{\partial e_2}{\partial t_2} - e_2 \frac{\partial e_1}{\partial t_2} \right]$$

Following the same procedures in the previous section, I substitute equations (4.22) and (4.23) in equation (4.26), the sign of $\frac{dE_1}{dt_2}$ is equivalent to the sign of $(\epsilon_i - 2)$, so that we have

$$\frac{dE_1}{dt_2} > 0.$$

Similarly, we derive the first derivative of the total global emissions E with respect to the tariff t_2 :

$$(4.26) \quad \frac{dE}{dt_2} = \frac{\partial E_1}{\partial e_1} \frac{\partial e_1}{\partial t_2} + \frac{\partial E_1}{\partial e_2} \frac{\partial e_2}{\partial t_2} = \frac{3v}{(4e_1 - e_2)^2} \left[e_1 \frac{\partial e_2}{\partial t_2} - e_2 \frac{\partial e_1}{\partial t_2} \right] > 0$$

Hence the tariff increases the environmental damages in the less developed country and worsens the global environment compared to the free trade case.

Less developed countries levy a trade-distorting tariff on clean products from developed countries to protect their local industries from competition and create a “pollution haven” for those dirty manufacturing sectors and eventually worsen local and global environment.

4.6.2 WELFARE EFFECTS

To show the welfare effects of the tariff policy on the less developed country, I differentiate its social welfare function with respect to the tariff. The result yields:

$$(4.27) \quad \frac{dW_1}{dt_2} = \underbrace{\left[\frac{\partial CS_1}{\partial e_1} + \frac{\partial R_1}{\partial e_1} \right]}_{-} \underbrace{\frac{\partial e_1}{\partial t_2}}_{+} + \underbrace{\frac{\partial CS_1}{\partial e_2}}_{-} \underbrace{\frac{\partial e_2}{\partial t_2}}_{+} + \underbrace{\frac{\partial CS_1}{\partial p_1}}_{-} \underbrace{\frac{\partial p_1}{\partial t_2}}_{-} + \underbrace{\frac{\partial CS_1}{\partial p_1}}_{-} \underbrace{\frac{\partial p_1}{\partial t_2}}_{+} + \underbrace{\frac{\partial CS_1}{\partial p_2}}_{-} \underbrace{\frac{\partial p_2}{\partial t_2}}_{-} + \underbrace{\frac{\partial CS_1}{\partial p_2}}_{-} \underbrace{\frac{\partial p_2}{\partial t_2}}_{+} +$$

$$\underbrace{\left(1 - \frac{1}{t_2} \right)}_{+} \underbrace{\left[\frac{\partial R_2}{\partial e_1} \frac{\partial e_1}{\partial t_2} + \frac{\partial R_2}{\partial e_2} \frac{\partial e_2}{\partial t_2} \right]}_{-} + \underbrace{\frac{1}{t_2^2} R_2}_{+}$$

We consider $\frac{\partial CS_1}{\partial e_1} < 0$, $\frac{\partial CS_1}{\partial e_2} < 0$, $\frac{\partial CS_1}{\partial p_1} < 0$ and $\frac{\partial CS_1}{\partial p_2} < 0$, showing that the consumer surplus in the less developed country is negatively related to the unit emission level of both products. It is easy to show that $\frac{\partial R_1}{\partial e_1} < 0$, $\frac{\partial R_2}{\partial e_1} < 0$ and $\frac{\partial R_2}{\partial e_2} < 0$, suggesting that the Bertrand-Nash equilibrium revenue of clean firm are negatively related to the unit emissions of both products and the Bertrand-Nash equilibrium revenue of dirty firm are negatively related to unit emission of dirty product. Thus, the signs of the first, second and third terms of the welfare effect function are negative while the fourth term is positive. Unless the fourth term (tariff revenue) is sufficiently large, we consider that the tariff reduces the social welfare of the less developed country.

The less developed country levies the trade restriction on competing products to protect its local economy. But the domestic consumers suffer from the lower imports and the consumer surplus decreases due to the trade distortion. The tariff distorts the free economy and lowers welfare from the free-trade level. In this case we consider an *ad valorem* tariff policy imposed by the less developed country on the clean product produced in the developed country. The tariff impairs the environment of the less developed country and the whole world while reduces the social welfare, compared to the free trade case. As the less developed country restricts the imports of clean products from the developed country, its environment is getting worse compare to the free trade case. Thus in the Bertrand duopoly case, the less developed country should adopt a free-trade policy to improve its local and global environment and social welfare.

4.7 ENVIRONMENTAL EFFECTS OF STRATEGIC TARIFFS

In this section I compare the Bertrand-Nash equilibrium environmental outcome with a hypothetical free trade scenario. To analyze the net environmental effects of the strategic tariffs played simultaneously by both countries, I totally differentiate the global environmental emissions with respect to the strategic tariffs. Using equations (24) and (27), the derivative of global emissions with respect to the tariffs is solved as:

$$(4.28) \quad \frac{\partial E}{\partial t_1} dt_1 + \frac{\partial E}{\partial t_2} dt_2 = \frac{3v}{(4e_1 - e_2)^2} \left\{ \left[e_1 \frac{\partial e_2}{\partial t_1} - e_2 \frac{\partial e_1}{\partial t_1} \right] dt_1 + \left[e_1 \frac{\partial e_2}{\partial t_2} - e_2 \frac{\partial e_1}{\partial t_2} \right] dt_2 \right\} =$$

$$\frac{3v}{(4e_1 - e_2)^2} \left\{ \frac{-c_1'(e_1)}{\Delta} \left[e_1 \frac{\partial^2 \pi_2}{\partial e_1 \partial e_2} + e_2 \frac{\partial^2 \pi_2}{\partial e_2^2} \right] dt_1 + \frac{-c_2'(e_2)}{\Delta} \left[e_1 \frac{\partial^2 \pi_1}{\partial e_1^2} + e_2 \frac{\partial^2 \pi_1}{\partial e_1 \partial e_2} \right] dt_2 \right\}$$

The sign of equation 28 is dependent upon on the absolute value of second partial derivatives of profits.

If $\left| \frac{\partial^2 \pi_i}{\partial e_i \partial e_j} \right| > \left| \frac{\partial^2 \pi_i}{\partial e_i^2} \right|$, $(i, j = 1, 2, i \neq j)$, then $\frac{\partial E}{\partial t_1} dt_1 + \frac{\partial E}{\partial t_2} dt_2 > 0$. It means that in this

case the tariffs levied by both countries improve the global environment. If

$\left| \frac{\partial^2 \pi_i}{\partial e_i \partial e_j} \right| < \left| \frac{\partial^2 \pi_i}{\partial e_i^2} \right|$, $(i, j = 1, 2, i \neq j)$, then $\frac{\partial E}{\partial t_1} dt_1 + \frac{\partial E}{\partial t_2} dt_2 < 0$. It means that the tariffs levied by

both countries worsen the global environment.

4.8 WELFARE EFFECTS OF STRATEGIC TARIFFS

As I showed in previous section, the marginal welfare effects of an ad valorem tariff policy on the importing country is given by:

$$(4.29) \quad \frac{dW_i}{dt_j} = \underbrace{\left[\frac{\partial CS_i}{\partial e_i} + \frac{\partial R_i}{\partial e_i} \right]}_{-} \underbrace{\frac{\partial e_i}{\partial t_j}}_{+} + \underbrace{\frac{\partial CS_i}{\partial e_j}}_{-} \underbrace{\frac{\partial e_j}{\partial t_j}}_{+} + \underbrace{\left(1 - \frac{1}{t_j} \right)}_{+} \underbrace{\left[\frac{\partial R_j}{\partial e_i} \frac{\partial e_i}{\partial t_j} + \frac{\partial R_j}{\partial e_j} \frac{\partial e_j}{\partial t_j} \right]}_{-} + \underbrace{\frac{1}{t_j^2} R_j}_{+}, i, j = 1, 2, i \neq j$$

By Lagrange mean value theorem, there exists $t_i^* > 0$ at which $\frac{dW_j}{dt_i} = 0$. For $0 < t_i < t_i^*$, the

value of $\frac{dW_j}{dt_i}$ is greater than zero. For $t_i > t_i^*$, the value of $\frac{dW_j}{dt_i}$ is smaller than zero.

In the normative analysis of strategic tariffs, the governments of the importing countries are assumed to maximize the social welfare, rather than having their behavior determined by more fundamental individual actions such as voting or lobbying. Maximizing the social welfare W_i with respect to its tariff policy t_j yields a first order condition as equation (30). Governments of the importing countries choose the tariff level t_j^* at which $W_i'(t_j^*) = 0$ to maximize the social welfare. This non-cooperative equilibrium in which both governments use tariffs is normally welfare-inferior to the free trade regime where neither uses tariffs.

4.9 CONCLUSIONS AND FUTURE DIRECTIONS

Unlike previous studies, the model of the chapter has following distinctive features: first, the environmental effluents are created through consumption choices; second, in the model we have heterogeneous consumers with various preferences for environmental quality; third, firms pick the environmental quality level of their products; fourth, there exist a clean (dirty) firm producing a clean (dirty) product located in a developed (less developed) country.

Based on the Bertrand duopoly model, I draw the two important conclusions:

First, developed country with high environmental consciousness should restrict the imports of “dirty” products from less developed country in order to improve its local and global environment. Second, the less developed country should adopt free-trade policy and import the “clean” product from the developed country to protect the environment locally and globally and improve social welfare.

Based upon our conclusions in the paper, future studies can be developed in the following directions. First, though our model has implied the existence of optimal tariff with environmental valuation, I didn't solve the tariff rate specifically. Second, because I focus on analyzing the tariff impacts on the importing country, I didn't discuss the scenario of tariff policy games played simultaneously by both countries. For future researches, we can examine the trade policy games of the reciprocity in the global economy. The impacts of the trade policy games on the social welfare of the whole world economy can be analyzed given endogenous choice of environmental qualities. Moreover, I only consider the trade policy in the form of an ad valorem tariff in the paper. Future researches can extend to the mixed trade barriers of tariffs, import quotas and/or import (production) subsidies.

CHAPTER 5

CONCLUSION

This chapter concludes the thesis, offering some discussion, implications for policy and outlining scope for future research.

5.1 DISCUSSION

This section gathers together the results of the three analytical studies which form the core of this thesis and offers some broad conclusions.

In the last two decades there have been a number of important developments in the field of environmental economics, with major steps forward taken in both empirical and theoretical treatments. Environmental concern has been a significant driving force behind this progress. As the rapid growth of biofuel production, the academic literature on biofuel policies has proliferated consequently. Because the issue of trade and the environment has appeared in most trade negotiations including WTO, there has been a heated debate in academic world on finding the real relationship between trade and the environment. However, there are many questions unanswered in the literature. This thesis examines three unresolved issues.

Chapter 2 addresses the question of second-best tax credit policy. What government tools to apply to subsidize biofuel? How to design those policies? What the impacts of tax credit policy on the general economy through fiscal interaction effects? What are the benefits? What are the drawbacks? The study presented in Chapter 2 addresses these questions by investigating the effects of tax credit on the general economy and estimating the level of the second-best policy. The estimate results of the marginal welfare effects show that the negative marginal costs from the tax credit is higher than the positive marginal benefits, which shows that the tax credit policy is welfare reducing in the second-best setting. Also I derive the analytical formula of the second best tax credit and estimate the level of it. The second-best tax credit is estimated to be

\$0.22/GEEG (\$0.15/gallon), which is 67% lower than the current tax exemption of \$0.475/GEEG (\$0.45/gallon). The estimate result suggests that there exists “water” in the current tax credit and there is a significant part of it is redundant, which is consistent with previous studies.

The next issue addressed in this thesis in Chapter 3 is second-best ethanol mandate policy. The aims in Chapter 3 are to measure the welfare effects of quantitative ethanol mandate and rank the tax credit versus the mandate policy. Given the pre-existing policies, how does the quantitative ethanol mandate function in partial equilibrium and general equilibrium? How does the quantitative ethanol mandate affect the general economy in the literature of double dividend? What is the ranking between tax credit and ethanol mandate? The analytical study presented in Chapter 3 addresses these questions by inheriting and adapting the general equilibrium model developed in Chapter 2. Results show that in the presence of lab tax and fuel tax policies, ethanol mandate is welfare enhancing and ethanol mandate dominates tax credit.

Chapter 4 addresses the trade-environment question: how to use trade tools to protect the local and global environment in the imperfect global competition? Specifically, in the asymmetric economy how should developed country with high environment standard react to the exports from the less developed country? What is the policy implication for the less developed country of lower environmental regulation? Using a modified Bertrand model, Chapter 4 suggests that if the developed country has a high environment consciousness, it should restrict imports of the dirty product from the less developed country and the less developed country should choose a free trade policy for the clean product from the developed country.

The studies contained in Chapter 2, Chapter 3 and Chapter 4 offer findings that are well-defined and actionable. But more importantly they have clear implications for economic policies. The next section discusses these implications.

5.2 POLICY IMPLICATIONS

This section discusses the policy implications stemming from the three analytical studies that make up this thesis.

Studying government intervention in the biofuel markets yields a number of policy-relevant results. Compared to other developed countries, the US has one of the lowest gasoline tax rates. The lower carbon intensity of biofuel compared to gasoline expands the options for reducing carbon emissions. Unlike a tax, policies that encourage greater domestic biofuel production and consumption through the use of subsidies and mandates appear to garner more political support. Thus it is significant to determine the welfare effects of these policies, especially through the fiscal interaction effects. Given the pre-existing government distortions, the best policy is a “second-best” policy because the true optimum cannot be attained. My first and second study extends the double dividend literature on biofuel polities by examining the welfare effects of the tax credit and ethanol mandate and policy implications of including those policies in the tax system. U.S. ethanol policy has generated considerable debate as to its efficacy in solving a host of policy problems including diversifying energy supply, improving the environment and farm incomes, reducing tax costs of farm subsidy programs and stimulating rural development. The potential misalignment of policy effects and stated objectives poses serious challenges for policy analysis and shows the paramount importance of understanding the basic economics of U.S. ethanol policies.

For policymakers, the first study of the thesis suggests that the current level of the tax credit policy is too high and a significant part of it is abundant, the result of which agrees with the previous studies. The second study of the thesis suggests that ethanol mandate is more welfare enhancing than the tax credit policy and is more plausible in the areas of improving environment and reducing the tax burden on the society.

In the asymmetric global economy, developed countries with higher environmental consciousness are more likely to use stringent trade policies than the less developed countries to

punish the polluting industries. Concerns have been raised about the effects of those policies on trade, environment and welfare. Many developed countries implement drastic measures to restrict trade in a product associated with environmental pollution. Trade agreements recognize countries' right to set their own standards and regulations on trade in order to protect human, animal, or plant health or life. For example, two World Trade Organization (WTO) agreements, the Sanitary and Phytosanitary (SPS) Measures Agreement and the Technical Barriers to Trade (TBT) Agreement, allow countries to set their own standards to protect plant and human health. In practice, some countries impose stricter-than-necessary conditions on imported goods to isolate domestic producers from international competition (James and Anderson, 1998). Those existing tariff barriers may lead to questionable impediments to imports that compete with domestic products, which may cause welfare losses for importing countries and mercantilist losses ("injury" in WTO language) for exporting countries due to reduced exports.

Chapter 4 uses a modified Bertrand duopoly model with environmentally differentiated products to analyze the effects of an ad valorem tariff on the environment and welfare of the importing country and the global environment. There are two cases considered in the study: the trade barrier levied by a developed country and a less developed country. Two important policy implications are concluded for both developed country and the less developed country: For the developed country with a high environmental standard and strict regulation, it should restrict imports of the dirty products, because tariff barrier improves its local and global environment while reduces the social welfare in total; For the less developed country, it should adopt free-trade policy to better the local and global environment and improve the total social welfare.

5.3 FUTURE RESEARCH

This section offers some thoughts on the extent to which future research can build on this thesis and draw on its findings.

The findings presented here on second-best policies offer a number of avenues for further research. One avenue is to investigate the effects of the second-best policy mix on the general economy. To what extent the second-best policy mix, which may include tax credit, mandate (quantitative, ratio), farm subsidy etc., jointly affects the general economy through fiscal interaction effects? Does the assessment of the general equilibrium differ from that of partial equilibrium from the previous studies? Should the biofuel policies play a smaller or bigger role in environment protection, energy security and rural development than what is commonly assumed?

Another intervention issue that offers scope for future research is that the effectiveness of the biofuel policies in open economy. For nations that pursue an environment and energy target in their biofuel policies, to what extent can policy be shown to be effective if consider international trade? That is, to what extent does the intervention succeed towards its target as intended if two or more nations are competing for the same target? Also future researches can extend the literature to the case that barely considered in previous studies that given the endogeneity of oil price how biofuel policies affect the general economy. Little attempt has been made to explore the effectiveness of the second-best biofuel policies based on implicit price setting.

One of the key findings in this thesis is that using the modified Bertrand model to analyze the effects of the trade policy on local and global environment and social welfare. Future research should explore alternative theoretical frameworks in a similar setting. For instance, using Cournot model in the duopolistic competition will yield completely different results from those derived from Bertrand model. To be specific, for various industries in the duopolistic competition competing in price or quantity will yield different analytical results. Also, future researches can extend to solve for the optimal tariff rate. In my thesis, it implied the existence of optimal tariff with environmental valuation, but I didn't solve the tariff rate specifically. Future studies can be developed in this direction. Considering the scenario of tariff policy games played simultaneously by both importing and exporting country, the effects of tariff on those countries

will differ from the results in the thesis as well. Future researches can extend the literature by examining the reciprocity of trade policy in the asymmetric global economy. Last, we only consider the trade policy in the form of an ad valorem tariff in the paper. Future researches can incorporate the mixed trade barriers of tariffs, import quotas and/or import (production) subsidies.

While this thesis offers plenty of scope for analytical extensions and further research, the intention is that in itself, this thesis represents a useful contribution to the fields of environmental economics and international trade.

APPENDIX A
FORMAL DERIVATION OF WELFARE EFFECTS

The representative consumer's utility function is assumed to be

$$(A1) \quad U = u(\tau(q_c, q_e + q_g), l) - \varphi(P),$$

and the agent faces the budget constraint,

$$(A2) \quad (p_e' + t)q_e + p_c q_c + (\bar{p}_g + t)q_g = (1 - t_L)L + G + \pi,$$

time constraint,

$$(A3) \quad l + L = \bar{L},$$

and price assumption,

$$(A4) \quad p_e' = \bar{p}_g = 1/\theta_g \text{ and } p_c = 1/\theta_c.$$

The solution to the problem is the demand for corn, ethanol, gasoline and leisure. They can be expressed by a function of exogenous variables:

$$(A5) \quad q_c(t, t_L, t_c), q_e(t, t_L, t_c), q_g(t, t_L, t_c), l(t, t_L, t_c).$$

The derived demand for pollution can be expressed as a function of exogenous variables as well:

$$(A6) \quad P(t, t_L, t_c).$$

Substituting the derived demands (A5) and (A6) into the utility function (A1) gives the indirect utility function,

$$(A7) \quad V = V(t, t_L, t_c) - \phi(P(t, t_L, t_c)).$$

From Roy's identity,

$$(A8) \quad \frac{\partial V}{\partial t} = -\lambda(q_e + q_g), \frac{\partial V}{\partial t_L} = -\lambda(\bar{L} - l), \frac{\partial V}{\partial t_c} = \lambda q_g.$$

where λ is the marginal utility of income.

Differentiating the indirect utility function (A7) with respect to t_c , holding t and t_L constant, and using the functions derived from Roy's identity (A8) gives,

$$(A9) \quad \frac{1}{\lambda} \frac{dV}{dt_c} = \frac{1}{\lambda} \frac{\partial V}{\partial t_c} + \frac{\phi'}{\lambda} \frac{dP}{dt_c} = q_e + \frac{\phi'}{\lambda} \frac{dP}{dt_c},$$

$$\text{where } \frac{dP}{dt_c} = \frac{\partial P}{\partial t_c} + \frac{\partial P}{\partial G} \frac{dG}{dt_c}.$$

The government constraint is

$$(A10) \quad G = t_L L + t(q_e + q_g) - t_c q_e.$$

Totally differentiating the government budget constraint (A10) and holding t and t_L constant, we can obtain:

$$(A11) \quad \frac{dG}{dt_c} = t_L \frac{dL}{dt_c} + t \frac{dq_e}{dt_c} + t \frac{dq_g}{dt_c} - t_c \frac{dq_e}{dt_c} - q_e.$$

Substituting (A11) into (A9), we obtain:

$$(A12) \quad \frac{1}{\lambda} \frac{dV}{dt_c} = \frac{1}{\lambda} \frac{\partial V}{\partial t_c} + \frac{\phi'}{\lambda} \frac{dP}{dt_c} = q_e + \frac{\phi'}{\lambda} \left[\frac{\partial P}{\partial t_c} + \frac{\partial P}{\partial G} \frac{dG}{dt_c} \right] = \frac{\phi'}{\lambda} \frac{\partial P}{\partial t_c} + t_L \frac{dL}{dt_c} + t \frac{dq_e}{dt_c} + t \frac{dq_g}{dt_c} - t_c \frac{dq_e}{dt_c}$$

Matching the analytical formula with fiscal interaction effects, we obtain:

$$\begin{aligned}
 \text{(A13)} \quad \underbrace{\frac{1}{\lambda} \frac{dV}{dt_c}}_{\text{Welfare effects of tax credit}} &= \underbrace{\frac{\phi'}{\lambda} \frac{dP}{dt_c}}_{\text{Environmental welfare gain}} \underbrace{-t_c \frac{dq_e}{dt_c}}_{\text{Own effects of primary cost}} + \underbrace{t \frac{dq_e}{dt_c}}_{\text{Subsidy-interaction effect in ethanol market}} + \\
 &\quad \underbrace{t \frac{dq_g}{dt_c}}_{\text{Subsidy-interaction effect in gasoline market}} + \underbrace{t_L \frac{dL}{dt_c}}_{\text{Tax-interaction effect}}
 \end{aligned}$$

APPENDIX B

FORMAL DERIVATION OF THE OPTIMAL TAX CREDIT

To determine the optimal tax credit t_c^* , we will set the equation (A15) to zero. Before that, we write its components in terms of empirically measurable elasticities. First, consider the second term in (A15). Totally differentiating the function of the government budget constraint in (A13) and considering the income tax t_L and fuel tax t constant, it yields the expression for $\frac{dL}{dt_c}$,

$$\frac{dL}{dt_c} = \frac{(t_c - t)q_e\eta_e - tq_g\eta_g}{t_c t_L}$$

where η_e is the price elasticity of ethanol and η_g is the price elasticity of gasoline demand to the tax credit.

Then we can rewrite the last term in (A15) as the product of the price of pollution and the price elasticity of pollution,

$$\frac{\phi' dP}{\lambda dt_c} = \frac{CP\eta_P}{t_c}$$

where $C \equiv \frac{\phi'}{\lambda}$ is the price of pollution, η_P is the price elasticity of pollution.

Similarly, we can rewrite the other terms in (A15) in the expression of elasticities. We rearrange the expressions and the optimal tax credit is derived as:

$$t_c^* = \frac{CP\eta_P}{q_g - q_e + q_e\eta_e}$$

APPENDIX C

ETHANOL PRODUCTION FUNCTION AND INVERSE SUPPLY CURVE OF

ETHANOL

We assume Leontief technology for ethanol production, $q'_e = \min(\lambda_c C, L'_e)$, where q'_e is ethanol output measured in volume units (gallons), C and L'_e are the inputs of corn and labor respectively, λ_c is a production coefficient. Following Mathews and McConnell (2009), dried distiller's grains with solubles (DDGS) and corn are perfect substitutes in feed use, we assume a unite of corn produces σ_1 units of byproduct and the price of the byproduct is of proportion to corn price (P_c), say $\sigma_2 P_c$. Hence, the ethanol production can be rewritten as $q'_e = \min(\sigma c, L'_e)$, where $\sigma = \lambda_c / (1 - \sigma_1 \sigma_2)$. We consider ethanol is measured in gasoline energy equivalent units, given the fact that one gallon of ethanol equals only .69 GEEG, we redefine $q_e \equiv \alpha q'_e$ and $L_e \equiv \alpha L'_e$, where $\alpha \approx 0.69$. Hence ethanol and labor input are measured in gasoline energy equivalent units. Ethanol production is rewritten as: $q_e = \min(\rho c, L_e)$, where $\rho = \alpha \lambda_c / (1 - \sigma_1 \sigma_2)$. The cost function for ethanol production is $(\frac{P_c}{\rho} + 1)q_e$, where the price of labor is normalized to one. With given input prices, the supply price of ethanol is $P_e^S = \frac{P_c}{\rho} + 1$. The derived inverse ethanol supply curve is $P_e^S(q_e) = P_c(q_e/\rho)/\rho + 1$. The slope of the derived inverse supply curve for ethanol is $\frac{dP_e^S}{dq_e} = [\rho^2 C'(P_c)]^{-1} > 0$, where $C(P_c)$ is the residue supply function of corn to ethanol production and $C'(P_c) > 0$. That is, $C(P_c) = q_c^S(P_c) - q_c(P_c)$, where $q_c^S(\cdot)$ is the corn output, $q_c(\cdot)$ is the household consumption of corn, $P_c(\cdot) \equiv C^{-1}(\cdot)$.

APPENDIX D
COMPARATIVE STATISTICS

Total differentiating the equilibrium arbitrage relations yields:

$$\begin{cases} dP_g^s(.) + \frac{\partial p_g}{\partial q_g} * dq_g = dP_f^s(.) + \frac{\partial p_f}{\partial q_f} * dq_f - dt \\ dP_e^s(.) + \frac{\partial p_e}{\partial q_e} * d\bar{M} = dP_f^s(.) + \frac{\partial p_f}{\partial q_f} * dq_f - dt \end{cases}$$

Using $\frac{\partial P_f}{\partial q_f} = \frac{1}{D'_f} < 0$, $\frac{\partial P_g}{\partial q_g} = \frac{1}{S'_g} > 0$ and $\frac{\partial P_e}{\partial q_e} = \frac{1}{\rho^2 C'} > 0$, the equilibrium arbitrage functions

become:

$$\begin{bmatrix} \frac{2(D'_f - S'_g)}{D'_f S'_g} \\ \frac{2}{D'_f} \end{bmatrix} \begin{bmatrix} dq_g \\ 0 \end{bmatrix} = \begin{bmatrix} \frac{2}{D'_f} & -1 \\ \frac{2(D'_f - \rho^2 C')}{D'_f \rho^2 C'} & 1 \end{bmatrix} \begin{bmatrix} d\bar{M} \\ dt \end{bmatrix}$$

The comparative static effects of fuel tax and ethanol mandate on prices and quantities are derived as:

$$\begin{aligned} \frac{dP_g}{dt} &= \frac{D'_f}{2(-D'_f + \rho^2 C' + S'_g)} < 0, \quad \frac{dq_g}{dt} = \frac{D'_f S'_g}{2(-D'_f + \rho^2 C' + S'_g)} < 0, \quad \frac{dP_f}{dt} = \frac{\rho^2 C' + S'_g}{2(-D'_f + \rho^2 C' + S'_g)} > 0, \quad \frac{dq_f}{dt} = \\ &\frac{(\rho^2 C' + S'_g) D'_f}{2(-D'_f + \rho^2 C' + S'_g)} < 0, \quad \frac{dP_g}{d\bar{M}} = \frac{1}{\rho^2 C'} > 0, \quad \frac{dq_g}{d\bar{M}} = \frac{S'_g}{\rho^2 C'} > 0, \quad \frac{dP_f}{d\bar{M}} = \frac{\rho^2 C' + S'_g}{\rho^2 C' D'_f} < 0, \quad \frac{dq_f}{d\bar{M}} = \frac{\rho^2 C' + S'_g}{\rho^2 C'} > 0 \end{aligned}$$

APPENDIX E
DERIVATION OF WELFARE EFFECTS

The representative consumer's utility function is assumed to be

$$(E1) \quad U = u(\tau(q_c, q_f), l) - \varphi(P),$$

and the agent faces the budget constraint,

$$(E2) \quad p_c q_c + p_f q_f = (1 - t_L)L + G + \pi,$$

time constraint,

$$(E3) \quad l + L = \bar{L},$$

and fuel blending requirement,

$$(E4) \quad q_f \equiv \bar{M} + q_g.$$

Substituting the conditions (E3), (E4) into the budget constraint (E2), the consumer's budget constraint becomes:

$$(E5) \quad p_c q_c + p_f \bar{M} + p_f q_g = (1 - t_L)(\bar{L} - l) + G(\bar{M}) + \pi(\bar{M}).$$

The solution to the problem is the demand for corn (q_c), fuel (q_f) and leisure (l). They can be expressed by a function of exogenous variables (t, t_L, \bar{M}):

$$(E6) \quad q_c(t, t_L, \bar{M}), q_f(t, t_L, \bar{M}), l(t, t_L, \bar{M}).$$

The derived demand for pollution (P) and government transfer (G) can be expressed as a function of exogenous variables as well:

$$(E7) \quad P(t, t_L, \bar{M}) \text{ and } G(t, t_L, \bar{M})$$

Substituting the derived demands (C6) and (C7) into the utility function (C1) gives the indirect utility function,

$$(E8) \quad V = V(t, t_L, \bar{M}) - \phi(P(t, t_L, \bar{M})).$$

From Roy's identity,

$$(E9) \quad \frac{\partial V}{\partial t} = -\lambda q_f = -\lambda(\bar{M} + q_g), \frac{\partial V}{\partial t_L} = -\lambda(\bar{L} - l), \frac{\partial V}{\partial \bar{M}} = \lambda MP_e,$$

where λ is the marginal utility of income, MP_e is the marginal profit of ethanol production. In equilibrium, $MP_e \equiv MC_e = p_e + \frac{\bar{M}}{\rho^2 c'}$. Thus,

$$(E10) \quad \frac{\partial V}{\partial \bar{M}} = \lambda(p_e + \frac{\bar{M}}{\rho^2 c'}).$$

Differentiating the indirect utility function (E8) with respect to \bar{M} , holding t and t_L constant, and using the functions derived from Roy's identity (E9) and (E10) gives,

$$(E11) \quad \frac{1}{\lambda} \frac{dV}{d\bar{M}} = MP_e - \frac{\phi'}{\lambda} \frac{dP}{d\bar{M}},$$

$$\text{where } \frac{dP}{d\bar{M}} = \frac{\partial P}{\partial \bar{M}} + \frac{\partial P}{\partial G} \frac{dG}{d\bar{M}}.$$

The government constraint is

$$(E12) \quad G = t_L L + t q_f = t_L L + t(\bar{M} + q_g).$$

Totally differentiating the government budget constraint (C12) and holding t and t_L constant, we can obtain:

$$(E13) \quad \frac{dG}{d\bar{M}} = t_L \frac{dL}{d\bar{M}} + t \frac{dq_e}{d\bar{M}} + t \frac{dq_g}{d\bar{M}}.$$

Substituting (E13) into (E11), we obtain:

$$(E14) \quad \frac{1}{\lambda} \frac{dV}{d\bar{M}} = \left(P_e - \frac{P_c}{\rho} - 1 \right) - \frac{\phi'}{\lambda} \frac{dP}{d\bar{M}} + t \frac{dq_e}{d\bar{M}} + t \frac{dq_g}{d\bar{M}} + t_L \frac{dL}{d\bar{M}}.$$

Matching the fiscal interaction effects with the analytical formula, we have:

$$(E15) \quad \underbrace{\frac{1}{\lambda} \frac{dV}{d\bar{M}}}_{\text{Welfare effects of mandate}} = \underbrace{\left(P_e - \frac{P_c}{\rho} - 1 \right)}_{\text{Own effects of price difference}} + \underbrace{\left(-\frac{\phi'}{\lambda} \frac{dP}{d\bar{M}} \right)}_{\text{Environmental welfare gain}} + \underbrace{t \frac{dq_e}{d\bar{M}}}_{\text{Subsidy-interaction effect in ethanol market}} + \underbrace{t \frac{dq_g}{d\bar{M}}}_{\text{Subsidy-interaction effect in gasoline market}} + \underbrace{t_L \frac{dL}{d\bar{M}}}_{\text{Tax-interaction effect}}$$

APPENDIX F
DETERMINATION OF SIGN OF DELTA

The determinant of the matrix is expressed as:

$$\Delta = \frac{\partial^2 \pi_1}{\partial e_1^2} \frac{\partial \pi_2^2}{\partial^2 e_1^2} - \frac{\partial^2 \pi_1^2}{\partial e_1 \partial e_2} \frac{\partial^2 \pi_2^2}{\partial e_1 \partial e_2}.$$

In the model, the following equations hold:

$$e_i \frac{\partial^2 R_i}{\partial e_i^2} + e_j \frac{\partial^2 R_i}{\partial e_i \partial e_j} = -2 \frac{\partial R_i}{\partial e_i}, i, j = 1, 2, i \neq j.$$

$$-\frac{\partial R_i}{\partial e_i} = -t_i C'_i, i = 1, 2.$$

Using the two equations above, we can rewrite the determinant as follows:

$$\Delta = \frac{e_1}{e_2} \frac{\partial^2 R_1}{\partial e_1 \partial e_2} \left(t_1 \frac{C'_1}{e_1} \right) (2 - \epsilon_1) + \frac{e_2}{e_1} \frac{\partial^2 R_2}{\partial e_2 \partial e_1} \left(t_2 \frac{C'_2}{e_2} \right) (2 - \epsilon_2) + \left(t_1 \frac{C'_1}{e_1} \right) (2 - \epsilon_1) \left(t_2 \frac{C'_2}{e_2} \right) (2 - \epsilon_2).$$

where $\epsilon_i \equiv \frac{e_i C''_i}{(-C'_i)} > 0, i = 1, 2$. Based on the nature of the cost functions, it holds that $\epsilon_i = \epsilon +$

$1 > 2, i = 1, 2$.

In the Bertrand duopoly case, we have positive cross partial coefficients, the sign for the determinant Δ is positive.

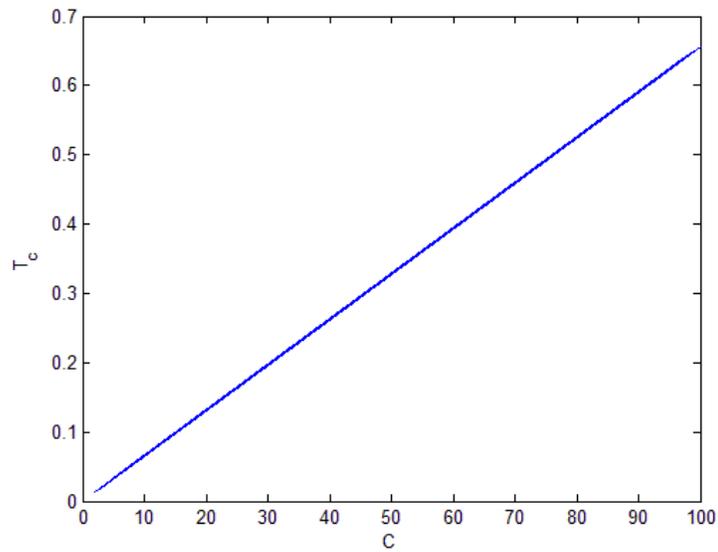


FIGURE A. RESPONSE OF THE OPTIMAL TAX CREDIT (\$/GEEG) TO A RANGE OF COST OF CO2 EMISSION (\$/TCO2

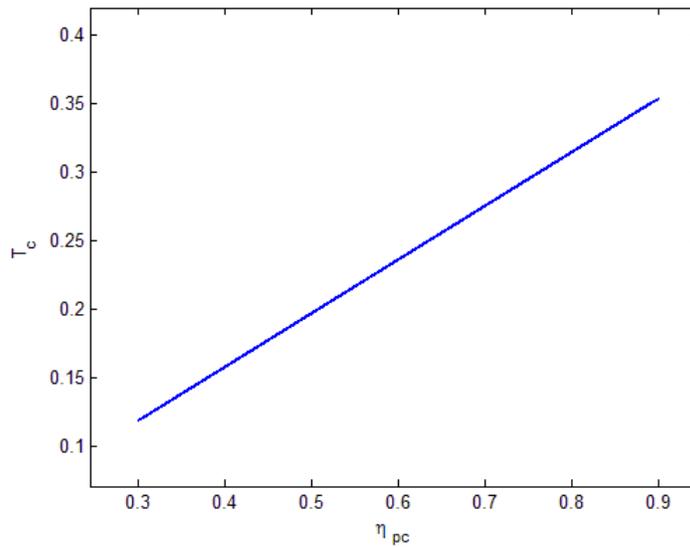


FIGURE B. RESPONSE OF THE OPTIMAL TAX CREDIT (\$/GEEG) TO A RANGE OF PRICE ELASTICITY OF GASOLINE

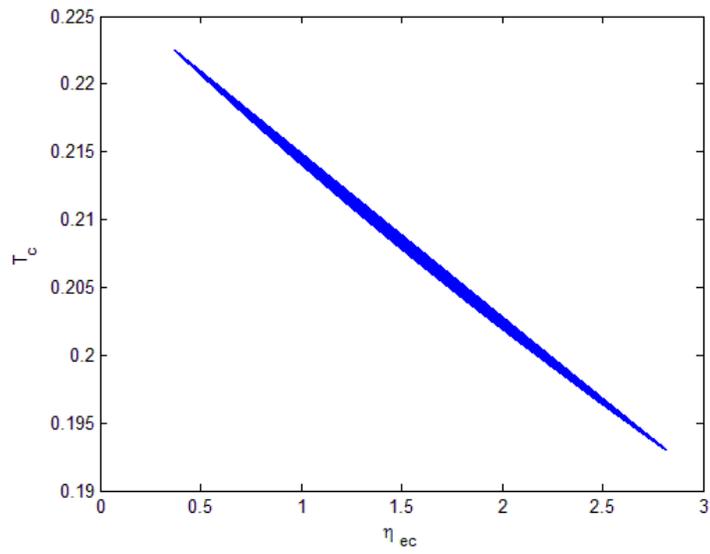


FIGURE C. RESPONSE OF THE OPTIMAL TAX CREDIT (\$/GEEG) TO A RANGE OF PRICE ELASTICITY OF ETHANOL

TABLE A PARAMETER VALUES

Parameter	Benchmark Value	Range
Tax & Subsidy		
Federal fuel tax (\$/gallon)	0.184	
State fuel tax (average,\$/gallon)	0.203	
Total fuel tax (\$/gallon)	0.387	
Ethanol tax (converted, \$/GEEG)	0.561	
Tax credit (\$/gallon)	0.45	
(\$/GEEG)	0.475	
Labor Tax (\$/labor)	0.39	
Price		
Ethanol price (\$/gallon)	1.79	
(\$/GEEG)	2.59	
Gasoline price (\$/GEEG)	2.11	
Fuel price (\$/GEEG)	2.5	
Quantity		
Oil (produced, billion barrel)	1.93	
(imported, billion barrel)	3.29	
Ethanol (produced/consumed, billion gallon)	10.67	
(produced/consumed, billion GEEG)	7.43	
Fuel (consumed, billion gallon)	134.4	
(consumed, billion GEEG)	131	
Gasoline (consumed, billion GEEG)	123.6	
Labor supply	8.6	
Externalities		
CO2 Emission Rate (of gasoline, kg/GEEG)	11.29	
CO2 Emission Rate (of corn ethanol, kg/GEEG)	8.42	
Cost (\$/tCO2)	33	2 to 100
Elasticities		
Gasoline price	0.55	0.3 to 0.9
Ethanol price	0.81	0.37 to 2.82
Gasoline-price of ethanol demand	4.35	0.5 to 5.0
Pollution output	0.008	

TABLE B. ESTIMATES OF MARGINAL WELFARE EFFECTS DUE TO TAX CREDIT

Elements	Estimates	
	Components	Total
Marginal benefits		
Environmental welfare gain (bil GEEG)	0.79	7.9
Subsidy-interaction effect in ethanol market (bil GEEG)	7.11	
Tax-interaction effect (GEEG)	1142.96	
Marginal costs		
Own effects of primary cost (bil GEEG)	6.02	64.5
Subsidy-interaction effect in gasoline market (bil GEEG)	58.46	
Net Marginal Welfare Loss (bil GEEG)		56.6
Optimal tax credit (\$/GEEG)		0.22

TABLE C. MONTE CARLO RESULTS FOR THE OPTIMAL TAX CREDIT

Level,t_c (dollars/GEEG)	Probability, $t_c^* < t_c$
0.00	0.062
0.05	0.094
0.10	0.137
0.15	0.192
0.20	0.258
0.25	0.334
0.30	0.417
0.35	0.505
0.40	0.592
0.45	0.675
0.50	0.750
0.55	0.815
0.60	0.868
0.65	0.910
0.70	0.941
0.75	0.963
0.80	0.977
0.85	0.987
0.90	0.993
0.95	0.996
1.00	0.998

TABLE D. PARAMETER VALUES

Parameter	Benchmark Value	Range
Corn Production		
Units of byproduct produced per unit of corn (σ_1)	0.303	
Proportion of byproduct price to corn price (σ_2)	0.776	
Ethanol Production		
GEEG units of ethanol per gallon (λ)	0.69	
Gallons of ethanol produced per bushel of corn (λ_c)	2.8	
Ethanol production coefficient ($\rho = \alpha\lambda_c/(1 - \sigma_1\sigma_2)$)	2.2	
Price		
Corn price (\$/bushel)	3.74	
(\$/gal)	0.4	
Gasoline price (\$/GEEG)	2.11	
Fuel price (\$/GEEG)	2.5	
Tax		
Federal fuel tax (\$/gal)	0.184	
State fuel tax (average, \$/gal)	0.203	
Total fuel tax (\$/gal)	0.387	
Quantity		
Gasoline (unblended, bil gal) (q_g)	85.28	
Ethanol mandate (bil gal) (\bar{M})	13	
Elasticities		
Corn supply (η_c^S)	0.23	
Gasoline demand (η_e^D)	-0.55	(-0.9, -0.3)
Gasoline-price (cross-price) of ethanol demand ($\eta_{e,g}$)	2.7	(2.5, 3)
Ethanol demand (η_e^D)	-0.81	(-2.82, -0.37)
Externality		
CO2 Emission Rate (of corn ethanol, kg/GEEG)	8.42	
Cost (\$/tCO2) ($-\frac{\phi'}{\lambda}$)	33	2 to 100
Labor market		
Labor tax (\$/labor) (t_L)	0.39	
Labor supply elasticity (η_L^S)	0.2	(0.1, 0.3)
Labor supply in ethanol production (2007)	6,594	

TABLE E ESTIMATES OF MARGINAL WELFARE EFFECTS DUE TO ETHANOL MANDATE

Elements	Estimates	
	Components	Total
Marginal benefits (\$/gal)		1.183
Own effects of price differences	0.61	
Environmental welfare gain	0.186 (0.012,0.581)	
Subsidy-interaction effect in ethanol market	0.387	
Marginal costs (\$/gal)		0.52
Subsidy-interaction effect in gasoline market	0.52	
Tax-interaction effect	$4.7 * 10^{-7}$	
Net Marginal Welfare Gain (\$/gal)		0.663

TABLE F CALIBRATIONS OF WELFARE EFFECTS

Welfare Effects Components	Ethanol Mandate	Tax credit
Own effects of primary cost (bil dollars)	0	-2.86
Own effects of price differences (bil dollars)	7.93	0
Environmental welfare gain (bil dollars)	2.418	0.38
Subsidy-interaction effect in ethanol market (bil dollars)	5.031	3.38
Subsidy-interaction effect in gasoline market (bil dollars)	-6.76	-27.77
Tax-interaction effect (mil dollars)	-0.005291	0.000543
Net Welfare Change (bil dollars)	8.61	-26.87

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