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REVENUE-NEUTRAL TAX-SUBSIDY POLICY FOR CARBON EMISSION REDUCTION

By

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Abstract

One of the benefits of biofuel use is a reduction in greenhouse gas emissions relative to fossil fuels, but no policy directly targets carbon emissions across the full spectrum of renewable and nonrenewable fuels. In light of the political unpopularity of carbon taxes in the United States, we develop a model for a revenue neutral price instrument that maximizes social welfare subject to an exogenously determined net tax revenue target. This approach may be more palatable because it has the potential to change the relative price of the low-carbon and high-carbon components of blended fuel while limiting increases in taxes and motor fuel prices. Our model shows that the targeted tax revenue level and share of output to total gross domestic product in all fuel sectors are important factors determining the revenue-neutral tax levels for each fuel type. Interestingly, we also find that the marginal damages of pollution are not the primary determinants of the revenue neutral price instrument, but instead it is the relative marginal damages per unit price of each fuel type. This implies the counterintuitive possibility that with a revenue neutrality constraint, higher net carbon emitting fuels such as gasoline or diesel may implicitly be subsidized using revenues from carbon taxes on lower emitting fuels.

Keywords: Non-renewable resources, carbon tax, carbon dioxide emissions, revenue recycling, revenue neutral

JEL Classifications: Q32, Q54, D62, H21

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1. Introduction

Two important issues regarding energy use have become prevalent: the development of alternative fuel sources to reduce dependence on fossil fuels and mitigation of greenhouse gases from fuel production and consumption. Approximately 70-75% of carbon dioxide emissions are due to the combustion of fossil fuels (Halverson et al, 1989), and biofuels have been touted as a viable alternative to fossil fuels for lowering carbon emissions from combustion engines. Although there is substantial debate about actual and potential life-cycle emissions from biofuels, examples include corn ethanol that emits about 22% less greenhouse gas than gasoline (Feng et al., 2008). Given the same energy equivalent from a coal power plant, poplar fed power plants produce approximately 5% of net emissions when taking into account the carbon sequestration potential of trees during growth (Kline et al, 1998).

Generally, a carbon tax is often cited by economists as a means to address externalities associated with carbon dioxide emissions from fuel production and use (Tol 2005). Welfare gains from emission taxes are significantly larger than other policies such as non-auctioned emission permits and quantity standards in the case of major industry innovations (Parry, 1998). However, despite the efforts of a number of high-profile advocates of carbon taxes, many policymakers see the implementation of a carbon tax as politically infeasible in the United States, especially in the short run. There are several potential reasons for this distaste for carbon taxes, but two of them are likely to be a distaste for adding “yet another” clearly identifiable tax on taxpayers, and an increase in fuel prices (Gilbert 2008).[1]

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[1] Another, perhaps more widely cited reason in the economics literature, is that taxes tend to be more costly to firms than quantity-based systems (McKibben and Wilcoxen 2002)

In this paper we examine a policy option that has not received much attention that may be more politically palatable than a pure carbon tax: providing tax credits (subsidies) for low carbon fuels based on carbon emissions that are funded solely by carbon taxes on high carbon fuels. To examine this possible policy alternative, we develop a model to maximize social welfare subject to an exogenously determined net tax revenue constraint. We derive the optimal market incentive instrument that internalizes the effects of greenhouse gas emissions given a net revenue constraint and investigating the cost and benefits of such a policy. This revenue constraint may require no net increases in total fuel tax revenues such that all revenues from positive fuel carbon taxes are used to fund subsidies for other types of fuels. Further, because the tax revenues from one blendstock are implicitly used to pay for the subsidy of another blendstock, the net price effect on blended motor fuel for a given content standard will be lower than a pure carbon tax. Policymakers and their constituents are likely to be more amenable to new tax structures when an increase in a tax in one sector is offset by a decrease in tax in another sector.

One common approach for promoting biofuel production and use is the application of biofuel consumption and blend mandates. The Federal Government is requiring an increasing level of consumption of renewable fuels ranging from 9 billion gallons in 2008 to 36 billion gallons in 2022.[2] The 2008 consumption standard implies an estimated 7.76% renewable fuel content of motor fuels (EPA 2008) and the increase in the renewable fuel standards will lead to roughly 24% ethanol content in gasoline by 2022 (DOE/EIA 2008).[3] Such a mandate implicitly taxes fossil fuels and subsidizes renewable fuels through its upward pressure on the derived

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[2] See The Energy Security and Independence Act of 2007; available at http://www.ethanol.org/pdf/contentmgmt/Full_Text_of_HR6.pdf

[3] This is an approximation using the total ethanol supply estimates and the total motor gasoline consumption numbers (net of the ethanol estimate) from DOE/EIA (2008).

demand for pure renewable fuel and downward pressure on the derived demand for fossil fuel (de Gorter and Just 2008). Furthermore, the Energy Security and Independence Act imposes a requirement that an increasing fraction of renewable fuels be comprised of advanced biofuels based on biomass and alternative feedstock types.

Even though carbon emissions reduction is often touted as a potential benefit of biofuel use, no state or federal policies to date directly target the carbon emission characteristics of biofuels. California is developing a Low Carbon Fuel Standard, which requires fuel producers to satisfy a maximum average carbon intensity limit per unit of fuel sold, and other states are now considering this approach as well. British Columbia has imposed a carbon tax on fossil fuels, but biofuels are exempt.

Subsidies for biofuel production have been broadly applied by the federal and state governments in the United States. Government subsidies to biofuel production have been justified for at least two reasons: changing the relative price of motor fuels to favor renewable fuels with lower carbon emissions and reduction of dependence on fossil fuels through technological innovations. Subsidies that help technological innovation in biofuel production and mitigation of greenhouse gases are commonly applied at both the state and federal level, and help decrease renewable fuel production costs while improving economic viability of biofuels in the long run.[4]

The revenue recycling literature has shown the potential of further reducing market imperfections by using pollution revenues to lessen distortions from taxes in other sectors (Parry, 1995, Parry 1997, Bovenberg and Mooji 1994). The literature focuses on the imposition of

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[4] Historically, however, these subsidies for biofuels are funded from general tax funds. The result is that blended fuel prices will decline relative to having no subsidy, and taxpayers in general pay from the subsidy rather than fuel users, and blended fuel consumption could likely increase.

pollution taxes to correct for market externalities and using the revenues to decrease employment or income taxes, leading to higher marginal value of labor productivity and after-tax income. For example, British Columbia's carbon tax program is designed to be revenue neutral in that the carbon tax revenues from fossil fuels are used to fund reductions in income and other taxes.[5] Our conceptual framework is similar, but with a focus on the fuel sector by deriving the optimal tax structure that corrects for the pollution externality while meeting a tax revenue target.

Applying the proposed revenue-neutral price instrument has the potential to avoid some of the drawbacks of quantity control instruments such as fuel content standards. Price instruments versus quantity instruments have been studied to determine the optimal policy yielding the better welfare outcome (Weitzman 1974). Several authors have determined that price incentives offer the higher welfare results than quantity instruments in dealing with global climate change problems (Fischer and Newell 2008, Parry and Pizer 2007, Newell and Pizer 2003, Hoel and Karp 2002, Pizer 2002, McKibbin and Wilcoxon 1997). In this regard, carbon taxes have been touted as a means of reducing carbon dioxide emissions.

We develop a multi-sector model representing varying fuel types. Fuel sectors are connected through their contribution to accumulated atmospheric carbon dioxide from emissions and sequestration during the lifecycle of fuel production and consumption. A social planner selects a carbon tax/subsidy schedule to reduce carbon emissions while constraining pollution tax revenues to be revenue neutral.

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[5] British Columbia's system does not incentivize life-cycle carbon emission reduction of biofuels because biofuels are exempt from the carbon tax, and no carbon-indexed tax credits are provided for biofuels either based on the carbon tax or from general funds. See British Columbia Ministry of Small Business and Revenue. 2008 at http://www.sbr.gov.bc.ca/documents_library/notices/BC_Carbon_Tax_Update.pdf.

We find that a social planner imposes standard a carbon tax rate that is increasing in emissions level when unconstrained by budgetary factors. If a revenue neutrality constraint is imposed, three important factors determine the tax structure: total tax revenue target, share of output to total Gross Domestic Product from all fuels, and the relative marginal damages from pollution per unit price of the good. When the exogenous net tax revenue target is lower, the constrained tax rates are also lower. The proportion of output to total Gross Domestic Product from all fuels affects the magnitude of the policy. Interestingly, we also find that relative marginal damages per unit price, and not just marginal damages, determine the sign and magnitude of the pollution tax. In fact, under some circumstances, high carbon-emitting fuel types may be faced with a lower tax or even subsidized if their output price is significantly larger than low-carbon fuel types.

The rest of the article is organized in the following manner. Section 2 presents the model. Section 3 provides simulations given various fuel types. Section 4 summarizes the results of the study and enumerates future directions of the study.

2. Pollution tax model for multiple fuel types

We assume that the economy is composed of three sectors: a fossil fuel sector (F), a biofuel sector (B) and a clean sector (C). Firms in each sector produce output according to a production function of the form:

$$y_i = y_i(K_{ij}, L_{ij}) \qquad \forall i = B, F, C$$

where K_{ij} and L_{ij} are capital and labor in sector i allocated by the *jth* firm. Each *jth* firm in sector i maximize profit, π_{ij}, by optimally selecting capital and labor,

$$\pi_{ij} = (p_i - t_i) y_i(K_{ij}, L_{ij}) - wL_{ij} - rK_{ij} \qquad \forall i = B, F$$

where w and r are endogenously determined input price of labor and capital, respectively. Producers receive a net price equivalent to the gross price of the fuel, p_i, in each sector minus a pollution tax, t_i, for each output sold in the market. The clean sector is considered the numeraire good and faces a similar profit maximizing problem without a pollution tax. Firms in the clean sector are not taxed since we assume that pollution is not a by-product during the production or consumption of the clean final good.

We assume that capital in each sector is quasi-fixed but labor is allowed to move between the three sectors of the economy.[6] The revenue function in each sector i=B,F can be written as:

$$R_i[p_i, t_i, p_k, t_k, K, L] \equiv \max_{K_{ij}, L_{ij}} \left\{ \sum_j ((p_i - t_i) y_i(K_{ij}, L_{ij}) - wL_{ij} - rK_{ij}) : \sum_j K_{ij} = K; \sum_j L_{ij} = L \right\} \quad \forall i \neq k.$$

where K and L are total capital and labor endowments, respectively, in the economy and a subscript k implies an alternative sector from sector i. Total gross domestic product, G, in the economy is the summation of revenues in each sector plus tax revenues paid by all firms in each sector,

$$G[p_B, t_B, p_F, t_F, p_C, K, L] \equiv \sum_{B,F,C} R_i[p_B, t_B, p_F, t_F, p_C, K, L] + \sum_{B,F} t_i y_i^*(p_B, t_B, p_F, t_F, p_C, K, L),$$

where $y_i^*(p_B, t_B, p_F, t_F, p_C, K, L)$ is the indirect production function in sector i. Here, production in sector i is increasing in its own price, p_i, tax in the other sector, t_k, and input endowments K and L. Total tax revenues, T, are equal to the total output produced in each sector multiplied by

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[6] We assume perfect substitutability of labor skills across sectors. Relaxing the degree in which labor is substitutable across sectors adds to the complexity of the model by allowing for a vector of wages corresponding to a vector of labor skills. However, this does not change the qualitative results of our model.

the tax rate such that $T = \sum_{B,F} t_i y_i^*(p_B, t_B, p_F, t_F, p_C, K, L)$. We consider the case where T is endogenously determined in the economy and when it is exogenously determined by an agent.

Total pollution in the economy is dependent on total production of fossil fuel and biofuel. Total carbon emissions, E, are equal to

$$E = \sum_{B,F} e_i y_i^*(p_B, t_B, p_F, t_F, p_C, K, L),$$

where e_i is net carbon emissions rate from output in the sector. We assume that total net carbon emissions during the production and consumption cycle of fossil fuels are greater than biofuels, $e_F > e_B$. It is may also be likely that net carbon emissions from different biofuel feedstocks are less than zero given the carbon sequestration potential during the growth process of feedstocks such as wood. We do not assume that $e_B < 0$ but we do allow for this potential to occur.

All consumers in the economy receive utility from gross domestic product but disutility from the flow of carbon emissions. The indirect utility function, V, representing aggregate consumer welfare is quasilinear and written as

$$V = U(G) - \delta E,$$

where $U(G)$ is the aggregate utility derived from gross domestic product and δ is the marginal disutility from total carbon emissions. We assume that utility is concave in gross domestic product. Marginal disutility from carbon emissions may differ depending on the geographical location of consumers but we assume that they are the same for all agents.

2.1. Pollution tax with endogenously determined tax revenues

In the baseline case, we assume that the government chooses taxes to internalize the effect of the externality from firms in each sector without any constraints on the tax instrument. The objective of the government is to maximize aggregate consumer welfare by optimally determining tax rates in each sector subject to private sector behavior in the fossil fuel and biofuel sectors, production possibilities and fixed gross prices. The utility from reinvestment of carbon tax revenues is taken into account and the target of the reinvestment is unconstrained. We can write the government's problem as

$$(1) \qquad \max_{t_F, t_B} V = U(G) - \delta E .$$

The first order conditions yields

$$(2) \qquad \frac{\partial V}{\partial t_i} = U'(G)\left(\frac{dR_i}{dt_i} + y_i^* + t_i \frac{dy_i^*}{dt_i} + t_k \frac{dy_k^*}{dt_i}\right) - \delta\left(e_i \frac{dy_i^*}{dt_i} + e_k \frac{dy_k^*}{dt_i}\right) = 0 \qquad \forall i = F, B .$$

Simultaneously solving for tax rates in each sector yields the unconstrained tax for pollution, t^u_i, in each sector,

$$(3) \quad t_i^u = \frac{\delta e_i}{U'(G)} \qquad \forall i = F, B .$$

Expression (3) can be interpreted as a standard Pigouvian carbon tax equal to the marginal damages from the production of fuel in each sector. Since we assume that $e_F > e_B$, Pigouvian taxes for fossil fuels are higher than for biofuels. If net carbon emissions from a particular biofuel are negative, a subsidy for biofuels would be instituted to maximize welfare.

We illustrate the optimal Pigouvian tax combination in tax space in Figure 1. The indirect utility function from gross domestic product, *U(G)*, is quasiconvex in taxes. Lower contour levels of U(G) represent higher utility. Total carbon emissions, *E*, can also be drawn in the space. Here, we find that higher contour sets of *E* imply lower carbon emissions levels since higher tax rates decrease output levels and, subsequently, emission levels. The point of tangency shows the optimal tax revenue, *T**, that maximize utility of the economy. Thus, the tangency between *U(G)* and *E* illustrates the optimal Pigouvian taxes in both sectors.

The model can be extended to account for more than two fuel types. Each fuel type can be considered a separate sector in the economy. Without any restrictions on the tax structure, it is easy to show that the optimal Pigouvian taxes are chosen similar to (3). Here, we find that as taxes are increased in the fuels sector, labor is reallocated across sectors until the value of marginal product of labor across all sectors are equal. Since the clean sector is not taxed, we would expect relatively more labor to enter into the clean sector once the government imposes the optimal Pigouvian pollution tax.

2.2. Pollution tax with exogenously determined net tax revenue constraint

We turn to the case where the government institutes pollution taxes subject to a revenue neutral constraint. A general revenue neutrality constraint for a fixed total net revenue $T = t_F y_F^* + t_B y_B^*$ implies a constant and a linear relationship between the two tax rates given optimal production levels: $t_F = \frac{T}{y_F^*} - t_B \frac{y_B^*}{y_F^*}$. A more specific form of this constraint is when net revenues are zero implying $t_F = -t_B \frac{y_B^*}{y_F^*}$.

The government's objective function in this case remains the same as (1) but now we constrain taxes to a predetermined tax revenue level, *T*. We write the government's problem as,

$$(4)\ \max_{t_F, t_B} V = U(G) - \delta E \quad s.t.\ T = t_F y_F^* + t_B y_B^* .$$

The corresponding Lagrangian function is

$$(5)\ \max_{t_F, t_B} L = U(G) - \delta E + \lambda (T - t_F y_F^* - t_B y_B^*) \ ,$$

where λ is the Lagrange multiplier and is interpreted as the marginal utility from the predetermined net tax revenue level, T. The first order conditions are

$$(6)\ \frac{\partial L}{\partial t_i} = U'(G)\left(\frac{dR_i}{dt_i} + y_i^* + t_i\frac{dy_i^*}{dt_i} + t_k\frac{dy_k^*}{dt_i}\right) - \delta\left(e_i\frac{dy_i^*}{dt_i} + e_k\frac{dy_k^*}{dt_i}\right) - \lambda\left(y_i^* + t_i\frac{dy_i^*}{dt_i} + t_k\frac{dy_k^*}{dt_i}\right) = 0 \qquad \forall i \neq k$$

$$(7)\ \frac{\partial L}{\partial \lambda} = T - t_F y_F^* - t_B y_B^* = 0\,.$$

Simultaneously solving for the constrained taxes and optimal λ, t_i^c in each sector yields

$$(8)\ t_i^c = \frac{\delta\left(e_i + \frac{dy_k}{dy_i}e_k\right)y_k - TU'(G)\frac{dy_k}{dy_i}}{U'(G)\left(y_k - \frac{dy_k}{dy_i}y_i\right)} \qquad \forall i \neq k$$

where $\frac{dy_k}{dy_i}$ is the marginal rate of transformation between the output in the two sectors of the economy (see Appendix 1). The denominator is positive since the marginal rate of transformation is negative and marginal utility from gross domestic product is positive. If total tax revenue targets are aimed to raise revenues, pollution taxes are likely to be positive. In fact, revenue-neutral pollution tax is increasing in the total tax revenue target *T.* If total tax revenues are constrained to zero and output prices are equal, the fuel type with higher marginal damages will have a positive tax rate while the other fuel type will need to be subsidized.

Figure 2 illustrates the constrained taxes in each sector when total tax revenues are constrained to zero. Using the contour sets for U(G) and E, a constraint of total tax revenue to T'=0 implies U(G) and E are tangent at t_F^c and t_B^c. In this case, since we have assumed that fossil fuel net emissions are larger than biofuels and output prices are equal, the former will be taxed a positive amount while the latter is subsidized.

To understand the important factors determining optimal pollution tax levels when net tax revenues from the policy are equal to zero, we manipulate (8). In equilibrium, the marginal rate of transformation (slope of the production possibility frontier) is equal to the ratio of output prices (slope of the isorevenue line), resulting in $\frac{dy_k}{dy_i} = -\frac{p_i}{p_k}$. Hence, when T=0, we have

$$(9)\ t_i^c = \frac{\delta\left(e_i - \frac{p_i}{p_k}e_k\right)y_k}{U'(G)\left(y_k + \frac{p_i}{p_k}y_i\right)} \qquad \forall i \neq k\cdot$$

Re-arranging terms and recognizing that the unconstrained Pigouvian tax is given by (3), we have

$$(9')\ t_i^c = \left(\frac{t_i^u}{p_i} - \frac{t_k^u}{p_k}\right)p_i\Gamma_k \qquad \forall i \neq k,$$

where $\Gamma_k = \frac{p_k y_k}{\left(p_k y_k + p_i y_i\right)}$.

If total tax revenues are targeted to be zero, two factors determine the value of the constrained tax: the share of output in a fuel sector to total gross domestic product and the relative marginal damages per unit price from fuel use. The share of output to total Gross Domestic Product does not determine the sign of the tax. However, it serves to augment or reduce the value of the tax or subsidy imposed since a larger share of output increases the value of the policy. To determine the sign of the tax, one would need to compare the relative marginal damages *per unit price* from a good. We find that if the marginal damage per unit price of good *i* is larger than that of good *k*, i.e. $t_i^u / p_i > t_k^u / p_k$, good i needs to be taxed more. We find an important result: the difference between marginal damages *per unit price* of fuels (not just marginal damages) determines optimal revenue-neutral pollution taxes.

The reason that the optimal revenue-neutral tax is dependent in part on prices is as follows. Because net tax revenue is fixed, a tradeoff in setting the optimal revenue-neutral tax occurs between the change in value of production among each of the taxed industries and a reduction in emissions. The higher the value of output due to a higher relative output price in a sector, the higher the opportunity cost of reducing emissions in that sector relative to other sectors, *ceteris paribus*. Thus, the welfare gains from increasing the tax rate to internalize emissions externalities are weighted by the respective prices in a sector.

This result implies a few important points. First, optimal revenue neutral taxes vary as prices and output levels change even if the optimal Pigouvian tax remains constant. This is a potentially important complication for implementing such a tax structure and has implications for economic welfare. Second, to maximize social welfare it would be possible to impose a lower pollution tax on a fuel with a high net coefficient of carbon emissions compared to a fuel with low net carbon emissions if the price of the output of the former is many times higher than the latter in order. We discuss these issues in the next section.

As with the Pigouvian tax structure, the model with an exogenous tax revenue constraint can be extended to include multiple fuel types. With *N* fuel types, we can generalize the problem of the government as

$$(4') \quad \max_{t_1,\ldots,t_N} V = U(G) - \delta E \quad s.t. \; T = \sum_{i}^{N} t_i y_i^* .$$

The corresponding first order conditions from (4') are,

(6')

$$\frac{\partial L}{\partial t_i} = U'(G)\left(\frac{dR_i}{dt_i} + y_i^* + t_i\frac{dy_i^*}{dt_i} + \sum_{k=1}^{N-1} t_k\frac{dy_k^*}{dt_i}\right) - \delta\left(e_i\frac{dy_i^*}{dt_i} + \sum_{k=1}^{N-1} e_k\frac{dy_k^*}{dt_i}\right) - \lambda\left(y_i^* + t_i\frac{dy_i^*}{dt_i} + \sum_{k=1}^{N-1} t_k\frac{dy_k^*}{dt_i}\right) = 0 \qquad \forall i \neq k$$

$$(7') \quad \frac{\partial L}{\partial \lambda} = T - \sum_{i=1}^{N} t_i y_i^* = 0 .$$

Simultaneously solving for N pollution taxes and λ using N expressions similar to (6') along with (7') will yield the optimal the constrained tax levels in each sector. Given the complexity of the solution, we turn to numerical simulations to describe the results of the model in a multi-fuel setting.

3. Simulated pollution taxes for multiple fuel types

We apply this model in the presence of five different fuel types: gasoline, diesel, corn ethanol, cellulosic ethanol and biodiesel. We impose a set of assumptions about net greenhouse gas emissions for each of these fuel types that are roughly consistent with the current literature.[7] Gasoline and diesel are petroleum based and considered to have higher net carbon emissions than the other fuel types. Corn ethanol and biodiesel are considered "first generation" biofuels with relatively lower net carbon emission than gasoline or biodiesel. Cellulosic ethanol is considered a "second generation" biofuel that can be derived from plants, agricultural residues, wood and wood residues, among other sources.[8] Carbon emissions from cellulosic ethanol are assumed here to be lower than corn ethanol or biodiesel. Based on these and other assumptions developed below, we simulate the unconstrained and tax revenue-constrained pollution taxes and their welfare implications for the economy under several scenarios.

3.1. Parameters and functional forms

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[7] It is worth reiterating here, that the science behind estimating life –cycle net greenhouse gas emissions for biofuels is currently contentious and unsettled. We use the available estimates in the literature for our simulations.

[8] The relative standings in carbon emissions is based on analysis of processes that have developed in markets that do not directly impose a charge on carbon. It is not clear how the relative emissions reductions of these types of biofuels would change if a carbon tax or subsidy were imposed.

The revenue function and utility function are needed to calculate optimal pollution taxes. To simplify the analysis, we assume that utility is linear in gross domestic product. This would imply that the marginal utility of GDP is constant and we set it equal to 1. The production function is assumed to be Cobb-Douglas and quasi-fixed capital is normalized to 1 such that

$$y_i = L_{ij}^{\alpha_i} \qquad \forall i = B, F, C,$$

where α_i is the input elasticity of labor. In equilibrium, the value of marginal products across all sectors are equalized such that

$$(p_i - t_i)\alpha_i L_i^{\alpha_i - 1} = (p_k - t_k)\alpha_k L_k^{\alpha_k - 1} = \ldots = p_c \alpha_c L_c^{\alpha_c - 1},$$

where *i* and *k* represent sectors that emit carbon dioxide and sector c is the clean sector. Using the equilibrium condition along with the labor constraint, $\sum_i L_i = L$, we want to solve for the optimal level of labor in each sector of the economy. To obtain a simple closed form solution, we assume that input elasticities across sectors are equal. Algebraic manipulation shows that for any fuel sector emitting carbon dioxide, the revenue function is of the form

$$R_i = \frac{\left(p_i - t_i\right)^{1/(1-\alpha)} L^{\alpha}}{\left(\sum_q^N \left(p_q - t_q\right)^{1/(1-\alpha)} + p_c^{1/(1-\alpha)}\right)^{\alpha}}.$$

In this specification, there are N fuel sectors emitting carbon dioxide and one clean sector. Here, revenue is increasing in own prices and pollution taxes from other sectors but decreasing in prices of other fuels and own taxes.

Table 1 summarizes the parameters for emissions coefficient of various fuels and prices from studies in the literature. Cellulosic ethanol is a new fuel which has not been fully developed. For the meantime, we assume that the price of this fuel source is the same as corn ethanol. Estimates for emissions coefficient for cellulosic ethanol range from the same level as corn ethanol to 10% of corn ethanol emissions (Farrell et al. 2006). We calculate pollution taxes across a range of emissions coefficients. In estimating marginal damages from pollution, we start with the average market price of long term carbon sequestered at \$20 / ton of carbon and convert it to utils per kilogram.[9]

3.2. Simulation Results

Table 2 summarizes pollution taxes with and without tax revenue constraints. Unconstrained Pigouvian taxes range from \$0.048/gal for biodiesel to \$0.088/gal for diesel. Since all net emissions are positive for the five fuel types, marginal damages from fossil fuel use are positive leading to positive taxes. If we assume that the government imposes net tax revenue equal to zero across all fuel types and output prices are equal, we find that the ranking of carbon taxes across fuels are based on the emissions level. Diesel has the highest carbon tax at \$0.018/ gal and two fuel types, cellulosic ethanol and biodiesel, are subsidized most at \$0.016/gal and \$0.024/gal, respectively.

When prices of fuel types are allowed to vary based on market prices in Table 1, only biodiesel is subsidized and we now find that ethanol has the highest pollution tax at \$0.041/gal while diesel is third highest at \$0.027/gal. The main reason why this result occurs is because of the difference between relative marginal damages *per unit price* between ethanol and gasoline. Even though marginal damages from gasoline is \$0.004/gal more than ethanol, the output price of ethanol is 31% lower than gasoline. Thus, the marginal damages per unit price of ethanol are actually higher than that of gasoline and should be taxed more given our revenue neutral

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[9] See Table 1 for more detail in the calculation of marginal disutility from pollution.

constraint. Only biodiesel should be subsidized while the four other fuel types should be taxed to maximize social welfare.

This outcome is highlighted if we take into consideration the upward trend of gasoline and diesel prices during the summer months. Assuming output prices for gasoline and biodiesel of $4 and $5 per gallon, respectively, we find that gasoline pollution taxes lower to $0.004 and diesel is now subsidized at $0.011 per gallon given the revenue neutral constraint. Again, this is due to the difference in relative marginal damages per unit price across fuel types.

Given the uncertainty in emissions coefficient for cellulosic ethanol, we vary the parameter. When we decrease the emissions coefficients for cellulosic ethanol to half of corn ethanol, a subsidy is imposed on cellulosic ethanol instead of a tax, under the revenue neutral tax structure. To subsidize production of cellulosic ethanol and biodiesel, taxes for ethanol, gasoline and diesel need to be increased. If the actual emissions coefficient is only 10% of corn ethanol emissions, the subsidy for cellulosic ethanol increases and taxes on corn ethanol, diesel and gasoline continue to increase to maximize social welfare.

Table 3 provides a comparison of the welfare outcomes of the different policy approaches. In this model, the optimal unconstrained Pigouvian Tax provides the highest welfare while the lowest welfare is received when emissions taxes are not imposed. We normalize the highest potential change in welfare with the unconstrained Pigouvian tax from the no tax case as a 100% gain in welfare. The intermediate welfare outcomes are calculated as the percentage gain in welfare from the no tax case relative to the maximum welfare gain. That is, the formula for the intermediate welfare percentage gains, W_i, is $W_i=100*(U_i-U_{min})/(U_{max}-U_{min})$, where U_i, U_{min} and U_{max} are the utility derived from the intermediate policy case, unconstrained Pigouvian Tax and no tax case, respectively.

The revenue neutral tax provides welfare increases equivalent to 89% of the improvement with an optimal unconstrained Pigouvian tax. Thus, although the revenue neutral tax does not increase welfare as much as the first best policy, it contributes significantly to total welfare relative to the no tax case. In contrast, we measure the welfare gains in the case that the application of the revenue neutral tax is based on relative emissions alone rather than the price-weighted relative emissions as indicated by the optimal revenue neutral tax. This implies that we assume output prices are the same resulting in a modified revenue neutral tax, t_i^{cc}, in (9') simplified to $t_i^{cc} = (t_i^u - t_k^u)\Gamma_k$ because prices cancel. The resulting revenue neutral taxes would increase welfare by 44% relative to the optimal Pigouvian tax. The increase in welfare is less than half of the welfare gains with revenue neutral taxes based on the marginal damages per unit price. This highlights the importance of using relative marginal damages per unit price and not just marginal damages in determining the optimal revenue neutral tax.

The optimal revenue-neutral policy requires varying revenue-neutral taxes when output prices or emissions coefficient change. Given the inflexible nature of legislated taxes and the difficulties measuring net carbon emissions, we investigate two cases: one in which output prices change but the tax is not optimally adjusted, and another in which an inaccurate estimate of relative emissions for one of the fuels is used. If we assume that gasoline and diesel prices rise to $4 and $5 per gallon respectively, but revenue neutral taxes remain in the same level as in the previous case, welfare gains are 23% relative to the optimal Pigouvian tax. This is substantially lower than the 89% gain in welfare from revenue neutral taxes with corrected market prices but it is important to note that welfare gains still occur.

Suppose now that the actual emissions coefficient of one fuel, cellulosic ethanol, is actually lower than the estimate used to calculate the revenue-neutral tax. If the emissions coefficient for this fuel is 10% of corn ethanol but the revenue neutral tax is calculated based on our original estimates where cellulosic ethanol emits 70% of corn ethanol, the gain in welfare is only 63% of optimal unconstrained Pigouvian tax policy. Interestingly, if Pigouvian taxes were not allowed to adjust for the actual emissions rate, welfare gains would only yield 72% relative to the optimal unconstrained Pigouvian tax policy. Thus, welfare efficiency gains with the revenue neutral tax policy is fairly close to the unadjusted Pigouvian tax policy.

4. Conclusion

The objective of this article is to derive the optimal market incentive instrument that internalizes the effects of greenhouse gas emissions and satisfies a more politically feasible revenue neutral constraint. We find that the targeted tax revenue level, share of output to total gross domestic product in all fuel sectors and relative marginal damages per unit price of each fuel type are important factors determining the revenue-neutral tax levels for each fuel type.

Although the mechanism is second-best to pure carbon taxes except in special cases, this approach has the potential for being more politically palatable than a pure carbon tax, because of the distaste in the United States for increasing taxes and increasing motor fuel costs. Nonetheless, because the optimal revenue-neutral tax depends on prices and production levels, a fixed tax applied over long periods of time (as is often necessary for political expediency) reduces the efficacy outcomes. Further, estimating life-cycle fuel carbon emissions is to date relatively poorly developed, and inaccuracies in this process can reduce the economic effectiveness of both standard Pigouvian taxes and revenue neutral taxes. Based on our simulations, however, administering such a policy could still increase social welfare over no policy at all.

This paper presents a starting point on research in a relatively more politically feasible carbon taxes. Future studies can easily extend the model to fully incorporate technological dynamics where revenue from taxes is used to internalize spillover externalities during the production of second generation biofuels. The model can also be used to calibrate for optimal levels of taxes, technological productivity levels and carbon coefficient levels over time. Alternatively, one can also modify the model to examine a price-neutral approach where there is no net motor fuel price change in response to a high-carbon tax and low-carbon subsidy. Lastly, the model can also be applied to regulating different types of pollutants.

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Appendix 1 Deriving optimal tax rate with constrained tax revenues

From (6) we can solve for λ,

$$\lambda=\frac{U'(G)\left(\frac{dR_i}{dt_i}+y_i^*+t_i\frac{dy_i^*}{dt_i}+t_k\frac{dy_k^*}{dt_i}\right)-\delta\left(e_i\frac{dy_i^*}{dt_i}+e_k\frac{dy_k^*}{dt_i}\right)}{y_i^*+t_i\frac{dy_i^*}{dt_i}+t_k\frac{dy_k^*}{dt_i}}\qquad\forall i\neq k$$

Divide the numerator and denominator by $1\Big/\frac{dy_i^*}{dt_i}$ and recognizing that $\frac{dR_i}{dt_i}=-y_i^*$ from envelope theorem yields,

$$\lambda=\frac{U'(G)\left(t_i+t_k\frac{dy_k^*}{dt_i}\frac{dt_i}{dy_i^*}\right)-\delta\left(e_i+e_k\frac{dy_k^*}{dt_i}\frac{dt_i}{dy_i^*}\right)}{y_i^*\frac{dt_i}{dy_i^*}+t_i+t_k\frac{dy_k^*}{dt_i}\frac{dt_i}{dy_i^*}}\qquad\forall i\neq k\cdot$$

A similar expression for λ is found for sector k. Equating the expressions for lambda together and solving for t_i as a function of t_k yields,

$$t_i=\frac{\delta\left(e_i+e_k\frac{dy_k^*}{dt_i}\frac{dt_i}{dy_i^*}\right)-t_kU'(G)\frac{dy_k^*}{dt_i}\frac{dt_i}{dy_i^*}}{U'(G)}\qquad\forall i\neq k\,.$$

Using the above equation along with the tax revenue constraint yields,

$$t_i^c=\frac{\delta\left(e_i+\frac{dy_k^*}{dt_i}\frac{dt_i}{dy_i^*}e_k\right)y_k-TU'(G)\frac{dy_k^*}{dt_i}\frac{dt_i}{dy_i^*}}{U'(G)\left(y_k-\frac{dy_k^*}{dt_i}\frac{dt_i}{dy_i^*}y_i\right)}\qquad\forall i\neq k\cdot$$

Any change in output in sector *i* will affect taxes chosen by the government in sector *i*. This will in turn have an impact on output in sector *k*. Using chain rule, this implies that $\frac{dy_k^*}{dt_i}\frac{dt_i}{dy_i^*}=\frac{dy_k^*}{dy_i^*}$.

Thus we arrive at equation (7).

Figures

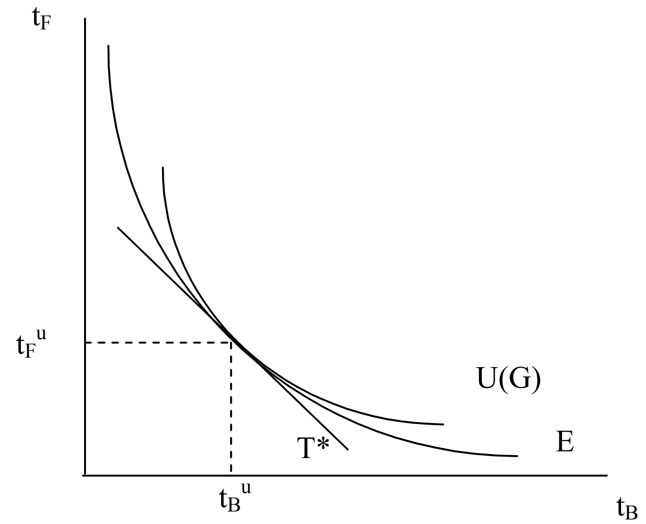

Fig. 1. Optimal Pollution Tax with Endogenously Determined Tax

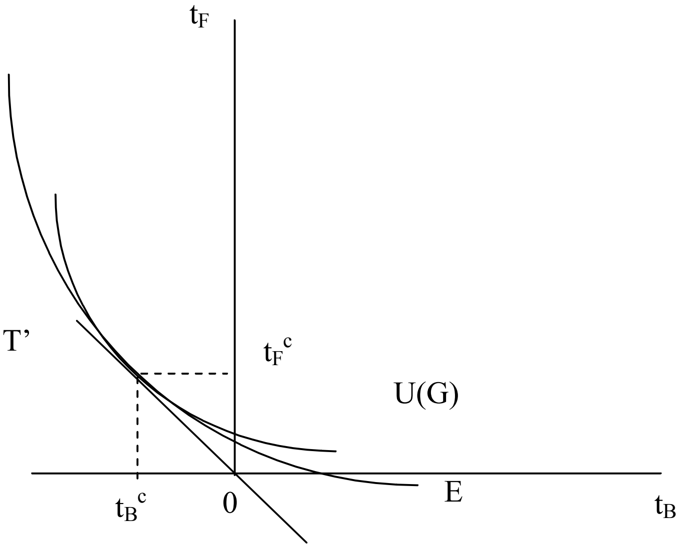

Fig. 2. Optimal Pollution Tax with Exogenously Determined Tax

Tables

Table 1 Parameters used in the simulation

Fuel type	Emissions per gallon (e) (kg/gallon) [a]	Price $ per gallon (P)[a]	Input elasticity for labor	Labor endowment	Marginal utility from GDP (utils/$)	Marginal damages from emissions (δ) (utils/kg)[b]
Diesel	11.35	2.14				
Gasoline	10.75	1.789				
Ethanol	10.21	1.363	0.5	1	1	0.0077631670
Cellulosic ethanol	7.19	1.363				
Biodiesel	6.13	3.44				

[a] Prices are wholesale blendstock prices as of November 4, 2008 from http://www.dtnethanolcenter.com/index.cfm?show=10&mid=38&pid=2. Emissions coefficients are taken from the same source.

[b] Marginal damages are based on the average market price of $20/ton of carbon. There is 907.18 kilograms per ton and 3.785 kilograms per gallon. Using these conversion parameters, a $20/ton of carbon is similar to a $0.08345/gallon ($20/ton*ton/907.18kg*3.785 kg/gal). Assuming an emission coefficient for gasoline of 10.75 kg/gal along with $0.08345/gallon, marginal damages would be equal to 0.0077utils/kg (0.08345/10.75).

Table 2 Simulated Pollution Taxes

		Revenue Neutral Tax with T=0 ($/gallon)				
Fuel type	Pigouvian Taxes ($/gallon)	All output prices are equal	Varying output prices[a]	Summer output prices[b]	Emissions from Cellulosic Ethanol is half of Corn Ethanol[c]	Emissions from Cellulosic Ethanol is 10% of Corn Ethanol[d]
Diesel	0.088	0.018	0.027	-0.011	0.030	0.033
Gasoline	0.083	0.014	0.032	0.004	0.035	0.037
Ethanol	0.079	0.009	0.041	0.053	0.043	0.045
Cellulosic ethanol	0.056	-0.016	0.017	0.029	-0.010	-0.029
Biodiesel	0.048	-0.024	-0.054	-0.021	-0.048	-0.044

[a] Output prices based on parameters from Table 1.

[b] Output prices for gasoline and diesel are increased to $4 and $5 per gallon, respectively.

[c] The emissions per gallon of cellulosic ethanol is lowered by half the current estimate from 7.19 to 3.595. Note that with this emissions coefficient, the unconstrained Pigouvian tax for Cellulosic ethanol is now $0.028/gallon.

[d] The emissions per gallon of cellulosic ethanol is lowered to 10% of ethanol to 1.021. Note that with this emissions coefficient, the unconstrained Pigouvian tax for Cellulosic ethanol is now $0.008/gallon.

Table 3 Relative welfare under different emissions taxation regimes.

Type of tax	Increase in social welfare (% of maximum change form the first best optimal Pigouvian tax policy)
Unconstrained Pigouvian tax with baseline parameters	100.0%
No emissions tax	0.0%
Optimal revenue neutral tax with baseline parameters [a]	89.0%
Revenue neutral tax based on relative emissions only [b]	43.8%
Uncertainty in Parameters	
Wrong emissions estimate for cellulosic ethanol applied to revenue neutral tax [c]	62.8%
Wrong fuel prices applied to revenue neutral tax [d]	23.3%

Note: The formula for the intermediate welfare percentage gains, W_i, is $W_i=100*(U_i-U_{min})/(U_{max}-U_{min})$, where U_i, U_{min} and U_{max} are the utility derived from the intermediate policy case, unconstrained maximum Pigouvian tax and no tax case, respectively.

[a] Baseline parameters are taken from Table 1.

[b] Parameters are taken from Table 1 except all output are normalized to 1.

[c] Parameters are taken from Table 1 except the emissions coefficient for cellulosic ethanol is 1.021.

[d] Parameters are taken from Table 1 except output prices for gasoline and diesel are \$4 and \$5 per gallon, respectively.