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CARBON TAXATION WHEN CLIMATE

AFFECTS PRODUCTIVITY

by

William K. Jaeger
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Carbon taxation when climate affects productivity

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Abstract

Optimal carbon taxation is evaluated in a model where climate change affects productivity. With a numerical US economy model with preexisting taxes, the optimal carbon tax is found to exceed marginal social damage by 53 percent and "marginal private damage" (the sum of households' marginal willingness to pay) by 73 percent. The welfare gain from optimal carbon taxation is estimated at \$3.58 billion per year when marginal damages are \$40/ton; employment also increases. Setting the carbon tax at the Pigouvian rate raises welfare by only \$3.17 billion. The contrasting results in the "tax interaction" literature are due to the use of "marginal private damage" when applied to amenity externalities. (JEL: Q2, Q4, H2)

I. INTRODUCTION

Global climate change is thought to be among the most serious environmental threats to humanity, one that presents enormous intellectual and policy challenges in a complex setting where the stakes are high. The policy questions surrounding climate change have attained heightened importance since 1997, when 160 nations signed the Kyoto Protocol and agreed to significantly reduce emissions of greenhouse gases. This situation represents an important opportunity for economists to provide policymakers with sound analysis and clear guidance at a time when there is growing recognition of the advantages of market-based policies. In this context, there has been renewed interest and considerable controversy surrounding optimal environmental taxation in a second-best setting with preexisting taxes.

Tullock (1967) was the first to suggest that revenues from environmental taxes could be used to finance reductions in preexisting revenue-motivated taxes as a way to improve the environment and reduce the welfare costs associated with the overall tax program. This notion, now widely referred to as the "double dividend hypothesis," also carries with it the intuitive inference that the optimal environmental tax would generally exceed marginal environmental damages when the revenues are used in this way (see Terkla 1984; Lee and Misiolek 1986; Pearce 1991; and Oates 1995).

Despite the intuitive appeal of the double dividend hypothesis, a more recent literature has raised questions about its validity and its implications for setting optimal environmental taxes. Although the authors of this literature concur that the use of environmental tax receipts to finance reductions in preexisting taxes will indeed have a positive welfare effect, they find that the optimal environmental tax lies below, rather than above, the marginal social damage from pollution even when environmental tax revenues are used to finance reductions in preexisting taxes (Bovenberg and de Mooij 1994; Parry 1995; Bovenberg and Goulder1996). To explain this result, the authors postulate that a previously unrecognized welfare cost or "tax interaction effect" offsets the positive effect associated with the double dividend. The unexpected implication of this "tax interaction" literature is that the welfare gains from environmental tax reform, and the ability to control pollution efficiently, is much more limited than previously thought.[1] If correct, these results have profound implications for climate change policy and many other environmental and non-environmental issues (Parry and Oates 2000).

The approach taken in the tax interaction literature has generally been to specify analytical or numerical general equilibrium models where an environmental amenity affects utility directly, where labor is the only source of income, and where demands for polluting and non-polluting goods are assumed to be similar from a revenue-raising perspective (so that in the absence of an externality, uniform taxation would be optimal).

The current analysis employs a model in which climate change damage reduces welfare by affecting labor productivity, rather than as an amenity. In a numerical model of the US economy, a welfare maximizing algorithm is employed to choose optimal taxes which both raise revenues and control carbon emissions. The analysis finds that the optimal carbon tax exceeds marginal social damages from climate change by about 53 percent, a result that supports the logic of the double dividend hypothesis. These results are also shown to be consistent with analytically-derived expressions for the optimal taxes.

A comparison of the current analysis with that from the tax interaction literature reveals that two different definitions of marginal social damage are being used. In the current analysis, the definition of marginal social damage is based on the social marginal rate of substitution between income and environmental quality. In the tax interaction literature, the definition is based on the marginal private damage for an individual household, and then summed over the population. The two definitions will differ whenever there are revenue implications from changes in either income or climate. When the definition used in the tax interaction literature is applied to the current model, the optimal carbon tax exceeds marginal social damages by an even greater amount, 73 percent. Only for an amenity externality, and when marginal social damage is defined as the sum of households' marginal private damage, is this relationship reversed.

The general model and numerical simulation results are presented in section II. Section III evaluates the differences with the tax interaction literature using both the numerical model and analytical results. Section IV concludes.

II. THE MODEL

We begin with a climate economy model which contains two endowments, income in the form of household time (T) and a global climate. There are *m* identical households who allocate their time between leisure (V) and labor supply (L). Utility is a function of consumption (C) and leisure. Consumer goods are produced with two intermediate inputs, one using fossil fuels (F), and one using non-carbon inputs (N), such that C = c(F,N). We can therefore write utility as

$$U = u(C, V). \tag{1}$$

Production is assumed to be competitive, and labor is assumed to be the only input used to produce the intermediate inputs F and N.

The model is assumed to be for one period and thus does not attempt to solve a dynamic problem. Expected carbon damages are therefore being characterized as contemporaneous damages rather than future consequences of cumulative carbon emissions. Climate quality is altered when carbon emissions result from the consumption of F, where E = mϕF. Labor productivity is in turn a function of carbon emissions, or h(E), where $dh/dE<0$. For a given E, the marginal product of labor is assumed to be constant so that mh(E)L = mF + mN + mG. Units are chosen so that marginal rates of transformation among F, N, and G all equal one.

Although we have assumed that climate affects labor productivity only, alternative representations could include effects on the productivity of other factors such as land or in models where productive factors must be redirected toward defensive and restorative efforts in the face of climate damages. Indeed, describing climate damages as a production externality is appropriate since many types of expected climate damages involve reduced output or losses of productivity. For example, Cline (1992) estimates that about three-fourths of climate change damages will come from losses to agriculture, forestry and from sea level rise.

Exogenously determined revenues, *m*G, are collected using excise taxes on F and N. For simplicity these revenues are returned to households in the form of lump-sum transfers, rather than introducing an explicit and detailed representation of the public sector. Taxes can be interpreted as payments out of labor income. Assuming competitive production and with no direct taxes on C, the tax problem will be unchanged if we substitute the production function into the utility function to reflect derived demands for F and N. We can therefore write the representative household's maximization problem as

$$\text{[2]} \qquad \begin{aligned} &\underset{F,N,V}{\text{Max}}: && \text{u}(c(F,N),V) \\ &s.t.\ (\lambda) && (1+t_F)F+(1+t_N)N = h(mN)L+G \end{aligned}$$

where λ denotes the private marginal utility of income corresponding to the value of the implied Lagrange multiplier.

To maximize social welfare, W, the planner's problem can now be written as

$$\text{[3]} \qquad \underset{t_F, t_N}{Max:} \quad m\begin{bmatrix} \underset{F,N,V}{\text{Max:}} & \text{u}(c(F,N),V) \\ s.t.(\lambda) & (1+t_F)F + (1+t_N)N = h(mN)L + G \end{bmatrix}$$
$$s.t.(\mu) \qquad mt_F F + mt_N N = mG$$

Let μ denote the shadow value of a unit of public revenue corresponding to the shadow value of the implied Lagrange multiplier for the revenue constraint. For [3] we can express the social marginal utility of carbon emissions as π where

$$\text{[4]} \qquad \pi \equiv \frac{dW}{dE} = m\lambda_t \frac{dh_t}{dE_t} L_t + m\mu_t \left(t_F \frac{\partial F_t}{\partial(h_t L_t)} \frac{\partial(h_t L_t)}{\partial E_t} + t_N \frac{\partial N_t}{\partial(h_t L_t)} \frac{\partial(h_t L_t)}{\partial E_t} \right).$$

(In an explicitly dynamic model we would write this as the present discounted value of expected losses in income due to induced changes in global climate over n years). Note that this expression includes both the direct effect on utility from reductions in private consumption (the first term on the right-hand side), plus the indirect effect due to lost revenues (the remaining terms on the right-hand side). The social marginal utility of a unit of income—in units of endowed time, T—can similarly be expressed as

$$\text{[5]} \qquad \alpha \equiv \frac{dW}{dT} = \lambda + \mu\left(t_F \frac{\partial F}{\partial T} + t_N \frac{\partial N}{\partial T} \right) + \pi m\phi \frac{\partial F}{\partial T}$$

This expression reflects the standard definition of the social marginal utility of income from Diamond (1985), but with the addition of the environmental damage term: the final term on the right-hand side reflects the disutility from additional carbon damages arising as a function of the marginal propensity to consume fossil fuels where dE= mϕdF. The marginal social damage

(MSD) from consumption of F is thus defined as the product of marginal emissions, mϕ, and the marginal rate of substitution between income and emissions, or

[6] $$MSD = MRS\frac{dE}{dF} = \frac{\partial W / \partial E}{\partial W / \partial T}\frac{dE}{dF} = \frac{\pi}{\alpha}m\phi$$

To examine the relationship between the optimal carbon tax and marginal social damages, we note that the optimal taxes on F and N will reflect both revenue-raising taxes and, in the case of F, an environmental component. In order to isolate the environmental component of the optimal tax on F, we will assume that both F and N are average substitutes for leisure—as has been the standard approach in the tax interaction literature. With appropriate restrictions on preferences, the optimal carbon tax can then be interpreted as $t^*_F - t^*_N$. The relationship between the optimal carbon tax and marginal social damage is estimated in the next section based on a numerical model for the US economy.

III. NUMERICAL MODEL AND RESULTS

The numerical general-equilibrium model involves constant elasticity of substitution functions for utility, u(C,V), and production, c(F,N), and represents a single period rather than as a dynamic problem. The model is similar in structure and calibration to the one specified for the US economy in Parry, Williams and Goulder (1999). Additional details of the model's structure and calibration are presented in the appendix.

For purposes of numerical estimation, nested optimization models such as [3] are often represented as a single maximization problem by introducing the household's first-order conditions as constraints on social maximization, similar to the first-order approach in principle-agent problems (Jewitt 1988). Letting subscripts denote partial derivatives with respect to variable j (e.g., U_j and C_j), we write the social welfare maximization problem as

$$\begin{aligned}
&\underset{t_F, t_N}{\text{Max}}: \quad m[\mathrm{u}(C(F,N),V)] \\
&s.t. \quad (\alpha) \quad (1+t_F)F+(1+t_N)N=h(E)L+G \\
[7] \quad &(\mu) \quad t_F F+t_N N=G \\
&(\eta_1) \quad U_C C_F(1+t_N)=U_C C_N(1+t_F) \\
&(\eta_2) \quad U_V(1+t_F)=U_C C_F h(E) \\
&(\pi) \quad E=e(m\phi F)
\end{aligned}$$

In this model, the shadow value of the Lagrange multiplier on income, α, will reflect the social value of a unit of income because all optima represent Pareto efficient states. For that reason, the private marginal utility of income, λ, does not appear directly in this formulation of the model because it does not represent a Pareto efficient use of a unit of income. Rather, it reflects a movement from a Pareto efficient state to a non-Pareto efficient state. To the extent that a unit increase in income causes an increase in tax payments (assuming a positive marginal propensity to pay taxes), the value of λ does not afford any value to these added tax receipts.

Prior to the introduction of a carbon tax, the initial condition of the model reflects a revenue constraint requiring 67 percent excise taxes on F and N, which is equivalent to a 40 percent income tax. Parameter values for h(E) are chosen so that the marginal social damage from carbon emissions (π/α) is \$40. The model is solved for the welfare maximizing taxes on F and N.

The optimal carbon tax corresponding to $t^*_F - t^*_N$ is \$61.3 per ton of carbon, or about 53 percent higher than marginal social damage (see table 1 for details). In a first-best setting with no binding revenue-requirements, the optimal carbon tax equals marginal social damage. Hence we can infer that the optimal carbon tax rises with increased revenue requirements, as indicated by the results in figure 1 from the numerical model. For example, increasing the revenue requirement in the numerical model 25 percent above the initial level produces an optimal carbon tax of $67/ton, or 68 percent higher than marginal social damages.

The welfare gain from the revenue-neutral introduction of the optimal carbon tax is estimated at $3.58 billion per year. Employment also increases by nearly $900 million in gross wages. These two changes broaden the tax base by introducing a tax on previously untaxed carbon emissions, and by inducing higher labor supply. If the carbon tax is set equal to marginal social damage, however, the welfare gain would be only $3.17 billion and employment would only rise by $640 million.

The intuition for these results can be recognized in several ways. First, the double dividend intuition suggests that using tax receipts to finance reductions in revenue-motivated taxes will lower the net welfare cost of environmental taxes and raise the optimal environmental tax above marginal social damage. This additional benefit lowers the net cost of emissions reductions, which in turn justifies a higher optimal carbon tax. Alternatively, carbon emissions can be viewed as simply another good in the economy, one that should be taxed above its social cost as part of a broadly-based Ramsey tax program. Like other goods, as revenue requirements increase, so too should the Ramsey tax premiums on goods and services.

Second, the global climate can be understood to be an untaxable endowment in much the same way that leisure is not directly taxable. From optimal taxation we know that revenue-motivated taxes are distortionary precisely because of the existence of untaxed endowments. In the current model two untaxed endowments exist: leisure and climate quality. Theory tells us that an increase in revenue-motivated taxes will generally encourages private agents to consume more of these untaxable endowments. The current model confirms this result for both leisure and climate.

Third, these results may at first glance appear to contradict the Samuelson Condition, whereby the optimal provision of a public good is understood to vary inversely with revenue requirements and the cost of public funds. In this case, however, there is no contradiction. The global climate is an endowed public good that is neither directly taxed nor publicly provided, so the cost considerations underlying the Samuelson Condition do not directly apply. However, the public good of atmospheric "waste disposal services" of greenhouse gases can be directly taxed in this case: households can be charged for emissions. Indeed, the model results demonstrate that a rise in the revenue requirement is accompanied by an increase in the carbon tax and a reduction in the consumption of these "carbon disposal services," a change that is fully consistent with the Samuelson Condition for this public good. Amelioration of climate damages comes indirectly, as a byproduct of raising taxes on carbon disposal services as well as on other taxable goods.

IV. THE "TAX INTERACTION" LITERATURE

The analyses contained in the tax interaction literature differ from the current analysis in three respects. First, they have generally modeled environmental externalities as amenities that affect utility directly rather than as production externalities which affect output. For a given value of marginal social damage, however, there is no apparent reason why this difference should affect the relationship between the optimal environmental tax and marginal social damage for the models being employed.

Second, the tax interaction literature uses a tax rule which includes a tax on labor supply (income) rather than introducing all taxes on expenditures. For this "income tax normalization," N becomes the untaxed good (or intermediate input) rather than leisure, and the tax on labor income serves as the revenue-motivated tax. It is understood in these models that a labor tax is equivalent to uniform taxes on all expenditures, and it will serve as an optimal revenue-raising tax if demands are symmetrical, that is if all goods are average substitutes for leisure (see Bovenberg and de Mooij 1994; Bovenberg and Goulder 1996). This symmetry condition has often been satisfied by assuming that all goods are homothetic and separable from leisure and environmental quality in the utility function. In the current context the use of a labor tax normalization is convenient because it implies that the entire tax on the polluting good can be interpreted as its environmental tax.

Models with one of these tax normalizations can be easily converted into the other normalization. The current model will satisfy the symmetry condition by assuming that both c(F,N) and u(C,V) are homothetic, and it can thus be renormalized to reflect a labor tax simply by dividing the household budget constraint in [3] by $1-t_L$, where t_L is the tax on labor supply and where $1+t_N = 1/(1-t_L)$. Although this change alters the definition of units in a way that is a function of the income tax rate, the differences due to the normalization will have no effect on the results of the model or on any real variables and should not affect their interpretation (Schöb 1996, Fullerton 1997).

The third difference between the current analysis and the tax interaction literature is the definition of the marginal social damage from pollution. In the current analysis, the definition of MSD has been based on the social marginal rate of substitution between income and environmental quality as expressed in [6]. By contrast, the definition of environmental damage used in the tax interaction literature reflects the sum of marginal damages for a representative household. Thus, this definition reflects "marginal private damages" (MPD), or the aggregate marginal willingness to pay to avoid climate damage. The differences between these two definitions have direct bearing on both the results and their interpretation.

In a model with preexisting taxes and a revenue requirement, the social marginal utility of a given resource (either income or environmental quality) will differ from its private marginal utility to the extent that there are taxes present and revenue consequences. Diamond (1985) was first to define the social marginal utility of income as the gain in social welfare from provision of additional income in numeraire units, "which is the sum of gains from individual consumption and from the marginal propensity to pay taxes out of income"(p. 336). Thus, the social marginal utility of income will exceed the private marginal utility of income so long as the marginal propensity to pay taxes is positive. In the current model, the social marginal utility of a change in climate similarly has two components, one reflecting the changes in private consumption and the other reflecting the changes in tax receipts, since climate damage reduces both private consumption and public revenues.

In contrast to this definition, the tax interaction literature has defined the marginal utility of income as λ, the Lagrangian multiplier for the household budget constraint, which reflects only the private consumption component of the social marginal utility of a unit increase in income and omits the terms in [5] that reflect the utility arising from the revenues generated by incremental tax payments. This is similar to the important distinction in benefit cost analysis between market prices and shadow prices. Thus, for the case of an environmental amenity which is additively separable in utility, the marginal change in tax payments due to a unit increase in environmental quality can be assumed to equal zero, in which case the social marginal utility of environmental quality will equal the private marginal utility of environmental quality when summed across households.

In the current model, however, climate change damages affect income directly, so that the social marginal utility of a unit improvement in climate will involve revenue consequences similar to those reflected directly in the social marginal utility of income. For the current model, MPD will differ in both its numerator and denominator from MSD, or

[8] $$MPD \equiv \frac{\pi^P}{\lambda} m\phi = \frac{m\sum_{t=0}^{q}\left[(1+r)^{-t}\lambda_t \frac{dh_t}{dE_t} L_t\right]}{\lambda} m\phi .$$

The numerator and denominator in [8] are smaller in magnitude than in [6] given the explicit expressions in [4] and [5]. Private agents are assumed to ignore the value of revenues generated as a consequence of their expenditures resulting from incremental changes in income—either exogenous changes or those resulting from climate change. Since both the numerator and denominator are higher in MSD compared to MPD, the ratios may not differ greatly. Indeed, for the current numerical model where MSD is $40, MPD is $35.4. With an optimal carbon tax of $61.3, this result implies that, had Parry, Williams and Goulder evaluated a model with production externalities, they would have found the optimal carbon tax to be 73 percent higher than MPD!

These numerical estimations are fully consistent with the analytical expressions for the optimal environmental tax in a second-best setting. A useful expression for the optimal environmental tax has been derived by Bovenberg and Goulder (1996) for their model with an amenity externality and an income tax normalization (An equivalent expression can be derived from the optimal tax expressions in Sandmo's (1975) seminal article.). The expression is

[9] $$\tilde{t}^*_F = \frac{\pi}{\tilde{\lambda}}\frac{\tilde{\lambda}}{\mu},$$

where a tilde over a variable denotes net income units corresponding to the income tax normalization. The correspondence between the two normalizations implies that $\lambda = \tilde{\lambda}(1-t_L)$ and $\tilde{t}^*_F = (t^*_F - t^*_N)(1-t_L)$. With these identities, and noting that $\alpha/\alpha = \tilde{\lambda}/\tilde{\lambda}$, we can substitute these expressions into [9] and plug in numerical values from table 1 to get

[10] $$t^*_F - t^*_N = \frac{\pi}{\alpha}\frac{\alpha(1+t_N)}{\mu} = \frac{\pi}{\alpha}\frac{0.4(1.641)}{.429} = 1.53\frac{\pi}{\alpha}$$

Thus, the optimal carbon tax from the direct numerical estimation is shown here to be consistent with the analytically-derived expression when shadow values for α and μ from the model are applied. It also confirms that this relationship is independent of the tax normalization.

We can also use the expression in [9] to identify the circumstances under which the optimal environmental tax may appear to be less than marginal damages. Consider a model like those from the tax interaction literature with an environmental amenity that is separable in utility, and where marginal environmental damage is defined by MPD rather than MSD. These assumptions ensure that a change in environmental quality will not affect households' allocation choices or tax payments, implying that $\pi=\pi^P$ so that the numerators in MSD and MPD will be identical. The only difference between MPD and MSD, therefore, will be from having λ in the denominator of MPD rather than α. Given $\pi=\pi^P$ we can express [9] by substituting $\lambda(1+t_N) = \tilde{\lambda}$ and plugging in values from table 1 to get

[11] $$\tilde{t}^*_F = \frac{\pi}{\tilde{\lambda}}\frac{\lambda(1+t_N)}{\mu} = \frac{\pi}{\tilde{\lambda}}\frac{0.255(1.641)}{0.932} = 0.97\frac{\pi}{\tilde{\lambda}}$$

This result demonstrates that when defining marginal environmental damage using MPD rather than MSD, the difference in their denominators between λ and α will raise MPD relative to MSD. If the numerators of the two expressions are the same, the difference between λ and α may be sufficient to produce the result that the optimal environmental tax lies below MPD.[2]

This result, however, should not cast doubt on the validity of the double dividend hypothesis because MPD does not reflect the social marginal rate of substitution between income and environmental quality. In particular, λ does not reflect the social value of a unit of income in a Pareto efficient use. For optimization models such as the one represented by [3] where households and planners are understood to respond the each other's actions, λ only reflects the increased consumption by households from a unit increase in income, but assuming no response on the part of the social planner to the changes in tax receipts. For an increase in income, this implies that incremental revenues go unused and unvalued; for a decrement of income, λ implies an infeasible situation in which consumption and tax payments have declined, but where lump-sum transfers (or provision of public goods) are unchanged.

In the case of an environmental amenity, MPD may exceed the optimal environmental tax making it appear as though the optimal tax lies below the "the Pigouvian rate that fully internalizes the marginal environmental damages" (Bovenberg and de Mooij 1994). However, the current analysis finds that this interpretation is misleading. Indeed, if the authors of the tax interaction literature had used MSD rather than MPD, or if they had modeled production externalities rather than amenities, they too would have concluded that the optimal environmental tax will generally exceed marginal environmental damage.

4. CONCLUDING COMMENTS

The welfare effects of environmental tax reform such as the introduction of a carbon tax have become an important policy question as well as a source of debate in the theoretical literature. It is accepted wisdom that using carbon tax revenues to finance reductions in preexisting taxes will lower the excess burden of the tax program. Intuitively this implies that the net welfare change from introducing a carbon tax will exceed that which would be inferred by simply comparing marginal social damages to marginal abatement costs; and it follows logically that the optimal carbon tax will exceed the marginal social damage (Lee and Misiolek 1986; Terkla 1984). The current analysis is consistent with this intuition and with the double dividend hypothesis. In a second-best setting with preexisting taxes, and where carbon damages affect production, the optimal carbon tax is found to exceed marginal social damages by 53 percent based on a numerical model of the US economy. When marginal climate damages are defined or estimated as the sum of household's marginal willingness to pay, then the optimal carbon tax will exceed this measure of marginal damages by 73 percent. The welfare gain from introducing this optimal carbon tax when marginal social damage is $40 per ton is estimated at $3.57 billion per year for the US economy. Employment also increases by $900 million in gross wages annually.

Differences between the current findings and the "tax interaction" literature stem primarily from differences in the way marginal social damage has been defined. In the current analysis, marginal social damage is defined based on the marginal rate of substitution between income and environmental quality for the social planner's problem. In the tax interaction literature, marginal social damage has been defined in a way that does not reflect the social marginal rate of substitution between income and environmental quality; their definition is an aggregation across households of marginal private damages, reflecting the private marginal utility of income rather than the social marginal utility of income.

The essential point is that as tax rates rise the private marginal utility of income will decline relative to the social marginal utility of income and the divergence between the two definitions will become greater, especially for models involving environmental amenities. If these distinctions are overlooked, the intuitive correspondence between the optimal environmental tax, the marginal social damage, and the validity of the double dividend hypothesis may be obscured.

Given the need to provide policymakers with clear guidance on climate change policy questions, these results, and the reasons for the divergent findings in the tax interaction literature, need to be fully recognized to avoid confusion by policymakers and the public. For example, using a model typical of the tax interaction literature, Bovenberg and van der Ploeg (1994) have concluded that environmental policy reduces economic activity and employment, and forces governments to choose between environmental policy and other public goods. These interpretations have been influential in policy discussions of green tax reform, especially in Europe. By contrast the current analysis demonstrates that environmental policy can increase employment and economic activity, and that environmental taxation lowers the cost of raising revenues for achieving other collective goals.

APPENDIX: Specification of the climate economy model

The numerical model representing the US economy is represented in [7]. The functional forms and parameter values are described here. These include a primary CES utility function, C=c(F,N) given as

$$U = \left(\gamma C^{-\rho} + (1-\gamma)V^{-\rho}\right)^{-1/\rho},$$

and a secondary CES production function defining substitutions between *F* and *N* in C=c(F,N) as

$$C = \left(\hat{a}F^{-\delta} + (1-\hat{a})N^{-\delta}\right)^{-1/\delta}$$

This production function is a single CES function rather than the more disaggregated, nested CES structure of production in the Parry, Williams and Goulder model (1999). The function H=h(E) is H = 1 – 0.00001122(E-1423.6), and where $\phi = 0.00225113$. The functions and parameters have been calibrated to correspond to the second-best marginal abatement cost function from Parry, Williams and Goulder. Setting $\delta = -0.5$ implies that the elasticity of substitution between carbon emitting and non-carbon emitting consumption, σ_{NF}, equals $(1/1+\delta) = 2.0$. The value of $\rho = -0.167$, so that the elasticity of substitution between consumption and leisure, σ_{CL}, equals $(1/1+\rho) = 1.2$. In addition, $\gamma = 0.836$, $\beta = 0.667$, and m=1. The desired labor supply elasticity (0.15) is achieved by calibrating the share parameter γ. The initial conditions are T = 4101534.9, G = 2,113,100, V = 931,980 and E=1423.6.

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Table 1. Optimal carbon taxation: results for numerical model of the US
(Marginal social damage = \$40 per ton)

Optimal tax, F:	0.779
Optimal tax, N:	0.641
Social marginal utility of emissions (π)	-15.98
Social marginal utility of income (α)	0.400
Social marginal utility of revenues (μ)	0.429
Optimal carbon tax ($t^*_F - t^*_N$) (per ton)	0.138 \$61.3
Private marginal utility of income (λ)	0.255
Private marginal utility of emissions (π_P)	-9.03
Ratio of optimal carbon tax to MSD (π/α)	1.53
Ratio of optimal carbon tax to MPD (π_P/λ)	1.73

Note: Resource allocation at the optimum is: N=2,620,500, F=556,040, C=1,763,700, V=931,080, and E=1,251.726

[1] This now-extensive literature includes Goulder 1995; Fullerton 1997; Schöb, 1997; Bovenberg and de Mooij 1997; Goulder, Parry, Burtraw 1997; Parry, Williams, Goulder 1999; and Goulder, Parry, Williams and Burtraw 1999, Parry and Bento 2000, among others.

[2] For the current numerical model, $\pi/\alpha = 40$, $\pi^P/\lambda = 35.4$, and $\alpha/\lambda = 1.57$, from which we can infer that $\pi/\pi^P = 1.77$. This ratio is larger than α/λ due to the substitution effect of a change in labor productivity, whereas α is strictly an income effect.