

When Can Carbon Abatement Policies Increase Welfare? The Fundamental Role of Distorted Factor Markets

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Discussion Paper 97-18-REV

Revised June 1998



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Abstract

This paper employs analytical and numerical general equilibrium models to assess the efficiency impacts of two policies to reduce U.S. carbon emissions – a revenue-neutral carbon tax and a non-auctioned carbon quota – taking into account the interactions between these policies and pre-existing tax distortions in factor markets. We show that tax interactions significantly raise the costs of both policies relative to what they would be in a first-best setting. In addition, we show that these interactions put the carbon quota at a significant efficiency disadvantage relative to the carbon tax: for example, the costs of reducing emissions by 10 percent are more than three times as high under the carbon quota as under the carbon tax. This disadvantage reflects the inability of the quota policy to generate revenue that can be used to reduce pre-existing distortionary taxes.

Indeed, second-best considerations can limit the potential of a carbon quota to generate overall efficiency gains. Under our central values for parameters, a non-auctioned carbon quota (or set of grandfathered carbon emissions permits) cannot increase efficiency unless the marginal benefits from avoided future climate change are at least \$17.8 per ton of carbon abatement. Most estimates of marginal environmental benefits are below this level. Thus, our analysis suggests that any carbon abatement by way of a non-auctioned quota will reduce efficiency. In contrast, our analysis indicates that a revenue-neutral carbon tax can be efficiency-improving so long as marginal environmental benefits are positive.

Key Words: carbon tax, carbon quota, pre-existing taxes, welfare effects

JEL Classification Nos.: L51, H23, D52

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WHEN CAN CARBON ABATEMENT POLICIES INCREASE WELFARE? THE FUNDAMENTAL ROLE OF DISTORTED FACTOR MARKETS

Ian W. H. Parry, Roberton C. Williams III, and Lawrence H. Goulder *

I. INTRODUCTION

The prospect of global climate change from the continued atmospheric accumulation of carbon dioxide (CO₂) and other greenhouse gases has prompted analysts to consider a number of policy options for mitigating emissions of CO₂. The issue has attained heightened importance since the signing of the Kyoto Protocol in December 1997, when 160 nations resolved to reduce emissions of CO₂ and other greenhouse gases. This paper focuses on alternative ways that the U.S. might achieve significant reductions in CO₂ emissions. The crucial point of departure from previous studies of CO₂ abatement policies¹ is the present paper's focus on connections between the efficiency impacts of CO₂ abatement policies and pre-existing tax distortions. The motivation for this focus stems from recent studies of environmental regulation in a second-best setting. These papers have shown that the costs of environmental regulations are higher in a world with pre-existing factor market distortions than they would be in the absence of such distortions.² The higher costs reflect two effects. First, by raising the costs of production in the affected industry, environmental regulations give rise to higher prices of output in that industry and thus a higher price of consumption goods in general. This, in turn, implies a lower real wage and a reduction in labor supply. If there are pre-existing taxes on labor, the reduction in labor supply has a first-order – that is, non-incremental – efficiency cost, which has been termed the *tax-interaction effect*.

Second, under some environmental policies, another effect can partially offset the tax-interaction effect. Pollution taxes and other environmental policies that raise revenue allow that revenue to be recycled through cuts in the marginal rates of pre-existing distortionary

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¹ See for example Nordhaus (1994) and Manne and Richels (1992).

² See for example Bovenberg and de Mooij (1994), Bovenberg and van der Ploeg (1994), Goulder (1995), Goulder *et al.* (1997), Parry (1995, 1997), and (in a somewhat different context) Browning (1997). Earlier papers by Terkla (1984), Lee and Misiolek (1986), and Ballard and Medema (1993) examine policies in which revenues from environmental taxes finance reductions in distortionary taxes, although these papers do not explicitly address the ways that pre-existing distortionary taxes raise the costs of new environmental taxes.

taxes. The lower marginal rates reduce the distortionary costs associated with these taxes, thus providing an efficiency gain. This is the *revenue-recycling effect*.

These considerations are highly relevant to the choice among alternative instruments for reducing emissions of CO₂. The most frequently cited instruments for dealing with CO₂ emissions are carbon taxes, carbon quotas (or "carbon caps"), and marketable carbon emissions permits.³ All of these policies generate a (costly) tax-interaction effect, but only some of them can exploit the offsetting revenue-recycling effect. Carbon taxes, as well as carbon quotas or tradable permits that are auctioned by the government, enjoy the revenue-recycling effect so long as the revenues obtained are used to finance cuts in marginal tax rates of distortionary taxes such as the income tax. In contrast, grandfathered (non-auctioned) carbon quotas and permits fail to raise revenues and thus cannot exploit the revenue-recycling effect. Carbon taxes whose revenues are returned through lump-sum transfers to households also fail to enjoy this effect. This paper shows that the inability to make use of the revenue-recycling effect can put the latter policies at a substantial efficiency disadvantage relative to the former policies.⁴ Indeed, the absence of the revenue-recycling effect may make it impossible for the latter policies to generate overall efficiency gains, despite the benefits from avoided future climate change!⁵ These results bear directly on current CO₂-abatement policy discussions in the U.S. and Europe, where grandfathered tradable carbon permits are gaining serious consideration.

In this paper we use analytical and numerically solved general equilibrium models to contrast the effects of two sorts of policies, where the crucial difference between the two policies is the presence or absence of the revenue-recycling effect. These policies are a carbon tax with revenues devoted to cuts in marginal tax rates, and a non-auctioned carbon emissions quota. To our knowledge, this is the first study to compare these CO₂-abatement policies in the presence of pre-existing distortionary taxes. As mentioned, the first policy exploits the revenue-recycling effect, while the second does not. For simplicity, we apply the

³ See for example Tietenberg (1991), Poterba (1993), Hoel (1991), Oates and Portney (1992).

⁴ Some earlier analyses of carbon taxes have recognized the potential importance of the revenue-recycling effect. Repetto et al. (1992) and Nordhaus (1993a) indicate that the costs of a carbon tax are much lower when revenues are returned through cuts in marginal tax rates than when revenues are returned lump-sum. These studies make a valid point about the relative costs of policies that do or do not exploit the revenue-recycling effect. However, the absolute costs of carbon tax policies are not fully captured in these studies because they do not integrate pre-existing taxes in the analysis and thus they cannot account for the tax-interaction effect. The presence or absence of the revenue-recycling effect can be linked to whether policy-generated rents are captured by the government and returned to taxpayers (as in the case of a pollution tax) or instead left in producers' hands (as in the case of pollution quotas or freely offered pollution permits). On this see Fullerton and Metcalf (1997).

⁵ The impossibility of efficiency gains was demonstrated through numerical simulations performed by Bovenberg and Goulder (1996a). They found that any carbon abatement through a carbon tax policy that recycles the revenues in lump-sum fashion (and thus does not exploit the revenue-recycling effect) will be efficiency-reducing, if the marginal environmental benefits from carbon abatement do not exceed a strictly positive threshold value. This restriction on environmental benefits does not apply to carbon tax policies involving recycling through cuts in marginal rates. The present study differs from the Bovenberg-Goulder study in decomposing the tax-interaction and revenue-recycling effects and in examining quota policies (and the treatment of quota rents) in some detail.

labels "carbon tax" and "carbon quota" to these policies, since it is cumbersome to refer repeatedly to the presence or absence of the revenue-recycling effect. It should be kept in mind that, as indicated above, some policies involving quotas or tradable permits would share efficiency properties of our former category, while some policies involving taxes or tradable permits would share efficiency properties of our latter category.

We begin by deriving analytical formulas indicating that the efficiency costs associated with the tax-interaction effect can be quite large relative to the direct costs of carbon abatement considered in typical policy models. We then perform numerical simulations that show that the absence of the revenue-recycling effect makes the carbon quota policy significantly more costly than the carbon tax. Under central values for parameters, the marginal costs of emissions abatement begin at approximately \$18 per ton under the quota, as compared with \$0 per ton under the revenue-neutral carbon tax. The quota's minimal marginal cost of \$18 per ton has some powerful implications for policy. Estimated marginal benefits from carbon abatement are typically below \$18 per ton (see in particular Nordhaus 1991a, 1994). If marginal benefits are indeed below this value, then only the carbon tax can produce an efficiency improvement in our model; a carbon quota (or set of grandfathered tradable permits) necessarily reduces efficiency, and potentially by a large amount. Clearly, there is enormous uncertainty as to the potential gains from reducing carbon emissions; as discussed below, under more extreme scenarios for climate change, benefit estimates can easily exceed \$18 per ton. Yet even in this case, there is still a very strong efficiency argument for preferring a carbon tax over a (non-auctioned) quota. Our numerical results indicate, for example, that a five percent reduction in carbon emissions is almost six times as costly under a quota than a carbon tax.

We would emphasize that the absolute costs of the carbon quota, and its cost relative to that of the carbon tax, are sensitive to different assumptions about labor supply elasticities, which are difficult to pin down accurately. Nonetheless, even under extremely conservative values for labor supply elasticities the marginal cost of the quota at zero abatement still significantly exceeds the central estimate of \$5 per ton for marginal environmental benefits in Nordhaus (1994). Our analysis also abstracts from a number of potentially significant considerations, such as capital accumulation and pre-existing sources of distortion in the economy due to non-tax factors. However, as we discuss at the end of the paper, generalizing the analysis may well strengthen rather than weaken our empirical results.

Our results are consistent with – but in some ways more striking than – the results obtained by Goulder et. al (1997) in a study of the sulfur dioxide (SO₂) permit program under the 1990 Clean Air Act Amendments. Goulder et al. found that, under central estimates for marginal environmental benefits from SO₂ reductions, a system of grandfathered (freely-allocated) SO₂ permits allows for an improvement in efficiency relative to the unregulated status quo. The present study indicates that the prospects for efficiency gains through quotas or non-auctioned permits are much dimmer in the CO₂ context. Quotas or non-auctioned permits have a greater chance at yielding efficiency gains in the SO₂ case because the central estimates for marginal environmental benefits are relatively high (compared with marginal

abatement costs) in this case. In contrast, central estimates for marginal environmental benefits from CO₂ reductions are fairly low relative to marginal abatement cost.⁶

The rest of the paper is organized as follows. Section II develops and applies our analytical model. This model is fairly simple, containing two final goods, a clean and dirty intermediate input, and one primary factor – labor. In Section III, we describe an extended version of the original model that distinguishes different fossil fuels and identifies different non-fuel intermediate goods. Section IV applies the extended model, which is solved numerically. The numerical solution method enables us to consider large (non-incremental) policy changes, and this turns out to be relevant to the relative costs of the different policies. Section V discusses the sensitivity of the results to alternative values for important parameters. Section VI concludes and discusses some limitations of the analysis.

II. THE ANALYTICAL MODEL

Here we present an analytically tractable model that reveals the efficiency impacts of carbon taxes and non-auctioned carbon quotas in a second-best setting. This model shares some features of analytical models developed by Parry (1995, 1997) and Goulder et al. (1997). However, the present model is distinct from Parry's in deriving results explicitly from utility maximization. In addition, it differs from the model in Goulder et al. in incorporating a more flexible relationship between the levels of pollution emissions and the level of output produced by the regulated industry.

A. Model Assumptions

A representative household allocates its time endowment (\bar{L}) between labor supply (L) and leisure, or non-market time ($l = \bar{L} - L$). It also purchases two consumption goods, C_F and C_N . C_F represents an aggregate of final output from industries that use fossil fuels (F) intensively, and C_N is an aggregate of all other consumption goods. We ignore capital accumulation in the economy, which means that we just focus on behavior in one period, rather than solving a dynamic problem (see Section IV). The household utility function is given by:

$$u(C_F, C_N, l) - f(F) \tag{II.1}$$

where $u(\cdot)$, utility from non-environmental goods, is continuous and quasi-concave. f is disutility from current, anthropogenically caused additions to the stock of CO₂ in the atmosphere, caused by (combustion of) fossil fuels. These damages represent the present

⁶ Another option for reducing carbon emissions is to mandate certain technologies that require less fossil fuel input and thus entail lower emissions. A recent paper by Fullerton and Metcalf (1997) analyzes the efficiency impacts of a particular technology restriction, along with emissions taxes and quota, in a second-best setting. The paper shows that incremental abatement through a technology restriction need not be any more costly than incremental abatement under a pollution tax. Our analysis differs from that in Fullerton and Metcalf by concentrating specifically on CO₂ emissions reductions and in examining not only incremental emissions abatement but also large amounts of abatement. As emphasized below, the relative costs of quotas and taxes depend importantly on the extent of emissions abatement.

discounted value of the expected utility losses due to induced changes in future global climate.⁷ The separability in (II.1) implies that future climatic change does not affect the relative attractiveness of leisure and the two types of consumption.⁸

C_F and C_N are produced under constant returns to scale. The production functions are given by:

$$C_F = C_F(L_F, F_F, N_F); \quad C_N = C_N(L_N, F_N, N_N); \quad (\text{II.2})$$

where N is a "clean" (non-polluting) intermediate good. Labor is the only input used to produce the intermediate goods F and N , and the marginal product of labor in each of these two industries is taken to be constant. We assume that production in all four industries is competitive. The use of fossil fuels in the C_F and C_N industries leads to a proportional amount of carbon emissions. This is a standard assumption in energy models: unlike the case of SO_2 , there are no economically viable scrubber technologies to reduce CO_2 emissions per unit of fuel input. Aggregate fossil fuel use is:

$$F = F_F + F_N \quad (\text{II.3})$$

We choose units to imply one ton of carbon per unit of F .

We do not consider heterogeneity in the costs of emissions abatement among producers within a given industry. If regulators have imperfect information about these costs, in general they will be unable to achieve production efficiency in the allocation of quotas: marginal costs of abatement are likely to differ across producers. Under these circumstances a carbon tax or a system of tradable carbon permits would have an efficiency advantage over fixed carbon quotas, apart from the advantages associated with revenue-recycling, which are the focus of our analysis.⁹

Finally, we assume that the government has an exogenous spending requirement of G , which is returned to households as a lump sum transfer. The government also levies a proportional tax of t_L on labor income, and regulates carbon emissions using either a tax or a non-auctioned quota. The government budget is assumed to balance, and therefore any revenue consequences from regulation are neutralized by adjusting the rate of t_L .

Denoting the demand prices of C_F and C_N by p_F and p_N , and normalizing the gross wage to unity, the household budget constraint is given by:

⁷ Although we focus on the costs to the U.S. of carbon abatement policies, we use environmental benefit estimates for the world economy. This seems appropriate since we are dealing with a globally dispersed pollutant.

⁸ If pollution were to alter the tradeoff (marginal rate of substitution) between consumption and leisure (as would be the case if pollution affects consumer health or labor productivity) then the benefits of reduced pollution could be magnified or diminished by tax interactions. For more details on this point see Bovenberg and van der Ploeg (1994) and Williams (1997).

⁹ Policy analysts have paid considerable attention to this heterogeneity issue and the associated potential gains from trades. Perhaps as a result, tradable carbon permits seem to enjoy more political support than non-tradable quotas.

$$p_F C_F + p_N C_N = (1 - t_L) L + G \quad (\text{II.4})$$

Households choose C_F , C_N and L to maximize utility (II.1) subject to (II.4) and the time endowment. From the resulting first-order conditions and the household budget constraint, we obtain the (implicit) uncompensated demand and labor supply functions:

$$C_F(p_F, p_N, t_L); \quad C_N(p_F, p_N, t_L); \quad L(p_F, p_N, t_L) \quad (\text{II.5})$$

Substituting (II.5) into (II.1) gives the indirect utility function:

$$V = v(p_F, p_N, t_L) - f(F) \quad (\text{II.6})$$

From Roy's Identity:

$$\frac{\partial v}{\partial p_F} = -l C_F; \quad \frac{\partial v}{\partial p_N} = -l C_N; \quad \frac{\partial v}{\partial t_L} = -l L \quad (\text{II.7})$$

where the Lagrange multiplier l is the marginal utility of income.

Consider a policy – either a carbon tax or quota – that creates a wedge of t_F per unit between the demand and supply price of fossil fuels. Under constant returns to scale and competition, the general equilibrium increase in final product prices¹⁰ that results from an incremental increase in t_F is (see Appendix A):

$$\frac{dp_F}{dt_F} = \frac{F_F}{C_F}; \quad \frac{dp_N}{dt_F} = \frac{F_N}{C_N} \quad (\text{II.8})$$

that is, the ratio of fossil fuel input to final output. Finally, the equilibrium quantity of fossil fuels can be expressed as a function of the policy variables (see Appendix A):

$$F(t_F, t_L) = F_F(t_F, t_L) + F_N(t_F, t_L) \quad (\text{II.9})$$

where $dF/dt_F < 0$. These functions summarize the effect of changes in t_F on fossil fuel use through: (a) the substitution effect, that is, the replacement of labor and N for fossil fuels in production of C_F and C_N ; (b) the output effect, that is, the change in derived demand for fossil fuels from changes in the quantities of C_F and C_N caused by the effect of t_F on final product prices. Changes in t_L affect fossil fuels through their effect on the quantity of final consumption goods, in response to a change in the relative price of leisure.

B. Carbon Tax

Suppose t'_F represents a tax per unit paid by firms purchasing fossil fuels. Given the fixed proportions between fuel use and emissions, this is equivalent to a tax of t'_F per ton on carbon emissions. In this case, the government budget constraint is:

$$t'_F F + t_L L = G \quad (\text{II.10})$$

¹⁰ That is, the increase that applies when all prices and quantities are treated as variable.

that is, the sum of carbon tax revenues and labor tax revenues equals government spending.

Consider a balanced-budget policy change involving an incremental change in τ_F^t and t_L .

Totally differentiating (II.10) holding G constant and using (II.5) and (II.9) we can express the change in t_L as:

$$\frac{dt_L}{d\tau_F^t} = - \frac{F + \tau_F^t \frac{dF}{d\tau_F^t} + t_L \frac{\eta_L}{\eta_{\tau_F^t}}}{L + t_L \frac{\eta_L}{\eta_{t_L}}} \quad (\text{II.11})$$

where

$$\frac{dF}{d\tau_F^t} = \frac{\eta_F}{\eta_{\tau_F^t}} + \frac{\eta_F}{\eta_{t_L}} \frac{dt_L}{d\tau_F^t}$$

We define:

$$Z = \frac{-t_L \frac{\eta_L}{\eta_{t_L}}}{L + t_L \frac{\eta_L}{\eta_{t_L}}} \quad (\text{II.12})$$

This is the partial equilibrium efficiency cost from raising an additional dollar of labor tax revenue, or marginal excess burden of labor taxation. The numerator is the welfare loss from an incremental increase in t_L ; it is the wedge between the gross wage (equal to the value marginal product of labor) and net wage (equal to the marginal social cost of labor in terms of foregone leisure), multiplied by the reduction in labor supply. The denominator is marginal labor tax revenue (from differentiating $t_L L$).

The welfare effect of the policy change is obtained by differentiating the utility function (II.6) with respect to τ_F^t , allowing t_L to vary. This gives:

$$\frac{dV}{d\tau_F^t} = \frac{\eta_V}{\eta_{p_F}} \frac{dp_F}{d\tau_F^t} + \frac{\eta_V}{\eta_{p_N}} \frac{dp_N}{d\tau_F^t} + \frac{\eta_V}{\eta_{t_L}} \frac{dt_L}{d\tau_F^t} - f'(F) \frac{dF}{d\tau_F^t}$$

Substituting (II.3), (II.7), (II.8), (II.11) and (II.12) gives:

$$\frac{1}{l} \frac{dV}{d\tau_F^t} = \underbrace{\left(\frac{f'}{l} - \tau_F^t \right) \left(- \frac{dF}{d\tau_F^t} \right)}_{dW^P} + \underbrace{Z \left\{ F + \tau_F^t \frac{dF}{d\tau_F^t} \right\}}_{\eta_{W^R}} - \underbrace{(1 + Z)t_L \left(- \frac{\eta_L}{\eta_{\tau_F^t}} \right)}_{\eta_{W^I}} \quad (\text{II.13})$$

Thus, the welfare effect (in dollars) can be separated into three terms. The first, dW^P , is the effect within the fossil fuel market, or *primary welfare gain*. This is the overall incremental reduction in fossil fuel multiplied by the gap between the marginal social cost ($q_F + f'/l$), and marginal social benefit or demand price ($q_F + \tau_F^t$) of fossil fuel (where q_F is the supply

price of F). The second, \mathcal{W}^R , is the (marginal) *revenue-recycling effect*, or efficiency gain from using additional carbon tax revenues to reduce the labor tax. This equals marginal carbon tax revenue multiplied by the marginal excess burden of taxation. The third, \mathcal{W}^I , is the (marginal) *tax-interaction effect*. This consists of: (i) $t_L(-\mathcal{L}/\mathcal{L}t'_F)$, the welfare loss from the reduction in labor supply, caused by the effect of t'_F on increasing final goods prices and thereby reducing the real household wage; plus (ii) $Zt_L(-\mathcal{L}/\mathcal{L}t'_F)$, the resulting reduction in labor tax revenue multiplied by the marginal excess burden of taxation.

The tax-interaction effect can be expressed as (see Appendix A):

$$\mathcal{W}^I = mZF ; \quad m = \frac{h_F h_{FI}^c + h_N h_{NI}^c - h_{LI}}{s_F h_{FI}^c + s_N h_{NI}^c - h_{LI}} \quad (\text{II.14})$$

where h_{FI}^c and h_{NI}^c are the compensated elasticity of demand for C_F and C_N with respect to the price of leisure; h_{LI} is the income elasticity of labor supply; h_F and h_N are the shares of fossil fuels in the C_F and C_N sectors ($h_F + h_N = 1$); and s_F and s_N are the shares of C_F and C_N in the value of total output ($s_F + s_N = 1$). m is a measure of the degree of substitution between fossil-fuel-intensive consumption and leisure, relative to that between aggregate consumption and leisure. In general, both h_{FI}^c and h_{NI}^c are positive, because from the household budget constraint (II.4), aggregate consumption and leisure are inversely related. If C_F and C_N are equal substitutes for leisure (that is, $h_{FI}^c = h_{NI}^c$) then $m = 1$. In this case (comparing \mathcal{W}^I – that is, mZF – with \mathcal{W}^R), the tax-interaction effect equals the revenue-recycling effect when $t'_F = 0$, but exceeds it when $t'_F > 0$ (since $dF/dt'_F < 0$). Therefore, taking into account the pre-existing labor tax raises the slope, but does not affect the intercept (equal to zero), of the marginal cost of carbon emissions reduction.¹¹ Since C_F is carbon-intensive, the share of fossil fuels used in the C_F sector exceeds the share of C_F in total production ($h_F > s_F$). Therefore, if C_F were a stronger (weaker) substitute for leisure than Y (that is h_{FI}^c is greater (less) than h_{NI}^c), then m would be greater (less) than 1, and the marginal cost of emissions reduction would have a positive (negative) intercept.¹²

¹¹ This is the same qualitative result as that for a revenue-neutral pollution tax on a final good (Goulder et al. 1997). Note that, despite substitution of labor for fossil fuels in production of final goods, the aggregate effect on labor supply is still negative. This occurs because, given our assumptions of constant returns to scale and that labor is the only primary factor input, the aggregate demand for labor is perfectly elastic and changes in the quantity of labor are determined purely by changes in the real household wage (the non-substitution theorem is satisfied (Varian 1992, pp. 354). Any policy which causes final goods prices to increase, and hence the real wage to fall, will therefore reduce labor supply.

¹² For more discussion about how the costs of emissions taxes depend on the relative degree of substitution between output from the polluting sector and leisure see Bovenberg and van der Ploeg (1994), and Parry (1995).

C. Carbon Quota

Suppose instead that carbon emissions are reduced by a quota (or non-auctioned permits). We define this quota by t_F^q , the wedge it creates between the demand and supply price of fossil fuels (t_F^q can also be regarded as a "virtual tax"). t_F^q produces quota rents of $\rho = t_F^q F$ (since the price exceeds marginal private cost by t_F^q for each unit of F), which accrue to households, who own firms (in their role as shareholders). We will generally assume that this rent income is taxed at the same rate as labor income. (In the sensitivity analysis of Section V, we will consider the case where quota rents are not taxed.) In general, the government budget constraint is:

$$t_L(\rho + L) = G \quad (\text{II.10}')$$

If instead, rent income were taxed at 100 percent, or the quotas were sold by the government at a price of t_F^q , then the carbon quota would be equivalent to the carbon tax in this model.

Following the analogous procedure to before, we can express the welfare change from a marginal tightening of the quota (that is an increase in t_F^q) as (see Appendix):

$$\frac{1}{l} \frac{dV}{dt_F^q} = \underbrace{\left(\frac{f'}{l} - t_F^q \right) \left(-\frac{dF}{dt_F^q} \right)}_{dW^P} + t_L Z' \underbrace{\left\{ F + t_F^q \frac{dF}{dt_F^q} \right\}}_{\partial W^R} - (1 + Z') t_L \underbrace{\left(-\frac{\partial L}{\partial t_F^q} \right)}_{\partial W^I} \quad (\text{II.13}')$$

where

$$Z' = \frac{-t_L \frac{\partial L}{\partial t_L}}{L + t_L \frac{\partial L}{\partial t_L} + \rho} \quad (\text{II.12}')$$

Comparing (II.13') with (II.13), one will observe that the quota causes the same primary welfare effect as the tax. It also induces the analogous tax-interaction effect, since it increases the price of consumption goods in the same way as the carbon tax. The key difference is that it only produces an indirect revenue-recycling effect, through the taxation of quota rents, and this is equal to fraction t_L of the revenue-recycling effect under the carbon tax. Therefore when C_F and C_N are equal substitutes for leisure, the revenue-recycling effect will only partially offset the tax-interaction effect for the first unit reduction in carbon; hence the marginal cost of emissions reduction will now have a positive intercept. If the environmental benefits from carbon abatement are below this intercept, then a carbon quota cannot increase welfare.¹³

¹³ t_L in expression ∂W^R in (II.13') represents the fraction of quota rents that the government obtains through income taxation and uses to cut other taxes. In the case of a revenue-neutral auctioned quota t_L would be unity in this expression (as in equation (II.13)). Alternatively, in the case of carbon tax where the revenues are returned as lump sum transfers rather than used to cut distortionary taxes, $t_L=0$. Note that the marginal excess burden of taxation in (II.12') is slightly different than in (II.12), because increasing t_L now affects tax revenues from rent as well as labor income.

When C_F and C_N are equal substitutes for leisure, this threshold benefit level (\bar{B}) can be expressed as (see the Appendix):

$$\bar{B} = Z''(1-t_L) \frac{dt_F^q}{dF} F^0 \quad (\text{II.15})$$

where

$$Z'' = \frac{\frac{t_L}{1-t_L} e^c}{1 - \frac{t_L}{1-t_L} e^u} \quad (\text{II.12''})$$

and e^c and e^u are the compensated and uncompensated labor supply elasticity respectively. Z'' is an alternative, empirically useful expression for the marginal excess burden of labor taxation, that takes into account general equilibrium income effects.¹⁴ In the numerical model below, the benchmark parameter values we use for t_L , e^c , e^u are 0.4, 0.3, and 0.15, implying $Z'' = 0.22$. In addition, $dt_F^q / dF = \$0.085$ per million tons, and initial emissions are 1423 million tons. Substituting these values in (II.12''), *the analytical model predicts that the quota cannot increase welfare unless environmental benefits exceed \$16 per ton.*

III. THE NUMERICAL MODEL

The simplicity of the model in Section II lends to transparency of results, but it also limits the model's ability to gauge the empirical importance of the second-best issues of interest. In this section we introduce some extensions to the original analysis to gain a better sense of the significance of these issues. We extend the analysis in two main ways. First, we consider the effects of "large" policy changes, that is, policy changes that produce greater than incremental reductions in emissions. As will be shown below, the relative (as well as absolute) costs of carbon taxes and quotas depend importantly on the extent of carbon abatement achieved through these policies. In order to consider large changes, we must specify functional forms for the utility and production functions and solve the model numerically. The second extension is to disaggregate further the intermediate goods in production. We disaggregate fossil fuels into oil, coal, and natural gas to allow for emissions reductions not only through substitution of non-fuel inputs for fossil fuels (collectively), but also through substitution of low-carbon fuels (such as natural gas) for high-carbon fuels (such as coal). We also distinguish between energy-intensive and non-energy-intensive non-fuel inputs. This disaggregation allows us to perform a rich sensitivity analysis, which is not possible in the analytical model.

¹⁴ That is, when the dollar of revenue raised is returned to households as a lump sum transfer. (The formulas in (II.12) and II.(12') are partial equilibrium and do not take into account this income effect, and therefore depend only on uncompensated coefficients.) For a comprehensive discussion of the formula in (II.12'') see Browning (1987).

Subsection A describes the behavioral assumptions for households, firms, and the government, and the equilibrium conditions of the extended model. The complete set of equations for the model is presented in Appendix B. Subsection B describes the calibration of the model.

A. Model Structure

There are six intermediate goods. Fossil fuels are divided into coal (F_C), petroleum (F_P) and natural gas (F_N). Coal is the most carbon-intensive fuel per unit of energy and natural gas the least. The remaining intermediate goods are electricity (E), an aggregate of other energy-intensive intermediate goods (I), and an aggregate of non-energy-intensive intermediate goods (N).¹⁵ As in the analytical model, there are two consumption goods: C_N represents final output from industries that use N intensively, and C_I represents final output from industries that use the other five intermediate goods (notably energy) intensively. Labor time is the sole primary factor of production, and equals the household time endowment net of leisure. All of the intermediate goods and labor are used as inputs in production of intermediate goods. Final goods are produced using only intermediate goods as inputs.

As before, labor is taxed at a proportional rate of t_L . The tax revenue is used to provide a fixed level of lump-sum transfers to households. Carbon emissions¹⁶ are proportional to the use of each of the three fossil fuels, with a different carbon content for each. Again, we consider two instruments: a tax and a quota on carbon emissions.

i. Firm Behavior

We assume competitive producers that take input and output prices as given. Production functions in all industries have the following nested constant-elasticity-of-substitution (CES) form:

$$X_j = \left[\left(\sum_{i \in m} a_{i,j} X_{i,j}^{\tau_{jm}} \right)^{\frac{\tau_j}{\tau_{jm}}} + \left(\sum_{i \in g} a_{i,j} X_{i,j}^{\tau_{jg}} \right)^{\frac{\tau_j}{\tau_{jg}}} + a_{L,j} X_{L,j}^{\tau_j} \right]^{\frac{1}{\tau_j}} \quad (\text{III.1})$$

$m = \{I, N\}$, $g = \{F_N, F_C, F_P, E\}$, $j = \{F_N, F_C, F_P, E, I, N, C_I, C_N\}$ where the τ 's and the $a_{i,j}$'s are parameters; $\tau = (S - 1) / S$ and S is the elasticity of substitution between factors in production. This function divides inputs into three groups: energy (fossil fuels and electricity), materials (the two remaining intermediate goods) and labor, with different elasticities of substitution between inputs in the same group than between inputs in different

¹⁵ Energy-intensive intermediate goods are those for which a relatively large proportion of energy goods (fossil fuels and electricity) are used as inputs, such as metals processing and transportation. Non-energy-intensive intermediate goods are those with a relatively low proportion of energy inputs, such as services and agriculture.

¹⁶ This study measures emissions in terms of carbon content. One ton of carbon emissions is equivalent to 3.67 tons of carbon dioxide.

groups. Because this production function possesses constant returns to scale, supply curves in all industries are perfectly elastic for given input prices.

Producers choose input quantities in order to maximize profits. In the case of the carbon quota, this is subject to the constraint on emissions. Profits equal the value of output minus expenditures on labor and intermediate goods used in production, less any charges per unit of carbon emissions (t_c).¹⁷ Thus, profit for industry j (ρ_j) is given by:

$$\rho_j = (p_j - b_j t_c) X_j - \sum_I p_i X_{i,j} \quad (\text{III.2})$$

where p_i and p_j are the prices of inputs and outputs, respectively, and b_j represents the carbon emissions per unit of good j . b_j is zero for all goods except F_N , F_C , and F_P . Note that because this production function exhibits constant returns to scale, profits will equal zero under the carbon tax, but will equal the quota rents under the emissions quota. Total carbon emissions are:

$$e = b_{FN} X_{FN} + b_{FC} X_{FC} + b_{FP} X_{FP} \quad (\text{III.3})$$

ii. Household Behavior

We assume the following nested CES utility function:

$$U = U(l, C_I, C_N, e) = (a_l l^{\gamma_U} + a_C C^{\gamma_U})^{\frac{1}{\gamma_U}} + f(e) \quad (\text{III.4})$$

where

$$C = (a_{C_I} C_I^{\gamma_C} + a_{C_N} C_N^{\gamma_C})^{\frac{1}{\gamma_C}} \quad (\text{III.5})$$

l is leisure time and the a 's and γ 's are parameters. γ_U and γ_C are related to the elasticities of substitution between aggregate consumption and leisure and between the two consumption goods, respectively, in the same manner as in the production function. e denotes carbon emissions.¹⁸

The household maximizes utility subject to the budget constraint:

$$p_{C_I} C_I + p_{C_N} C_N = p_L L(1 - t_L) + \rho(1 - t_R) + p_C G \quad (\text{III.6})$$

where t_L is the tax rate on labor income, t_R is the tax rate on rent income, $L = \bar{L} - l$ is labor supply, ρ is the total rent generated by a quota policy, G is real government spending in the

¹⁷ We assume here that carbon taxes are levied on the producers of fossil fuels imposed at source, in keeping with most carbon tax proposals.

¹⁸ As in the analytical model, the damages from climate change are assumed to be separable in utility from goods and leisure. Weak separability between goods and leisure and homothetic preferences over consumption goods together imply that C_I and C_N are equal substitutes for leisure (see Deaton, 1981). Since there is no obvious reason or empirical evidence to suggest that energy-intensive goods are relatively strong or relatively weak substitutes for leisure, we regard this as a reasonable simplification.

form of transfers to households, and p_C is the composite price of consumption. This constraint requires that expenditure on consumption equal after-tax income in the form of wages, rents, and government transfers. Except in the sensitivity analysis in Section V, we assume that the tax rates on labor income and rent income are the same: $t_R = t_L$.¹⁹

iii. Government Policy

The numerical model considers the same two types of emissions regulation considered in the analytical model: a tax of t_t on carbon emissions, and an emissions quota yielding a virtual tax of t_q . As shown in Appendix B and in the analytical model, firms behave identically under the carbon tax as under the quota for a given level of abatement. The crucial difference between the two policies is that the tax directly raises revenue for the government and uses those revenues to finance reductions in pre-existing tax rates.

The government's budget constraint is given by:

$$p_C G = t_L L + t_R p + t_t e \quad (\text{III.7})$$

Under a carbon tax, p is equal to zero, while under a carbon quota, t_t equals zero. As before, any revenue consequences of carbon regulation are neutralized by adjusting the tax rates t_L and (if applicable) t_R so as to maintain a fixed level of real transfers, G .

iv. Equilibrium Conditions

The requirements of general equilibrium are that the demand for labor and for each good equal supply, that the government's revenue requirement be satisfied, and that carbon emissions equal a specified target (if applicable). We can reduce the set of equilibrium conditions to three equations: aggregate labor demand equals aggregate supply, government revenue equals expenditures, and carbon emissions equal the target level.²⁰ The model is solved by adjusting the primary prices: the pre-tax wage (p_L); the tax rate on labor income (t_L); and the tax rate on carbon emissions (t_t), or virtual tax rate (t_q), such that these three conditions hold.

B. Calibration of the Model

The benchmark data set, summarized in Table 1, approximates the United States economy in the year 1995, the most recent year for which the relevant energy data were

¹⁹ The effective tax on labor earnings (primarily personal income and payroll taxes) and non-labor earnings (personal and corporate income taxes) are roughly the same. For example, Lucas (1990) estimates them to be 40 percent and 36 percent respectively.

²⁰ Our assumptions of competition and constant returns to scale imply product prices equal marginal cost and that supply curves are perfectly elastic. The computational algorithm used to solve the model only uses the government budget and carbon emissions conditions. By Walras's law, if these two conditions are satisfied, then the aggregate excess demand for labor must also equal zero. As a check on the computation, we verify that the third equilibrium condition holds, and also that the result is consistent with the appropriate homogeneity conditions in prices and quantities.

available. We developed this data set by aggregating 1987 data from the *Survey of Current Business* on input uses, output levels, and consumption patterns into the six intermediate and two final goods industries in the model. We then scaled the data up to the year 1995, using data from the *Survey of Current Business* on growth rates in the different industries modeled, and information on 1995 electricity and fossil fuel use from the *1997 Annual Energy Update*.²¹

In the model, the sensitivity of labor supply to the after-tax wage is controlled by the parameter S_U . Based on the existing literature, we set $S_U = 1.20$, which implies an uncompensated and compensated labor supply elasticity of 0.15 and 0.3 respectively.²² The baseline labor tax rate is taken to be 40 percent, which is meant to account for taxes at both the Federal and state levels.²³

The elasticities of substitution in production of intermediate and final goods are aggregated from those estimated by McKibbin and Wilcoxon (1995). We adjusted the outermost elasticities (elasticity of substitution between labor, materials, and energy) so as to produce, in the absence of pre-existing labor taxes, a schedule of marginal costs of carbon emissions abatement that closely matches the curve derived by Nordhaus (1991b) from a survey of existing studies. The resulting elasticities are given in Table 1B.

The carbon content for each of the three fossil fuel intermediate goods (b) is calculated by dividing the 1995 emissions of carbon from the burning of each fuel, as reported in the *1997 Annual Energy Outlook*, by the quantity of each fuel burned. The α distribution parameters were calibrated based on the assumed elasticities of substitution and the identifying restriction that each industry utilized the cost-minimizing mix of inputs, or, equivalently, the restriction that in the absence of an emissions-control policy, the model will replicate the benchmark data.²⁴

²¹ We scaled up non-energy-industry data to 1993 using industry-specific growth rates, and then scaled the data up to 1995 levels using the rate of GDP growth from 1993-95, thus implicitly assuming that both non-energy industries grew at the same rate from 1993-95. Energy-industry data were scaled up based on 1995 use of each fuel and of electricity. We used Kuroda's method to ensure that the resulting data set met the necessary adding-up conditions. As shown in Section V, our results are largely insensitive to the relative size of different industries.

²² These elasticities also reflect the assumption that, in the initial data set, non-sleep leisure time equals 0.3 times hours worked. The labor supply elasticities are median estimates from the econometric literature (see the survey in Russek, 1996). They represent the effects of changes in net wages on the participation rate and average hours per worker. We regard these values as conservative, since they do not capture the effect of changes in net wages on effort per hour. Other tax-simulation models often assume somewhat higher values. For example Bhattarai and Whalley (1997) assume an uncompensated elasticity of 0.25.

²³ Other studies use comparable values. See, for example, Lucas (1990) and Browning (1987). The sum of Federal income, state income, payroll, and consumption taxes amounts to around 36 percent of net national product. This average rate is relevant for the participation decision. The marginal tax rate, which affects effort level and hours worked per employee, is higher because of various tax deductions. Our values for tax rates and labor supply elasticities imply a marginal excess burden of labor taxation equal to 0.22 (when additional spending is returned as a lump sum transfer).

²⁴ For a discussion of calibration methods for general equilibrium models, see Shoven and Whalley (1992).

Table 1. Benchmark Data for the Numerical Model

A. Input-Output Flows (in millions of 1995 dollars except carbon emissions in millions of tons)

	F_C	F_P	F_N	E	I	N	C_I	C_N	l	Total Input Value
F_C	2874.4	33.1	0.5	7729.2	3267.6	1453.4	490.8	9.7		15858.7
F_P	414.8	107334.5	22258.5	9823.6	26620.8	26553.9	10092.9	5538.3		208637.2
F_N	10.5	21371.3	36113.9	8987.5	11196.6	12315.4	2761.8	202.8		92959.9
E	653.7	3710.2	814.9	48.3	25181.9	41148.8	34003.6	44.5		105605.9
I	1569.9	22155.8	1512.5	10879.4	338137.4	469948.4	116320.4	8778.8		969302.5
N	4892.5	33651.2	16157.5	38359.5	233261.9	3326713.5	291455.2	2699669.1		6644160.3
L	5442.9	20381.1	16102.1	29778.5	331636.4	2766027.0			932167.0	4101534.9
Total Output Value	15858.7	208637.2	92959.9	105605.9	969302.5	6644160.3	455124.7	2714243.2		
e	507.3	598.7	317.6							1423.6

B. Parameter Values

	Elasticity of Substitution Among Energy, Labor, and Materials	S_E Elasticity of Substitution in Energy (fuels and electricity) nest	S_M Elasticity of Substitution in Materials nest
F_C	0.25	0.16	0.53
F_P	0.19	0.20	0.20
F_N	0.21	0.89	0.20
E	0.18	0.20	0.95
I	0.17	0.82	0.27
N	0.18	0.53	1.51
C_I	0.19	0.59	0.26
C_N	0.22	0.97	0.76

$S_C=0.5$, $S_L=1.2$ (elasticities of substitution between final goods and between consumption and leisure, respectively)

In the simulation experiments below we compare outcomes in a second-best setting (with the labor tax) to those in a first-best setting (when the labor tax is set to zero). The initial quantities of emissions and gross domestic product are each approximately 12 percent higher in the first-best case.²⁵ This means that, for a given proportionate reduction in emissions, the absolute gross cost in the first-best case is somewhat higher than the primary cost in the second-best setting.²⁶

C. Policy Proposals and Carbon Damage Scenarios

The Kyoto Protocol calls for industrialized nations (the so-called Annex I countries) to achieve significant reductions in a basket of greenhouse gases (including CO₂) by 2008-2012.

²⁵ Eliminating the labor tax increases the after-tax wage, so individuals supply more labor and thus GDP is higher. This has a roughly equal effect across all industries, so emissions rise by the same proportion.

²⁶ That is, environmental benefits minus the primary welfare gain.

The U.S., in particular, must achieve a level of emissions about seven percent below 1990 levels. Under business-as-usual conditions, emissions are projected to grow significantly from the present time until 2008-2012; hence meeting the Kyoto targets would compel the U.S. to reduce its emissions by considerably more than seven percent. In our numerical simulations, we consider emissions reductions ranging from 0 to 25 percent, a range that seems relevant to the reductions required from the Kyoto Protocol.

We consider a range of estimates for benefits from carbon abatement. Central estimates in the literature are typically below \$20 per ton (for example, \$5 per ton in Nordhaus 1994).²⁷ The "low" values for the central estimates reflect the notion that continued accumulation of greenhouse gases will not produce extreme changes in climate over the next century, and the idea that most economic activities are not exceptionally sensitive to modest climate change. In addition, discounting over long periods of time substantially reduces the benefit estimates, which are present values. However under extreme values for climate change, sensitivity of the economy to such change, or discount rates, much higher benefit estimates arise. Under an extreme scenario, Nordhaus (1991a), for example, estimates benefits to be \$66 per ton.²⁸ The simulations below aim to span a wide range of benefit scenarios, considering a range from 0 to 100 dollars per ton. In all cases, we assume marginal benefits are constant over the range of emissions reductions.²⁹

IV. NUMERICAL RESULTS

A. Marginal Costs of Emissions Reduction

Figure 1 (see page 35) shows how the pre-existing labor tax affects the marginal cost of reductions in carbon emissions. The bottom curve is the marginal cost when there is no distortionary labor tax. This curve is roughly the same in real terms as that in Nordhaus (1991b). The curve is upward sloping, reflecting the increasing difficulty of substituting fossil fuels for other inputs in production. In a first-best world, the same curve applies no matter whether the reduction is achieved by a tax or quota. In a second-best world, in contrast, the marginal cost curves differ significantly. In our central case scenario, which assumes a pre-existing labor tax (t_{LO}) of 40 percent, the quota policy shifts up the marginal cost curve, giving it a positive intercept. This upward shift reflects the tax-interaction effect. Under the carbon tax, the marginal cost curve pivots upward but retains the zero intercept that applies in the first-best case. The middle curve in Figure 1 represents marginal costs under the carbon tax. The zero intercept reflects the fact that the revenue-recycling effect exactly

²⁷ The first benefit estimate was \$7 per ton, by Nordhaus (1991a). Other estimates include \$12 (Peck and Teisberg, 1993) and \$20 (Fankhauser, 1994).

²⁸ The estimates have also been criticized for neglecting some ecosystem impacts, potentially adverse effects on the distribution of world income, and the possibility of non-linearities within the climate system. Nordhaus (1993b) provides insightful commentary on these issues.

²⁹ This seems a reasonable approximation (see Pizer, 1997).

offsets the tax-interaction effect at the first increment of abatement. The zero intercept implies that the carbon tax can increase welfare so long as marginal benefits from emissions reduction are positive. In contrast, under the quota marginal benefits must exceed a strictly positive value (\$17.8 per ton under central-case values for parameters) in order to increase welfare. These qualitative results were anticipated by the analytical model. The value of the intercept of the marginal cost under the quota is almost identical in both analytical and numerical models.³⁰

B. Average Costs of Emissions Reduction

Figure 2 (see page 36) shows the average total cost of reducing carbon emissions under the tax and quota, expressed relative to the average total cost of the same emissions reduction in a first-best setting with no pre-existing labor tax.³¹ For both policies, pre-existing taxes imply higher costs at all levels of abatement than would occur if the labor tax were zero. At all levels of abatement, the cost of the carbon tax is about 22 percent higher when the pre-existing labor tax is 0.4 than when there is no pre-existing labor tax.³² Under the quota policy, pre-existing taxes have a much greater impact. The average total cost of a 5 percent emissions reduction, for example, is six times as high with pre-existing taxes than without; the average cost of a 15 percent emissions reduction is 2.6 times as high. The very high ratios reflect the fact that the marginal costs of abatement begin at a strictly positive level in a second-best setting, whereas they start at zero in the absence of prior taxes, as shown in Figure 1.

Figure 2 shows that, on efficiency grounds, pre-existing taxes put the quota policy at a considerable disadvantage relative to the tax policy. For all levels of emissions reduction up to 25 percent, the cost of the quota is more than double that of the tax. Whatever the benefits from reducing carbon emissions, there is a strong efficiency case for preferring the carbon tax to the carbon quota. Note that the relative discrepancy between the tax and quota declines with the level of abatement. The marginal tax-interaction effect is approximately constant, but marginal tax revenue and hence the marginal revenue-recycling effect is declining. This occurs because the carbon tax base (F in (II.13)) declines with abatement. Eventually,

³⁰ The intercept of the quota curve is somewhat lower than that implicit in the numerical model of Bovenberg and Goulder (1996a), which incorporates a much more detailed treatment of the tax system. In their model, a carbon tax with revenues recycled through lump-sum transfers is efficiency-reducing unless marginal benefits from emissions reduction exceed \$55 per ton. This policy would be equivalent to the above quota policy if there were no taxation of quota rents. When we assume no taxes on quota rents in the present model, the intercept of the marginal cost curve rises to \$29.4 per ton (see Section V). The bulk of the difference results because we assume a lower (compensated) labor supply elasticity than in their model (we assume 0.3 for this elasticity while Bovenberg and Goulder assume 0.6). In addition Bovenberg and Goulder (1996a) incorporate pre-existing taxes on gasoline, which increases marginal abatement costs.

³¹ We compare average costs, rather than total costs, because baseline (unregulated) emissions are higher in the absence of a labor tax. As noted earlier, eliminating the labor tax encourages labor supply

³² The ratio of average costs between the first- and second-best setting is constant with respect to the amount of emissions reduction, in the carbon tax case. This is because the marginal net loss from the tax-interaction and revenue-recycling effects changes in proportion to the slope of the primary marginal cost of emissions reduction.

marginal tax revenue would become negative (when the downward sloping part of the Laffer curve is reached). In the limit, at 100 percent emissions reduction, the total cost of the tax and quota are identical. At this point, no revenues are raised under the tax, and hence there is no revenue-recycling effect and no difference between the tax and quota policies.³³

Our results indicate that in a second-best setting, under a carbon quota (or grandfathered tradable permits) even "small" amounts of abatement involve large costs. Thus, for example, the total cost of using a quota to reduce emissions by five percent is (a substantial) \$1.75 billion per annum. These costs reflect the presence of a significant tax-interaction effect (that is not offset by a revenue-recycling effect).³⁴

C. Efficiency Impacts under Second-Best Optimal Emissions Reduction

The second-best optimal emissions reduction is easily inferred from Figure 1: it is where a given (constant) marginal benefits curve intersects the applicable marginal cost curve. The second-best optimal emissions reduction under the tax is slightly less than 90 percent of the optimal reduction when there is no pre-existing labor tax. Under the carbon quota, the optimal emissions reduction is zero if damages are below \$17.8 per ton. If damages are "high," say \$60 per ton, the optimal emissions reduction is 12.3 percent and 19.5 percent respectively, under the quota and tax, and 21.7 percent if there were no labor tax.

Figure 3 (see page 37) shows the maximum efficiency gain – that is, the efficiency gain from the second-best optimal emissions reduction – under each policy as a function of environmental damages per ton of emissions. For any level of damages, the maximum efficiency gain under the carbon tax is around 75 percent of the maximum gain when there is no labor tax. However for the carbon quota, the maximized efficiency gain is much less; even if damages are \$70 per ton, the maximum efficiency gain is only \$6 billion, or 36 percent of the maximum gain in a first-best setting.

D. Efficiency Impacts under the Pigouvian Rule

Figure 4 (see page 38) shows the efficiency impact under the carbon tax and quota, if the Pigouvian or first-best rule is followed: that is, if the regulation reduces carbon emissions by the same fraction as the optimal policy in a world without labor taxes. Under the carbon tax, the efficiency change is always positive, and around 75 percent of that when there is no pre-existing labor tax, for any level of damages. However, imposing the carbon quota at the Pigouvian level *reduces* efficiency, unless damages exceed \$55 per ton. This welfare loss can be substantial; for example, it is \$2.1 billion, if damages per ton are \$20. Even if damages are \$100 per ton, the efficiency gain from the quota is only \$8.9 billion, or 30 percent of the gain

³³ For more discussion of this see Goulder *et al.* (1997).

³⁴ Similar results to those in Figures 1 and 2 were obtained by Goulder *et al.* (1997), in their study of the SO₂ permit program. They estimated that the threshold benefit level below which an SO₂ quota cannot increase welfare is \$103 per ton. In their equivalent of Figure 2, the cost of the 50 percent emissions reduction mandated by the program is 70 percent higher because of pre-existing taxes.

when there is no pre-existing labor tax. Thus, following the optimal policy rule implied by a first-best analysis can lead to perverse efficiency impacts.

V. SENSITIVITY ANALYSIS

Table 2 summarizes the sensitivity of marginal abatement costs to a range of values for important parameters. We vary the elasticity of substitution among the intermediate inputs in production, the labor supply elasticity, the pre-existing labor tax rate, and the share of fossil fuels in the economy. In addition, we consider the implications of allowing quota rents to remain untaxed.

The elasticity of substitution among intermediate inputs in the outer nest of the production function drives the primary marginal cost of abatement. The larger the value of this parameter, the easier it is to substitute other intermediate goods for fossil fuels, and the lower the (marginal) cost of emissions reduction. The overall marginal cost equals the primary marginal cost plus the marginal net loss from the tax-interaction and revenue-recycling effects. As shown in Rows 1a and b, this curve is somewhat sensitive to the production elasticity. However even when this elasticity is increased by 50 percent, the marginal cost under the quota still has a substantial intercept of \$14.8 per ton.

The second row displays results when we vary the consumption/leisure substitution parameter S_U . We alter this parameter so as to yield uncompensated labor supply elasticities ranging from 0.0 to 0.3, and associated compensated labor supply elasticities of 0.15-0.45. (These values roughly span the range of existing economy-wide econometric estimates.) This substantially affects costs under the quota. The intercept of the marginal cost function, in particular, varies between \$8.3 and \$29.8 per ton. This variation reflects the fact that the tax-interaction effect is directly related to the consumption/leisure elasticity. However, a larger consumption-leisure elasticity also implies a larger revenue-recycling effect, and hence the overall costs of the carbon tax are less sensitive to this change than those of the quota.

In the experiments reported in rows 3 and 4, we vary S_U and the labor time endowment so as to alter either the uncompensated labor supply elasticity alone (row 3) or the compensated elasticity alone (row 4). These simulations indicate that the costs of the carbon quota are somewhat more sensitive to the compensated than the uncompensated labor supply elasticity. This is because the recycling of quota rents offsets most of the income effect associated with higher consumption goods prices. The cost under the emissions tax is only sensitive to the uncompensated elasticity, since the increase in goods prices and reduction in labor tax rate are both uncompensated changes.

Thus, the absolute costs of the carbon quota and its cost relative to that of the carbon tax can be sensitive to different assumptions about labor supply elasticities. Nonetheless, even under extremely conservative values for labor supply elasticities, the marginal cost of the quota at zero abatement is still significantly above the central estimate of \$5 per ton for marginal environmental benefits in Nordhaus (1994) (see row 2a).

For a higher initial tax rate (row 5), the distortion between marginal social benefit and marginal social cost in the labor market is greater. Hence the revenue-recycling and tax-

Table 2. Marginal Abatement Costs Under Alternative Parameter Values and Model Specifications

	Carbon Emissions Quota			Carbon Tax		
	0%	10%	20%	0%	10%	20%
CENTRAL CASE	17.8	50.0	107.1	0.1	21.7	63.0
1. Outer-Nest Production Elasticities						
a. elasticities 3/2 of base elasticity	14.8	37.2	73.1	0.1	16.7	44.6
b. elasticities 2/3 of base elasticity	21.0	66.5	157.1	0.3	28.0	89.4
2. Both Labor Supply Elasticities						
a. $e^u = 0.00, e^c = 0.15$	8.3	32.9	78.2	0.1	19.8	57.6
b. $e^u = 0.30, e^c = 0.45$	29.8	71.5	143.6	0.3	24.6	70.7
3. Compensated Labor Supply Elasticity						
a. $e^u = 0.15, e^c = 0.20$	12.2	41.3	94.6	0.2	21.9	63.4
b. $e^u = 0.15, e^c = 0.45$	26.6	63.8	128.3	0.2	21.9	63.5
4. Uncompensated Labor Supply Elasticity						
a. $e^u = 0.00, e^c = 0.30$	16.2	45.6	98.1	0.1	19.8	57.7
b. $e^u = 0.25, e^c = 0.3$	19.4	55.1	119.7	0.2	23.6	68.1
5. Baseline tax rate						
a. $t_L=0.5$	32.5	77.3	155.1	0.3	25.9	74.5
b. $t_L=0.3$	10.5	36.5	83.4	0.1	20.1	58.1
c. $t_L=0.0$	0.1	18.1	51.9	0.1	18.1	51.9
6. Share of Fossil Fuels in GDP						
a. share doubled	17.7	49.0	101.0	0.1	21.7	61.5
b. share halved	20.4	64.9	156.2	0.6	26.6	86.0
7. Quota rents not taxed	29.4	69.4	140.0	n/a	n/a	n/a

interaction effects are larger. Thus, increasing the tax rate leads to a more than proportionate increase in marginal costs.³⁵

Row 6 illustrates that marginal costs from proportionate emissions reductions are not sensitive to changing the share of the fossil fuel sector in gross domestic product. While this change increases the sensitivity of consumption goods prices to fossil fuel prices, it also means that a ton of emissions reduction can be achieved with a smaller change in fossil fuel prices. Hence the cost of emissions reduction remains roughly the same.

Our previous experiments assumed that the rents generated by an emissions quota are taxed at the same rate as labor income. Thus, even the quota policy generates government revenue and enjoys a small revenue-recycling effect.³⁶ Row 7 indicates that if quota rents are not taxed, the marginal cost of emissions reduction is greater, and the intercept is higher. Thus, the efficiency disadvantage of the quota is reduced to the extent that taxes are imposed on quota rents. However, as shown in section II.B, these rents would have to be taxed 100 percent in order for the quota to suffer no efficiency disadvantage relative to the carbon tax.

VI. CONCLUSIONS AND CAVEATS

In this paper we have used analytical and numerical general equilibrium models to examine the efficiency impacts of revenue-neutral carbon taxes and quotas (or grandfathered carbon permits) in a second-best setting with pre-existing labor taxes. For each of these policies, the efficiency costs are considerably higher than would be the case in the absence of prior taxes. These higher costs reflect the tax-interaction effect: the efficiency cost stemming from the regulation's impact on labor supply as a result of higher output prices and a reduction in the real wage.

Pre-existing taxes imply especially high costs in the case of carbon quotas or grandfathered carbon permits. While emissions taxes and auctioned permits enjoy a revenue-recycling effect that offsets much of the tax-interaction effect, quotas and grandfathered permits policies do not exploit the revenue-recycling effect. The associated efficiency disadvantage can be very large: our central estimate is that, in the presence of prior labor taxes, achieving a five percent reduction in carbon emissions is almost six times as costly under a carbon quota as under a carbon tax; a 15 percent reduction is 2.6 times as costly.

Indeed, carbon quotas or grandfathered carbon permits may be unable to generate positive efficiency gains. Our central estimate is that the marginal social cost of emissions reductions begins at \$17.8 per ton for these policies. By comparison, typical estimates of marginal social benefits from carbon emissions reductions are below this level. This suggests

³⁵ This is because the (marginal) tax-interaction and revenue-recycling effects are proportional to the marginal welfare cost of taxation, and this increases more than in proportion to the tax rate.

³⁶ For example, at a 10 percent emissions reduction, it generates rent tax revenues of \$9.7 billion. However, the quota reduces the labor tax base, causing a loss of labor tax revenues that more than offsets the rent tax revenue, so the overall revenue change is -\$1.6 billion. In contrast, a carbon tax with the same effect on emissions produces a net revenue gain of \$13 billion.

that policies like carbon quotas and grandfathered carbon permits will be efficiency-reducing—regardless of the level of carbon abatement. In contrast, carbon tax policies can be efficiency-improving (provided that the level of abatement is not too great) because the marginal social costs of emissions reduction start at zero. In general, our results indicate that ignoring pre-existing tax distortions can give rise to highly misleading conclusions about the sign, as well as the magnitude, of the efficiency impacts from carbon abatement policies.

Some limitations to our analysis deserve mention. The analytical and numerical models are static, ignoring in particular the dynamics of capital accumulation. Considering capital as well as labor would introduce another relevant consideration in assessing the overall efficiency impacts: now these impacts would also depend on (1) pre-existing inefficiencies in relative taxation of labor and capital, and (2) the extent to which carbon abatement policies might reduce these inefficiencies by shifting the tax burden from one factor to another. Bovenberg and Goulder (1996b) indicate that for the U.S. economy, capital appears to be overtaxed relative to labor; that is, the marginal excess burden of capital taxes appears to be higher than that of labor taxes. In this setting, carbon abatement policies that ultimately shift the tax burden toward labor will induce a beneficial tax-shifting effect that mitigates the efficiency costs. The reverse is true if abatement policies shift more of the tax toward capital. Empirical analysis by Bovenberg and Goulder suggests that abatement policies tend to shift the burden toward capital, since the energy sector is relatively capital intensive. Thus our exclusive focus on labor may have biased downward our assessment of efficiency costs.

Another limitation of our analysis is that it ignores pre-existing distortions attributable to non-tax factors such as non-competitive market structures. Browning (1994) suggests that non-tax distortions add another 30 percent to the distortion in the labor market created by taxes. If so, incorporating non-tax distortions into our analysis would significantly increase the importance of second-best interactions and reduce the efficiency gains from carbon abatement policies.³⁷

In other respects, however, our analysis may understate the efficiency gains from carbon abatement policies. First, by employing static models we disregard dynamic issues associated with the benefits from carbon abatement. Marginal damages from carbon emissions (or benefits from emissions abatement) could increase with CO₂ concentrations (for example, the concentration-damage relationship could exhibit significant threshold effects). If this is the case, and if CO₂ concentrations continue to rise, then marginal damages from CO₂ emissions (marginal benefits from abatement) will increase over time. Under such circumstances, a carbon quota might be able to yield efficiency gains at some future date, when marginal damages are significantly higher. (However, in efficiency terms, it will always be better to adopt the carbon tax.) Second, carbon abatement policies – particularly carbon taxes – can produce dynamic efficiency gains by stimulating the invention and diffusion of less-carbon-intensive production technologies. This is especially important to the extent that there are market failures in the research market that have not been fully corrected

³⁷ On the significance of monopoly price distortions, in particular, see also Oates and Strassmann (1984).

by other government policies.³⁸ Third, the prospects for efficiency gains also improve if one considers ancillary benefits from carbon abatement policies, such as benefits from the reduction in other fossil-fuel-related pollutants (e.g. sulfur oxides, nitrogen oxides and particulates).

Finally, our analysis ignores distributional considerations. The decision whether to introduce a carbon tax or carbon quota fundamentally affects the distribution of wealth between taxpayers, on the one hand, and owners and employees of fossil-fuel-producing firms, on the other. Quota policies leave rents in producers' hands, while carbon taxes effectively tax these rents away. Some analysts might invoke these distributional impacts to favor the quota over the tax. The second-best issues examined in this paper do not diminish the importance of these distributional considerations, but at the same time they indicate that forgoing the redistribution towards taxpayers has efficiency costs that are much greater than would be suggested by a first best analysis.

³⁸ For further discussion of this issue, see, for example, Smulders (1996).

APPENDIX A: ANALYTICAL DERIVATIONS

Deriving Equation (II.8)

Given constant returns to scale, payments to inputs in the C_F industry exhaust value product (from Euler's theorem), that is:

$$p_F C_F = (t_F + q_F) F_F + q_N N_F + L_F \quad (\text{A1})$$

where q_F and q_N are the supply prices of the intermediate goods F and N , and the purchase price of fossil fuels includes the carbon tax. Totally differentiating (A1) gives:

$$dp_F C_F + p_F dC_F = dt_F F_F + (t_F + q_F) dF_F + q_N dN_F + dL_F \quad (\text{A2})$$

because q_F and q_N are determined by marginal product of labor in the F and N industries, and the gross wage, which are all constant. From differentiating the production function (II.2), we obtain

$$dC_F = \frac{\eta_{C_F}}{\eta_{L_F}} dL_F + \frac{\eta_{C_F}}{\eta_{F_F}} dF_F + \frac{\eta_{C_F}}{\eta_{N_F}} dN_F \quad (\text{A3})$$

Also, from the first order conditions for profit maximization, the marginal products equal the input price divided by the product price, or

$$\frac{\eta_{C_F}}{\eta_{L_F}} = \frac{1}{p_F}; \quad \frac{\eta_{C_F}}{\eta_{F_F}} = \frac{t_F + q_F}{p_F}; \quad \frac{\eta_{C_F}}{\eta_{N_F}} = \frac{q_N}{p_F} \quad (\text{A4})$$

Substituting (A4) in (A3), multiplying through by p_F , and subtracting from (A2) gives the expression for dp_F/dt_F in (II.8). The same procedure gives the analogous expression for dp_N/dt_F .

Deriving Equation (II.9)

From the cost minimization problem for firms in the C_F and C_N industries, we can derive the demands for inputs, conditional on the level of output, and input prices. Input prices can be summarized by t_F , since q_F , q_N and the gross wage are all fixed. Therefore, the conditional demands for fossil fuel are:

$$F_F(t_F, C_F); \quad F_N(t_F, C_N) \quad (\text{A5})$$

In equilibrium, the final output produced by firms equals that demanded by households. Therefore, substituting the expressions for C_F and C_N from (II.5) into (A5), and noting from (II.8) that changes in product prices are determined by changes in t_F , the equilibrium quantity of fossil fuels is summarized by (II.9).

Deriving Equation (II.14)

Using (II.5), (II.12) and (II.13), the tax-interaction effect can be expressed

$$\eta_{W'} = -\frac{L}{L + t_L(\eta_L/\eta_{t_L})} \left(\frac{\eta_L/\eta_{t_L}}{\eta_L/\eta_{t_L}} \right) t_L \frac{\eta_L}{\eta_{t_F}} = \frac{ZL}{\eta_L/\eta_{t_L}} \left\{ \frac{\eta_L}{\eta_{p_F}} \frac{dp_F}{dt'_F} + \frac{\eta_L}{\eta_{p_N}} \frac{dp_N}{dt'_F} \right\}$$

Substituting the Slutsky equations, and from (II.8) and (II.9) gives

$$\eta_{W'} = ZL \left\{ \frac{(\eta_{L^c}/\eta_{p_F})(F_F/C_F) + (\eta_{L^c}/\eta_{p_N})(F_N/C_N) - (\eta_L/\eta_I)F}{(\eta_{L^c}/\eta_{t_L}) - (\eta_L/\eta_I)L} \right\} \quad (\text{A6})$$

where "c" denotes a compensated coefficient, and I denotes disposable household income.

From the Slutsky symmetry property:

$$\frac{\eta_{L^c}}{\eta_{p_F}} = \frac{\eta_{C_F}}{\eta(1-t_L)}; \quad \frac{\eta_{L^c}}{\eta_{p_N}} = \frac{\eta_{C_N}}{\eta(1-t_L)} \quad (\text{A7})$$

Also, from differentiating the household budget constraint (II.4):

$$\frac{\eta_{L^c}}{\eta_{t_L}} = -\frac{\eta_{L^c}}{\eta(1-t_L)} = -\left\{ p_F \frac{\eta_{C_F}}{\eta(1-t_L)} + p_N \frac{\eta_{C_N}}{\eta(1-t_L)} \right\} \quad (\text{A8})$$

(since the first order effect L is neutralized in a compensated price change). Making these substitutions in (A6), and multiplying by $1-t_L$, we obtain (II.14), where

$$h_{F_I}^c = \frac{\eta_{C_F}^c}{\eta(1-t_L)} \frac{1-t_L}{C_F}; \quad h_{N_I}^c = \frac{\eta_{C_N}^c}{\eta(1-t_L)} \frac{1-t_L}{C_N}; \quad h_{L_I} = \frac{\eta_L(1-t_L)L}{\eta L};$$

$$h_F = \frac{F_F}{F}; \quad h_N = \frac{F_N}{F}; \quad s_F = \frac{p_F C_F}{L}; \quad s_N = \frac{p_N C_N}{L}$$

Note that, assuming carbon tax revenues are negligible relative to total gross labor income,

$$L = p_F C_F + p_N C_N \quad (\text{A9})$$

that is, gross labor income equals the value of output.

Deriving Equation (II.13')

Totally differentiating the government budget constraint (II.10') yields:

$$\frac{dt_L}{dt_F^q} = -\frac{t_L \left\{ F + t_F^q \frac{dF}{dt_F^q} + \frac{\eta_L}{\eta_{t_F^q}} \right\}}{L + \rho + t_L \frac{\eta_L}{\eta_{t_L}}} \quad (\text{II.11}')$$

The indirect utility function now includes net income from quota rents, $(1-t_L)\rho$. Equations (II.7) and (II.8) are the same as before, except that $\eta_{L^c}/\eta_{t_L} = -1/(L+\rho)$. Differentiating the

indirect utility function with respect to t_F^q , making the analogous substitutions to before, and using:

$$\frac{\eta_V}{\eta[(1-t_L)p]} \frac{d[(1-t_L)p]}{dt_F^q} = \left\{ (1-t_L) \left[F + t_F^q \frac{dF}{dt_F^q} \right] - p \frac{dt_L}{dt_F^q} \right\}$$

gives, after some manipulation, (II.13').

Deriving Equation (II.15)

Using (II.12') and (II.13'), when $t_F^q = p = 0$, gives:

$$\eta_{W^I} - \eta_{W^R} = t_L \frac{L \left(-\frac{\eta_L}{\eta t_F^q} \right) + t_L F \frac{\eta_L}{\eta t_L}}{L + t_L \frac{\eta_L}{\eta t_L}} \quad (\text{A10})$$

Changes in t_F^q affect rents, therefore:

$$\frac{\eta_L}{\eta t_F^q} = \frac{\eta_L^u}{\eta t_F^q} + \frac{\eta_L}{\eta} \frac{\eta[(1-t_L)p]}{\eta t_F^q} = \frac{\eta_L^u}{\eta t_F^q} + \frac{\eta_L}{\eta} (1-t_L) F^0 \quad (\text{A11})$$

where "u" denotes uncompensated. Substituting (A11) and the Slutsky equations for $\eta_L^u/\eta t_F^q$ and $\eta_L/\eta t_L$ in (A10), and multiplying and dividing by $t_L \eta_L^c/\eta t_L$ gives:

$$\eta_{W^I} - \eta_{W^R} = F^0 \left\{ \frac{(\eta_L^c / \eta t_F^q) L}{(\eta_L^c / \eta t_L) F^0} - t_L \right\} \frac{t_L (-\eta_L^c / \eta t_L)}{L + t_L \eta_L / \eta t_L} \quad (\text{A12})$$

Substituting

$$\frac{\eta_L^c}{\eta t_F^q} = \frac{\eta_L^c}{\eta p_F} \frac{dp_F}{dt_F^q} + \frac{\eta_L^c}{\eta p_N} \frac{dp_N}{dt_F^q},$$

(II.8), (A7), (A8), (A9), and the definitions of h_{FI}^c and h_{NI}^c , when these elasticities are equal, in (A12) gives (II.15), where

$$e^u = \frac{\eta_L}{\eta(1-t_L)} \frac{1-t_L}{L}; \quad e^c = \frac{\eta_L^c}{\eta(1-t_L)} \frac{1-t_L}{L}$$

APPENDIX B: THE NUMERICAL MODEL

Except where otherwise noted, i ranges over $L, F_N, F_C, F_P, E, I,$ and N , which represent inputs in production. Similarly, j ranges over $F_N, F_C, F_P, E, I, G, C_I,$ and C_N , which represent goods produced.

I. Parameters

Firm Behavior Parameters

a_{ij} distribution parameter for input i in production of good j
 $\Gamma_j, \Gamma_{jm}, \Gamma_{jg}$ substitution parameters for production of good j , in outer nest, materials nest, and energy nest, respectively
 (note: $\Gamma = (S - 1)/S$ where S is the elasticity of substitution)

Household Behavior Parameters

\bar{L} total labor endowment
 $a_b, a_{CF}, a_{CN}, a_{CI}$ distribution parameters for utility function
 Γ_C, Γ_U substitution parameters for utility function

Government Policy Parameters

\bar{e} carbon emissions target
 \bar{e}_j carbon quota for industry j
 G government spending (transfers to households, in real terms)

Emissions Parameters

b_j emissions of carbon per unit of good j used
 (note: b_j is non-zero only for j ranging over $F_N, F_C,$ and F_P)

II. Endogenous Variables

a_{ij} use of input i per unit of output of good j
 C_I and C_N aggregate demands for energy-intensive and non-intensive final goods
 C aggregate demand for composite consumption good
 AD_i aggregate demand for good i
 X_j aggregate supply of good j
 L aggregate labor supply
 l leisure or non-market time
 p_C price of composite final good

p_j	price of good j
ρ	total carbon quota rents
REV	government revenue
e_i	carbon emitted from use of good i (note: here i ranges only over F_N , F_C , and F_P)
e	total carbon emissions
U	total consumer utility
f	utility associated with carbon emissions
X_{ij}	use of good i in production of good j

III. Equations

Production Functions and Optimal Input Intensities

In all industries, output is produced according to:

$$X_j = \left[\left(\sum_{i \in m} a_{i,j} X_{i,j}^{r_{jm}} \right)^{\frac{r_j}{r_{jm}}} + \left(\sum_{i \in g} a_{i,j} X_{i,j}^{r_{jg}} \right)^{\frac{r_j}{r_{jg}}} + a_{L,j} X_{L,j}^{r_j} \right]^{\frac{1}{r_j}} \quad (\text{B1})$$

$$m = \{I, N\}, \quad g = \{F_N, F_C, F_P, E\}, \quad j = \{F_N, F_C, F_P, E, I, N, C_I, C_N\}$$

Profit for industry j is given by

$$\rho_j = (p_j - b_j t_t) X_j - \sum_i p_i X_{i,j} \quad (\text{B2})$$

Differentiating profit with respect to the inputs X_{ij} yields the first order conditions for the optimal input mix:

$$a_{ij} \equiv \frac{X_{ij}}{X_j} = \left(\frac{p_j - b_j t_t}{p_{ij}} \right)^{\frac{1}{1-r_j}} \quad i = \{g, m, L\} \quad (\text{note: } b_j = 0 \text{ for } j = E, I, N, C_I, C_N) \quad (\text{B3})$$

where X_m and X_g are the composite material and energy inputs, and p_m and p_g are the prices of these composite inputs. The makeup of the composites is given by:

$$a_{ijm} \equiv \frac{X_{ij}}{X_{mj}} = a_{ij}^{\frac{1}{1-r_{jm}}} \left(\frac{p_{mj}}{p_i} \right)^{\frac{1}{1-r_{jm}}} \quad i = \{I, N\}; \quad a_{ijg} \equiv \frac{X_{ij}}{X_{gj}} = a_{ij}^{\frac{1}{1-r_{jg}}} \left(\frac{p_{gj}}{p_i} \right)^{\frac{1}{1-r_{jg}}} \quad g = \{F_N, F_C, F_P, E\} \quad (\text{B4})$$

Equations (B2) through (B4) assume that carbon regulation is accomplished through a carbon tax. Firm behavior will be identical under a carbon quota. In this case, profit for industry j is:

$$\rho_j = p_j X_j - \sum_i p_i X_{i,j} \quad (\text{B5})$$

with the constraint that industry emissions equal the industry emissions quota \bar{e}_j

$$b_j X_j = \bar{e}_j \quad (\text{B6})$$

Maximizing profit under this constraint yields the Lagrangian function

$$p_j X_j - \sum_i p_i X_{i,j} - \lambda_j (b_j X_j - \bar{e}_j) \quad (\text{B7})$$

If the carbon quota is set such that the shadow price of carbon emissions λ_j equals t , the Lagrangian function in equation (B7) is equal to the profit function in equation (B2) with an additional constant term $t \bar{e}_j$, which represents quota rents.³⁹ Therefore, the first-order conditions resulting from this maximization will be the same as from maximizing equation (B2), implying that the carbon quota can be modeled as a virtual carbon tax in determining firm behavior.

Finally, substituting equations (B1), (B3) and (B4) into equation (B2) and differentiating with respect to the quantity produced, X_j yields an equation for the output price:

$$p_j = \sum_i p_i a_{ij} + t b_j \quad (\text{B8})$$

where t is either the carbon tax or virtual carbon tax, depending on whether the pollution-control policy is a tax or a quota. Solving this equation simultaneously for all intermediate goods yields the price vector for the intermediate goods.

Household Utility Function: Labor Supply and Final Good Demands

The representative household's utility function is:

$$U = U(l, C_I, C_N, e) = \left(\alpha_l l^{\rho_u} + \alpha_C C^{\rho_u} \right)^{\frac{1}{\rho_u}} + \phi(e) \quad (\text{B9})$$

where C represents composite consumption:

$$C = \left(a_{C_I} C_I^{\gamma_c} + a_{C_N} C_N^{\gamma_c} \right)^{\frac{1}{\gamma_c}} \quad (\text{B10})$$

The household maximizes utility subject to the budget constraint:

$$p_{C_I} C_I + p_{C_N} C_N = p_L (1 - t_L) L + (1 - t_R) p + p_C G \quad (\text{B11})$$

and the time endowment $l + L = \bar{L}$. This maximization yields the following equations which express the household's behavior:

³⁹ This assumes that the shadow price of carbon emissions will be the same across all polluting industries, as would be the case under a tradable quota, but not necessarily the case under a non-tradable quota. If the shadow price differed across industries, firm behavior could still be modeled with a virtual tax, but the virtual tax would also vary across industries. In the rest of this analysis, we assume that the virtual tax is constant across industries.

$$a_{c_I} \equiv \frac{C_I}{C} = \left[a_{c_I} + a_{c_N} \left(\frac{a_{c_I} p_{c_N}}{a_{c_N} p_{c_I}} \right)^{\frac{r_c}{r_c-1}} \right]^{\frac{1}{r_c}} \quad (\text{B12})$$

$$a_{c_N} \equiv \frac{C_N}{C} = \left[a_{c_N} + a_{c_I} \left(\frac{a_{c_N} p_{c_I}}{a_{c_I} p_{c_N}} \right)^{\frac{r_c}{r_c-1}} \right]^{\frac{1}{r_c}} \quad (\text{B13})$$

$$p_C = p_{c_I} a_{c_I} + p_{c_N} a_{c_N} \quad (\text{B14})$$

$$l = \frac{p_L(1-t_L)\bar{L} + p_C G + (1-t_R)\rho}{p_L(1-t_L) + p_C \left[\frac{a_I p_C}{a_C p_L(1-t_L)} \right]^{\frac{1}{r_U-1}}} \quad (\text{B15})$$

$$L = \bar{L} - l \quad (\text{B16})$$

$$C = p_C^{-1} [p_L(1-t_L)L + p_C G + (1-t_R)\rho] \quad (\text{B17})$$

Combining (B17) with (B11) or (B12) yields the optimal levels of C_I and C_N .

Government

Government revenues finance a fixed level of real government transfers to households, G . Revenues (REV) are determined by:

$$REV = t_L L + t_e e + t_R \rho \quad (\text{B18})$$

where $\rho = t_q \bar{e}$, t_q is the virtual carbon tax in the emissions quota case, and t_e is the actual carbon tax. Under a carbon tax, the reverse is true.

Throughout most of this analysis, we assume that the tax on rents is the same as the tax on labor income, thus:

$$t_R = t_L \quad (\text{B19})$$

Aggregate Demand and Supply

Aggregate demand for the two final goods is determined by the household, through equation (B17) and equation (B11) or (B12). Aggregate demand for labor and for the six intermediate goods is determined from the use of each good in production, yielding

$$AD_i = \sum_j X_{ij} \quad (\text{B20})$$

Since production of all goods follows constant returns to scale, supplies of both final goods and the six intermediate goods are determined by demand. Thus

$$X_{C_I} = C_I \quad (\text{B21})$$

$$X_{C_N} = C_N \quad (\text{B22})$$

$$X_i = AD_i \text{ for } i \text{ ranging over } F_N, F_C, F_P, E, I, \text{ and } N \quad (\text{B23})$$

Solving this last equation simultaneously for all values of i yields aggregate supplies and demands for the intermediate goods.

IV. EQUILIBRIUM CONDITIONS

The equilibrium conditions are:

$$L = AD_L \quad (\text{B24})$$

$$e = \bar{e} \quad (\text{B25})$$

$$REV = p_c G \quad (\text{B26})$$

To solve the model, we compute the values of t and t_L that satisfy (B25) and (B26), using p_L as the numeraire. By Walras's Law, if two of the three equilibrium conditions hold, the third will also hold, so the vector of primary prices that satisfies (B25) and (B26) also satisfies (B24).

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Figure 1
Marginal Cost of Emissions Reduction

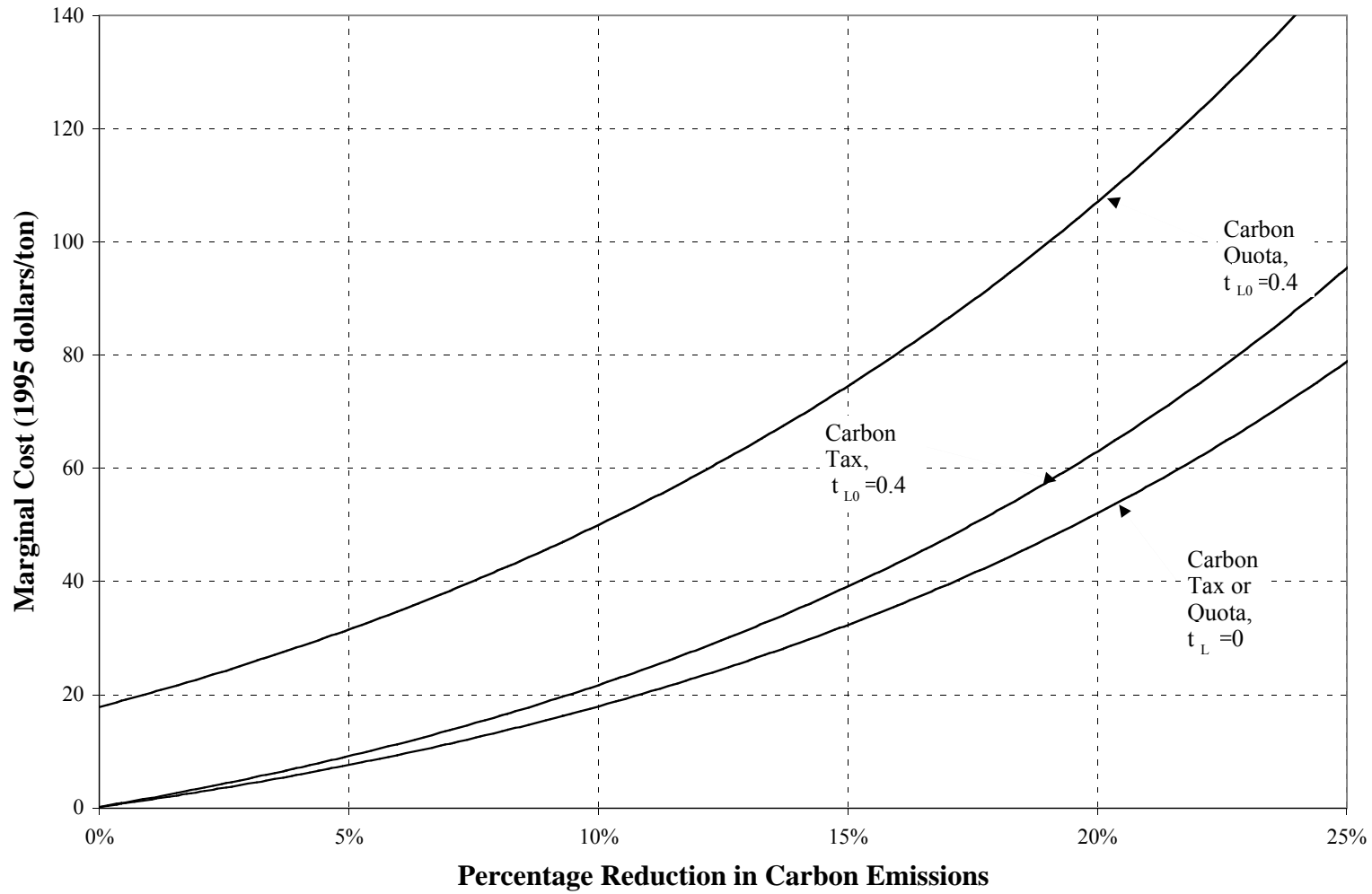


Figure 2
Ratio of Second-Best to First-Best Costs

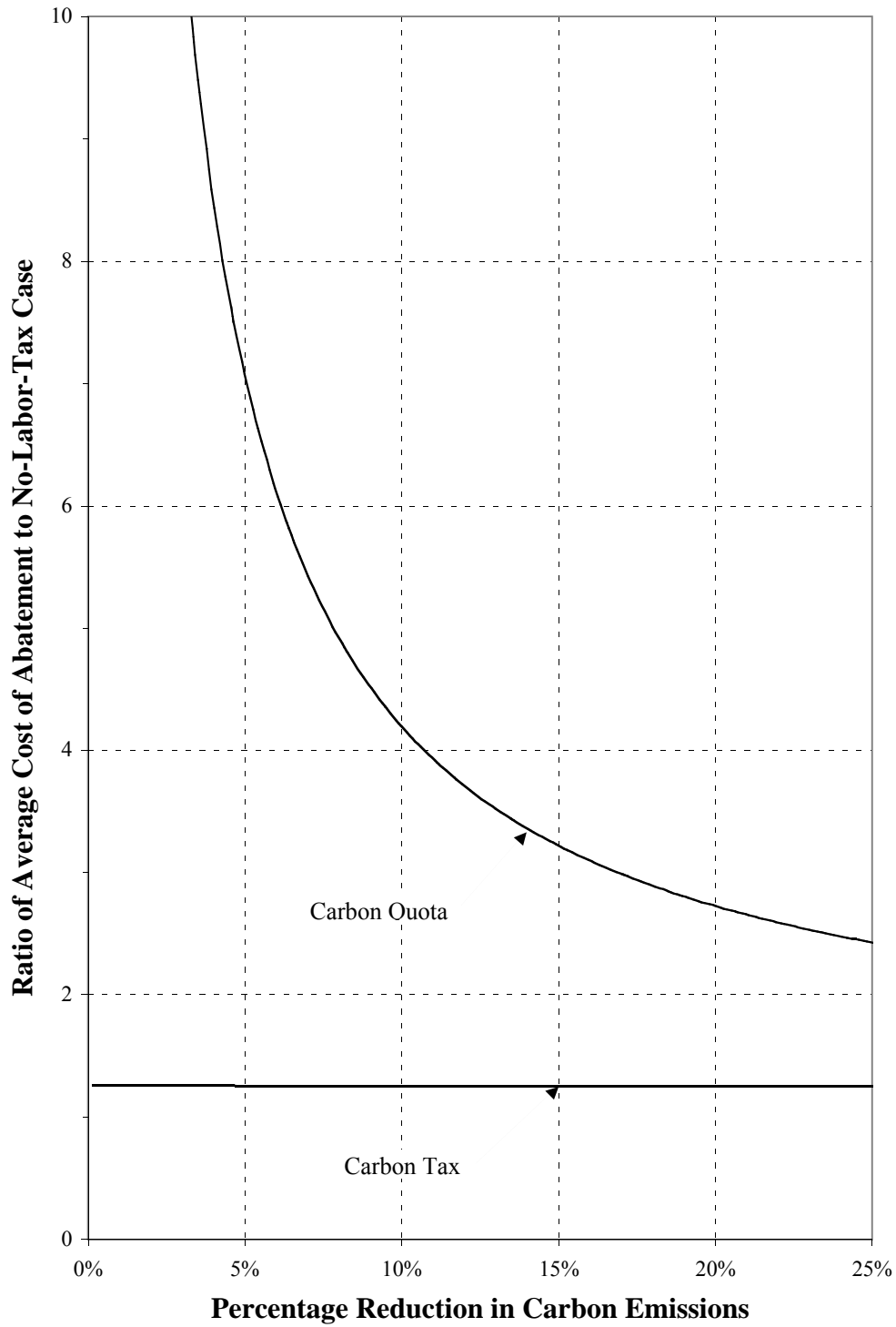


Figure 3
Net Welfare Gain from the Optimal Level of Regulation

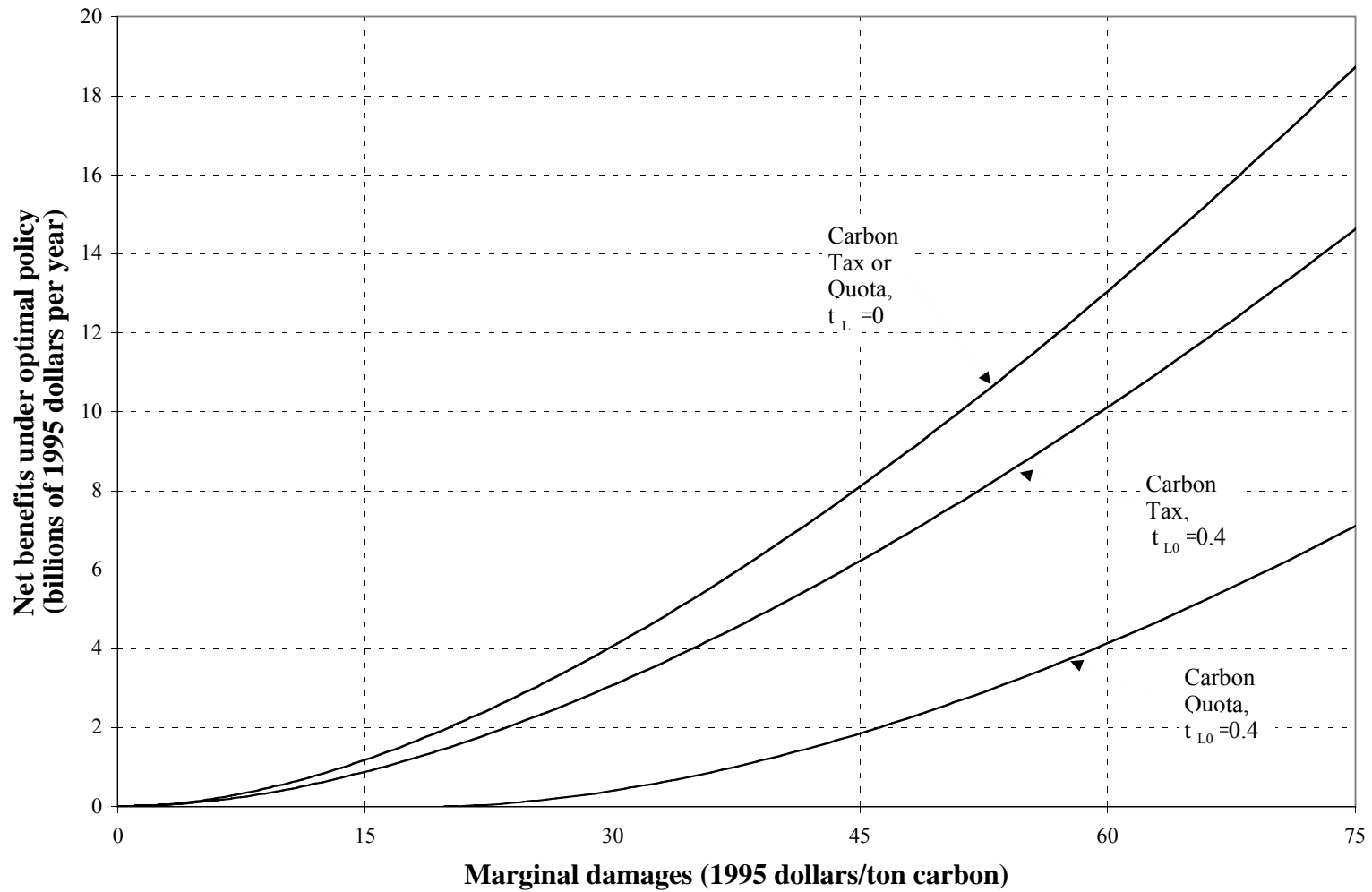


Figure 4
Net Welfare Gain Under the Pigouvian Rule

