# Average Substitution and Non-Market Effects in Second-Best Policies*

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**Abstract**

Two maintained assumptions characterize most of the recent studies of non-market policy and tax interaction effects. Leisure and non-market goods are assumed to be separable from all other consumption in the final demand system. These simplifications are potentially important because this literature concludes that labor supply responses are a primary source of the distortionary costs of new taxes and regulations. This paper explores the consequences of relaxing these assumptions in a framework consistent with the theory of environmental valuation. We provide a general, analytic discussion of Harberger-based measures of excess burden which include both market and non-market interaction effects. We illustrate their importance using a calibrated, numerical model for the United States that includes air quality as a non-separable, welfare-enhancing amenity. Deviations from leisure and non-market separability change estimates of excess burden as much as 30% in simulations where the benchmark value of air quality represents less than 1% of GDP. Furthermore, we show that there are conceptual reasons to treat these two assumptions as linked. Many non-market goods (such as air quality) come as a byproduct of other economic activity. In this case, the non-market good is itself a source of indirect excess burden through the variation it introduces in the relative degree of complementarity between leisure and other consumables.

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# I Introduction

The Harberger triangle (Harberger 1964) is a cornerstone in analysis of market distortions (Hines 1999). Goulder and Williams (2003) provide one of the first detailed evaluations of Harberger's simplest measure for deadweight losses. Their results indicate the typical application of the triangle logic ignores important general equilibrium effects from pre-existing distortions, often leading to a substantial understatement of the actual cost of a new tax. Equally important, these authors propose and evaluate a simple, alternative measure that captures the effects arising from one of the most important sources of these general equilibrium effects — income taxes.

An central assumption in Goulder and Williams (and nearly all of the literature on tax interaction effects and revenue recycling) is that the newly taxed commodity is "average" in its substitution pattern with leisure in the aggregate demand system. While their study (and others) acknowledges that if actual conditions depart from this assumption their findings may well be affected, to our knowledge, no one has attempted to describe just how important average substitution might be for excess burden measurement. Toward this end, this paper extends the Goulder-Williams analysis in four ways.

First, we show for several, common preference structures that one can, in fact, evaluate the importance of the relationship between the taxed good and leisure without full knowledge of the relevant cross-price elasticities. Second, we generalize the Goulder and Williams empirical model by including air quality as a non-separable, welfare-enhancing amenity. This extension allows us to describe an excess burden framework in which externalities create distortionary wedges in the *virtual* supply and demand prices of environmental services. When the non-market good is non-separable, it becomes an independent source of interaction effects through the changes it implies in the relative degree of complementarity between leisure and other consumables.

We consider two alternative preference structures — one in which a simple bundle of air quality and leisure trade off against other consumables in a two-level, nested CES function, and another where leisure is bundled with a composite of air quality and consumer services. This allows to explore non-market effects (through air quality), market effects (through services), and the interaction between these two channels. Demand for air quality is calibrated using EPA's (1995) emission factors by sector for particulate matter ($PM_{10}$) and the Smith and Huang (1995) summary benefit measures for $PM_{10}$. The benchmark calibration of the model is otherwise identical to the setup in Goulder and Williams. As a consequence, we are able to link our discussion very closely to an established framework — an opportunity that is both valuable and uncommon across studies that employ computable general equilibrium models.

In the first of our specifications, the results suggest the Goulder-Williams measure is more robust than previously claimed. The presence of air quality as a quasi-fixed, non-market good in the preference structure does little to change the relationship between leisure and market demands. The relationship between leisure and air quality, whether substitution or complementarity, does not affect the superior relative performance of the Goulder-Williams measure over the simple Harberger triangle. Nor does it change the absolute magnitude of the errors in either of these approximations very much. It does, however, influence the *direction* of the bias in the Goulder-Williams measure.

The market-based deviations from average substitution implied by the second specification of the model, however, has a marked impact on the performance of their proposed method for estimating excess burden. Both the magnitude of its error and the direction are affected. Complementarity between leisure and consumer services reverses the sign of the bias in their measure and increases the size of its error by over fifty percent. Their approach remains superior to reliance on the direct effects alone. The bias in the Harberger estimate remains negative with the relative size of the error insensitive, as expected, to the nature of the commodity interrelationships implied by preferences.

Introduction of air quality allows for a third extension. The model can consider the indirect effects of market substitutions in response to tax changes. That is, changes in the consumption of market goods alter the patterns of production and, in turn, affect pollution emissions. These effects "feedback" outside the market, and the non-market effects of air pollution alter the trade offs between market goods. This result follows because air quality makes a non-separable contribution to preferences.

Non-market effects (i.e. allowing air quality levels to adjust with the composition of the consumer's basket of market goods) on market-based measures of excess burden are important with both preference specifications. Substitution and complementarity have substantial effects on the bias in the Goulder-Williams measure in the presence of a non-market feedback.

Finally, our last extension considers the magnitude of the non-market effect on the true measure of the welfare cost of tax distortions. A tax on energy serves to reduce energy consumption and to reduce particulate emissions. When this effect is allowed to "count", the welfare losses attributed to the tax decline by about 20%. This is not due to the model's calibration. At the baseline, the share of "full income" that would be attributed to air quality is less than one percent (0.6%).

Overall, our findings confirm and extend the basic message of this literature — tax interaction effects exert important influences on general equilibrium measures of excess burden. However, in a world with non-separable preferences, the non-market feedbacks arising from pollution influence the size and the sign of the error in the Goulder-Williams measure of welfare loss. Moreover, the welfare-enhancing effects of non-market amenities offer the potential to partially offset the welfare losses of some types of taxes. These effects seem to be more important than the literature to date has acknowledged.

Section II provides context for the Harberger-based measures of excess burden and reviews the primary measure proposed by Goulder and Williams (2003). We also discuss how average substitution and non-separable amenities influence the final demand system within the Goulder-Williams framework. Section III introduces non-separable amenities into their analytical model and describes these influences to measures of excess burden. Section IV describes how a model designed to match the Goulder-Williams numerical example is calibrated with non-separable, non-market amenities. Section V describes our basic findings and section VI explores the sensitivity of the model to three elements in the calibration. The last section summarizes our conclusions.[1]

# II Background

## A The Measurement of Excess Burden

Over thirty years ago, Harberger (1971) offered a "plea" to economists to accept some basic postulates for applied welfare analysis. He outlined the conceptual logic for conducting these analyses and proposed three principles:

a.) the competitive demand price for a given unit measures the value of that unit to the demander;

b.) the competitive supply price for a given unit measures the value of that unit to the supplier;

c.) when evaluating the net benefits or costs of a given action (project, program, or policy), the costs and benefits accruing to each member of the relevant group (e.g. a nation) should normally be added without regard to the individual(s) to whom they accrue. (p. 785)

These conditions allow evaluation of the welfare losses for a host of market distortions using what have come to be known as "Harberger Triangles."[2] In fact, his approach begins with a more complex basis

[1] We include a detailed set of appendices with all the key derivations and the features of the data used in our calibrated model.

[2] See Hines (1999) for a careful overview of the history and impact of Harberger's work in applied welfare economics.

for approximating the welfare losses due to price distortions. It acknowledges the presence of interaction effects in other distorted markets as well as the triangle approximation for the welfare losses due to a price wedge in one market. For example, the excess burden (EB) for a change in one tax ($\tau_k$) in the presence of other tax distortions ($\tau_i, i = 1, \ldots, m$) would be measured by (1).[3]

$$EB = -\frac{1}{2}\tau_k^2 \frac{dx_k}{d\tau_k} - \sum_{i \neq k} \tau_i \tau_k \frac{dx_i}{d\tau_k} \tag{1}$$

$x_i$ is the quantity of commodity $i$. His simplification arises from two strategic assumptions. First, he adopts what he labels as a "substitution effects only" approach and assumes lump sum payments to households in order to *normalize* for any changes in their tax payments as a result of the change in $\tau_k$. Secondly, he assumes that the interactions with other markets (the second set of terms in (1)) are small and can be ignored.

Prior to Harberger, economists were not measuring the excess burden due to distortions.[4] Once they saw how useful these empirical estimates could be for policy analysis, they joined earlier advocates of using applied welfare economics in the context of public investments (e.g. Krutilla and Eckstein (1958)), in calling for wider use of benefit-cost analysis.

Today these assessments are commonplace. Most policy analysts take for granted that simplified versions of (1) (i.e. dropping the second set of terms on the right side of the expression) that restrict attention to the own-market effects are not overturned by general equilibrium price interactions.[5] There is also wider recognition of the potential for policy interaction effects that arise from regulatory policies. The largest of these effects is likely due to environmental policy. Efforts to quantify these interaction effects, due to second-best interactions of these regulations with taxes, suggest they may be substantial (see Goulder, Parry, Williams and Burtraw (1999)). While these effects rely exclusively on supply-side effects with respect to pollution, they reinforce the importance of considering how non-market effects can be incorporated in measures of excess burden.

Market interactions (for commodities other than the taxed goods) arise because there are wedges caused by the pre-existing distortions. That is, the demand and supply prices for these goods will not be equal. As a result, any change in the price of the newly tax goods affects the size of the welfare losses associated with these pre-existing distortions through the substitution and complementarity relationships (i.e. the $\frac{\partial x_i}{\partial \tau_k}$ terms in (1)) between the newly taxed good $k$ and these other taxed goods.

[3]Our notation follows Goulder and Williams (2003) except as indicated.
[4]Hines (1999), p. 186.
[5]See, for example, Ballard, Shoven and Whalley (1985) and citations in Hines (1999).

Efforts to include non-market distortions would parallel Harberger's original logic.[6] That is, for externalities, the failure to "price" these unintended effects implies the marginal value of being able to engage in activities that lead to external effects (i.e., a virtual price for the "disposal services" of the environment) will not be equal to the marginal cost (i.e., virtual supply price) experienced by those incurring the impacts (i.e., the receptors).[7] A comparable logic to that used for market interactions is often applied in rationalizing the omissions of the non-market consequences. That is, the amenities impacted by externalities are assumed to be separable in their contribution to household well-being. Thus, they are average substitutes. Bovenberg and Goulder (1997), Bovenberg and de Mooij (1994), Goulder (1995), Williams (2002), Williams (2003) are all examples of this approach.[8] For these authors, this proposal does not seem any more restrictive than what underlies the simplified Harberger rule. What has been missed in their logic is that complementarity between market and non-market goods underlies a large component of the revealed preference logic providing measures for the value of non-market goods to consumers. Moreover, even in the case of substitution effects — the feedback arising from substitution or complementarity effects of tax-induced changes in the levels of externalities is not taken into account. As a result, what might be described as changes in virtual income (i.e., income due to market activity and non-market gains or losses due to the positive or negative externalities experienced) are omitted from Harberger's normalization.

As we noted at the outset, Goulder and Williams (2003) challenge the first of the commonly held judgments in the literature. They find that the simplified version of Harberger's approach can underestimate excess burden by a factor of ten or more. The Goulder-Williams (GW) analysis also proposes a simple alternative that focuses on the general equilibrium interactions in one other market — the labor market — because it is likely to be the most important source of general equilibrium price interactions. This paper addresses the second by outlining the logic for considering further amendments to reflect important non-market interactions.

Assuming all consumption goods are average substitutes for leisure, the $EB^{GW}$ measure is given in (2).[9]

[6] Public goods can fit within the same logic as well. In this case, however, there is a need for different prices for each individual because the quantity available (for pure public goods) is the same for all.

[7] This logic is exactly the adaptation that Goulder et al. (1999) used in comparing the welfare costs of different policy instruments — permits, standards and effluent charges were converted to virtual tax wedges to consider the same logic as it relates to the generation of pollution. What has been omitted is the interaction arising because receptors substitute among market goods in response to changes in externalities.

[8] The only exception among the empirical analyses is Espinosa and Smith (1995).

[9] This expression incorporates the GW assumption that all commodities are average substitutes for leisure. Their equation (24) is a more general statement.

$$EB^{GW} = s_k y \frac{[(\tau_{C_k}^2/2P_{C_k}^2)\epsilon_{C_k} - (\tau_{C_k}\tau_L/P_{C_k})\epsilon_L]}{(1-\tau_L\epsilon_{Ly})} \tag{2}$$

$\tau$'s are tax rates (for the newly taxed good $C_k$ and labor, $L$) as before, $P_{C_k}$ is the market price, $s_k$ is the share of income spent on $C_k$; $y$ is income; $\epsilon_{C_k}$ is the compensated price elasticity of demand for $C_k$; $\epsilon_L$ is the compensated labor supply elasticity; and $\epsilon_{Ly}$ is the income elasticity of labor supply.

The GW analysis adopts a composite strategy. That is, they combine a comparative static analysis of the implications of changes in taxes, using general specifications for preferences and production, with an illustrative, but more restrictive, numerical model. The latter provides empirical context that supplements the qualitative insights from their theoretical analysis. To appreciate how the specific details of any application influences the simple Harberger measure and their suggested generalization we need to consider the implications of both components of their analysis. Three features of their composite strategy are important.

## B Average Substitution & Separability

The first issue concerns the treatment of substitution among commodities as well as between commodities and leisure. If all other consumption goods (aside from the one experiencing the tax change) have approximately equal cross-price elasticities (with the previously taxed commodity, in their case labor), then the importance of all these interactions to a measure of excess burden will depend on the revenues from pre-existing taxes in each market.[10] Based on GW definitions, this is one way that an assumption of average substitution influences Harberger's method. To evaluate its implications within the context of their numerical model, consider the consumption interaction terms dropped from the general Harberger measure (i.e. the second set of terms on the right of (1)), reflecting the cross-price substitution effects for consumption goods.[11] Their effects, designated here as $\widetilde{CPI}$ (shorthand for cross-price interactions), are represented in (3).

$$\widetilde{CPI} = \sum_{i \neq k} \frac{\tau_i C_i}{P_{C_k}} \cdot \epsilon_{C_i C_k} \tag{3}$$

Substituting for the compensated elasticity in terms of the Allen elasticity of substitution, $\sigma$, which will be constant for $C_i$'s in a CES specification, we have:

[10] As GW note this assumption is usually made because these cross-price effects are difficult to estimate.
[11] A comparable argument could be made for the interactions due to intermediate goods.

$$\widetilde{CPI} = \frac{\sigma}{P_{C_k}} \sum_{i \neq k} s_i \tau_i C_i \tag{3a}$$

Thus, a share weighted average of the tax revenue in the omitted sectors determines the importance of dropping this term for their empirical analysis.

Another aspect of average substitution influences the GW measure. It assumes that the compensated cross-price elasticity between the taxed good *and leisure* is equal to the share-weighted average of this elasticity for all consumption goods as in (4).

$$\epsilon_{C_k L} = \sum_{i=1}^{M} s_i \epsilon_{C_i L} \tag{4}$$

It is difficult to form specific intuition to support or refute this proposed restriction.[12] One way to gain more insight into the condition is to consider what (4) implies for their numerical model, a nested CES with leisure in one nest and all consumption goods in the other. To develop this logic, replace (as in (3)) the compensated elasticities, $\epsilon_{C_i L}$, using Allen partial elasticities of substitution then average substitution can be described with (4a).

$$s_k \sigma_{C_k L} = \sum_{i=1}^{M} s_i^2 \sigma_{C_i L} \tag{4a}$$

When leisure is separable from final goods consumption (as is the case in GW and almost every other study of tax interaction effects), $\sigma_{C_k L} = \sigma_{C_i L}$ for all $i$, so (4a) reduces to a less intuitive expression given in (5). In this case we see that the share for $C_k$ is required to equal the share-weighted average of shares for all consumption goods.

$$s_k = \sum_{i=1}^{M} s_i^2 \tag{5}$$

This condition is interesting in that it does not reflect the curvature of the preference function (i.e. whether goods are substitutes or complements). Instead the condition depends on the intensities of consumption choices among sectors represented in the economy in relation to the taxed sector.

There are at least two aspects of this simple re-interpretation of the meaning of average substitution for

[12] If $e(w, f(P_{C_1}, P_{C_2}, \ldots, P_{C_m}), u)$ designates the Hicksian expenditure function, then $\epsilon_{C_i L}$ can be written as: $\epsilon_{C_i L} = P_{C_i} \frac{e_{w_f} \cdot f_{P_{C_i}}}{e_w}$. Recognizing that $\sigma_{C_i L} = \frac{\epsilon_{C_i L}}{s_i} = w(\frac{e_{wf}}{e_f})$ we have that separability implies equality of the $\sigma_{C_i L}$ across all $i$.

the class of models consistently used in all evaluations of the interaction effects of taxes and regulations. First, it stems from treating leisure as separable from consumption goods. As a result, a judgment about the importance of tax interactions arising in the labor market can be made largely independent of the substitution patterns among consumption goods. This preference specification seems likely to be most consistent with the GW proposal that adjustments to take account of tax interactions in other markets can focus on labor alone.

Second, even when (4a) does not reduce to (5), this definition of average substitution will depend on the value share parameters in a straight-forward way. That is, if average substitution were defined as equality of the Allen substitution elasticities rather than in terms of an average of the cross-price elasticities, then baseline conditions (e.g. the importance of the taxed good relative to alternatives) is a simple adjustment to their interaction term, reflecting the baseline consumption shares of each sector (i.e. $s_k / \sum_{i=1}^{M} s_i^2$).

## C Quasi-Fixed Goods & Non-Homotheticity

The second and third features of our modifications to the GW structure arise from considering non-market tax interactions by introducing the services of environmental resources into preferences in a format that does not require separability.[13] Changes in the amount of amenity services delivered by environmental resources provide the means for pollution externalities to affect households. Much of the environmental literature on consumer behavior describes what can be learned from people's responses to spatial differences in amenities. The literature on excess burden, and the GW analysis in particular, adopt a representative agent model. This structure implies that the "agent" is intended to provide a description of all households' responses. In addition, there is usually no spatial dimension in these models. To represent external effects on amenities in this context, we assume the agent treats amenity services as a quasi-fixed good outside her choice. Other consumption choices of goods that lead to increased pollution emissions may change the level of amenities and, in turn, with non-separabilities, the demands for market goods. Once again pollution may alter demands and then amenities and so forth. This process impacts the market equilibrium but takes place outside the market. These "feedback loops" are not recognized by the agent as being associated with his or her consumption choices. Thus, in

[13] Williams (2002) and Williams (2003) introduce the effects of amenities as separable arguments. These formulations maintain the average substitution assumption between non-market goods and the market components of the economy. Their impact on individual choices can be seen as equivalent to income effects. The budget constraint is modified to include lower productivity and increased health costs. de Mooij (2000) devotes chapter 8 to a discussion of non-separable externalities in preferences and in production technologies, including numerical simulations. However, his simulations should be considered as a theoretical exercise and not a detailed, empirical investigation.

Harberger's logic the virtual demand price remains different from the supply price faced in "producing" the change in amenity services. Moreover, non-market interaction effects arise because the size of these virtual price wedges change with changes in the equilibrium prices (and associated consumption levels) of the market goods.[14] Thus substitution and complementarity relationships have a different type of influence than with market goods where quantity adjustments can be expected as a result of these price changes.

Introducing quasi-fixed goods non-separably in preferences implies that a homothetic preference function will appear to be non-homothetic. This result implies that when the analysis begins with a preference specification such as that of GW (e.g. homothetic) and introduces non-market goods, the resulting analyses of excess burden measures will reflect changes in responsiveness due to non-unitary income elasticities *as well as* the non-market interactions. These income effects are the third aspect of our modification to the GW logic. For most applications this modification is desirable. Non-unitary income elasticities for all goods (unitary elasticities are implied by the nested CES) provide another difference between the Harberger approximation and Hicksian measures of excess burden. In the unitary case, responses (in percentage terms) to income changes are equivalent across all goods. In our case, however, this dual feature of introducing quasi-fixed goods implies it is difficult to isolate the impacts of modifying the GW model to distinguish non-market interactions from the effect of non-unitary income elasticities — both stem from the same alterations in their model.

Perroni (1992) develops the logic for this conclusion using restricted and unrestricted expenditure functions.[15] If a consumer is endowed with a fixed amount of some good that does not trade (in our case the amenity services), then the observable total expenditures (and income with no saving) will be the difference between the unrestricted expenditures and the component of expenditures due to the restricted good. This amount depends on the level of the quasi-fixed good and the virtual price of that good (evaluated at the prices of other market goods and the level of the quasi-fixed good for a given utility level). Thus, the implied differential responsiveness of marketed goods to changes in income under these conditions reflects the differences in the degree of substitutability or complementarity between all

[14]Madden (1991) used the response of virtual price functions to define substitution and complementarity relationships between quasi-fixed (or rationed) and market goods. This is the type of response that underlies our argument for changes in the virtual price wedges — either exogenous changes in the pollution level or changes in market prices can alter these virtual prices. It is the substitution or complementarity relationships between goods that will determine the direction of change for the demand and supply-side virtual prices.

[15]His intention was to use a homothetic function to represent non-homothetic preferences in order to relax the assumption of non-unitary income elasticities.

market goods and the one that is quasi-fixed.[16]

# III Non-Market Contributions to Excess Burden

The basic logic for describing how a non-separable amenity influences the excess burden of taxes on consumption goods adds terms to the total differential of preferences (GW equation (12)) to reflect changes in the amenity, $q$, with changes in consumption goods. The latter changes as a result of the change in the $k^{th}$ good's tax together with the substitution or complementarity between $k$ and the other consumption goods. This is summarized in (6).

$$dU = \sum_{i=1}^{M} \frac{\partial U}{\partial C_i} \frac{\partial C_i}{\partial \tau_{C_k}} d\tau_{C_k} + \frac{\partial U}{\partial l} \frac{\partial l}{\partial \tau_{C_k}} d\tau_{C_k} + \frac{\partial U}{\partial q} \sum_{i=1}^{M} \frac{\partial q}{\partial C_i} \frac{\partial C_i}{\partial \tau_{C_k}} d\tau_{C_k} \tag{6}$$

The last set of terms on the right side of (6) describe how each $C_i$ affects $q$. Using first-order conditions for a consumer's choice of the market goods (i.e., $\frac{\partial U}{\partial C_i} = \lambda P_{C_i}$ and $\frac{\partial U}{\partial l} = \lambda(1 - \tau_L)$) and the first order conditions for the use of factors of production (e.g., labor $\frac{\partial f_i}{\partial L_{C_i}} = \frac{1}{P_{C_i} - \tau_{C_i}}$, and intermediate goods $\frac{\partial f_i}{\partial I_{ji}} = \frac{\tau_{I_j}+1}{P_{C_i} - \tau_{C_i}}$) we can replace $P_{C_i} \frac{\partial C_i}{\partial \tau_{C_k}}$ with $\left( \tau_{C_i} \frac{\partial C_i}{\partial \tau_{C_k}} + \frac{\partial L_{C_i}}{\partial \tau_{C_k}} + \sum_{j=1}^{N} (\tau_{I_j} + 1) \frac{\partial I_{ji}}{\partial \tau_{C_k}} \right)$ for all $i$.

Intermediate good production is simply labor allocated to each sector (i.e., $I_{ji} = L_{I_j}$), so the total time ($T$) is composed of labor allocated to consumption goods ($L_{C_i}$), intermediate good ($L_{I_j}$) and leisure ($l$). This implies

$$\frac{\partial l}{\partial \tau_{C_k}} + \sum_{i=1}^{M} \frac{\partial L_{C_i}}{\partial \tau_{C_k}} + \sum_{j=1}^{N} \frac{\partial L_{I_j}}{\partial \tau_{C_k}} = 0 \tag{7}$$

Substituting our expression for $P_{C_i} \frac{\partial C_i}{\partial \tau_{C_k}}$ and the balance condition on labor (equation 7) into 6, with

[16] If $\epsilon_{iy}$ = income elasticity, in the Perroni setting it is given as:

$$\epsilon_{iy} = \frac{E_{iy}}{E_y} \frac{E}{E_i}$$

with E = observable total expenditures
e = unrestricted expenditures
F = expenditures on quasi-fixed good
So E = e - F.
where subscripts refer to partial derivatives with respect to $i$ in the price (for $i$) and income (for $y$). This is written as:

$$\epsilon_{iy} = \left( \frac{e_i - e_k e_{ik}/e_{kk}}{e} \right) \frac{E}{y\ e_i}$$

Perroni outlines how this expression is represented in terms of Allen elasticities to provide

$$\epsilon_{iy} = (1 - s_k) \left( 1 - \frac{\sigma_{ik}}{\sigma_{kk}} \right)$$

where $s_k$ = share of $F$ in $e$ and $\sigma_{ik}$ is the unrestricted Allen elasticity of substitution, (see Perroni (1992), p. 21).

the latter adjusted to incorporate the first order conditions, we have equation (8).

$$\frac{1}{\lambda}\frac{dU}{d\tau_{C_k}} = \tau_{C_k}\frac{\partial C_k}{\partial \tau_{C_k}} + \sum_{i\neq k}\frac{\partial C_i}{\partial \tau_{C_k}} + \sum_{j=1}^{N}\tau_{I_j}\frac{\partial I_j}{\partial \tau_{C_k}} - \tau_L\frac{\partial l}{\partial \tau_{C_k}} + \frac{1}{\lambda}\frac{\partial U}{\partial q}\sum_{i=1}^{M}\frac{\partial q}{\partial C_i}\frac{\partial C_i}{\partial \tau_{C_k}} \tag{8}$$

The last step in the process is to replace the final consumption and intermediate good effects with compensated terms. For example, in the case of the $i^{th}$ consumption good

$$\frac{\partial C_i}{\partial \tau_{C_k}} = \frac{\partial C_i^C}{\partial \tau_{C_k}} - \frac{\partial C_i}{\partial y}\left(C_k - \frac{dG}{d\tau_{C_k}}\right) \tag{9}$$

The last term in (9) arises from the Harberger normalization (i.e., assuming lump sum return of tax revenue to consumers). Changes in the $\tau_{C_k}$ influence the amount returned to consumers and hence the $C_k$. Notice that we can combine terms, involving the non-market interactions and the tax interaction effects, after substituting from the Slutsky equation to derive

$$\begin{aligned}\frac{1}{\lambda}\frac{dU}{d\tau_{C_k}} = \quad & \left(\tau_{C_k} + \tfrac{1}{\lambda}\tfrac{\partial U}{\partial q}\tfrac{\partial q}{\partial C_k}\right)\tfrac{\partial C_k^C}{\partial \tau_{C_k}} + \textstyle\sum_{i\neq k}\left(\tau_{C_i} + \tfrac{1}{\lambda}\tfrac{\partial U}{\partial q}\tfrac{\partial q}{\partial C_i}\right)\tfrac{\partial C_i^C}{\partial \tau_{C_k}} + \textstyle\sum_{j=1}^{N}\tau_{I_j}\tfrac{\partial I_j}{\partial \tau_{C_k}} - \tau_L\tfrac{\partial l^C}{\partial \tau_{C_k}} \\ & + \left(\textstyle\sum_{i=1}^{M}\left(\tau_{C_i} + \tfrac{1}{\lambda}\tfrac{\partial U}{\partial q}\tfrac{\partial q}{\partial C_i}\right)\tfrac{\partial C_i}{\partial y} + \textstyle\sum_{j=1}^{N}\tau_{I_j}\tfrac{\partial I_j}{\partial \tau_{C_k}} - \tau_L\tfrac{\partial l}{\partial y}\right)\left(\tfrac{dG}{d\tau_{C_k}} - C_k\right)\end{aligned} \tag{10}$$

The analytic expressions are reasonably intuitive. Our derivation assumes there are no external effects from intermediate goods. This assumption will be relaxed in the numerical model that follows. $\frac{1}{\lambda}\frac{\partial U}{\partial q}$ is the virtual price of the amenity. When scaled by $\frac{\partial q}{\partial C_k}$ we have the equivalent of "environmental costing" of consumption goods. If $\frac{\partial q}{\partial C_k} < 0$, the feedback effects reduce the importance of distortionary taxes. The contribution to excess burden would depend on the "net" size of the tax in relation to the incremental environmental costs (through $\frac{1}{\lambda}\frac{\partial U}{\partial q}$) and on the consumption levels of all goods. The effects of separability (or the assumption of average substitution) enter through the response of the term involving the consumption of all other goods. The feedback effects enter through what is assumed about the $\frac{\partial q}{\partial C_i}$ terms.

Harberger's normalization (e.g., returning tax revenue) affects this expression in two ways. The second term on the right side of (10) suggests that changes in revenues need to be adjusted for the virtual income associated with unpriced amenities.[17] In addition, they contribute to the income adjustment as implied by the last term.

[17] Recall these distinctions between restricted and unrestricted expenditures in the general context are the source of Perroni's non-homotheticity.

The second effect is an important difference between market and non-market interactions that is more easily appreciated using Irvine and Sims (1998) application of the envelope theorem to characterize differences between the Harberger and Hicksian compensated demand responses to a single tax change.[18] Ignoring the cross market effects, a change in the $k^{th}$ consumption good to the tax along a "normalized" Harberger demand will approximate the Hicksian pure substitution effect, the error depending on the disparity between the consumption of the $k^{th}$ good at the initial tax versus what is consumed with given income at the new tax. If there is little difference, Harberger's measure of this tax effect will closely approximate the pure substitution effect. Once we introduce non-market effects that are not separable, this measure of the tax effect is seen to be incomplete. It ignores the feedback effect due to the non-separability. The contribution of the $k^{th}$ good to $q$ in both the first and the last term in (10) imply that, with recognition of non-market feedbacks, the slope and the position of the Harberger demand in relation to the Hicksian demand will change.

# IV The Numerical Model

In this section we describe a calibrated, numerical, general equilibrium model capable of evaluating the implications of average substitution and non-separable amenities. The model is structured to permit direct comparison of our results with Goulder and Williams' earlier study of the importance of tax interaction effects. The Goulder and Williams (2003) analysis is "state of the art" in the measurement of excess burden in presence of distortionary taxes.

[18] This argument adapts their analysis of Slutsky, Marshallian, and Hicksian demand responses to price, see p. 321 in the appendix to their paper. If we consider the consumer problem in Goulder and Williams' model (as it would be adapted to reflect Harberger's normalization for tax revenues) we can re-write their budget constraint (their equations (6) and (7) combined) as:

$$\sum_{j=1}^{N} \tau_{I_j} I_j^o - \sum_{i=1}^{M} (P_{C_i} - \tau_{C_i}) C_i^o - \tilde{\Delta}_k C_k^o = \sum_{j=1}^{N} \tau_{I_j} I_j - \sum_{i=1}^{M} (P_{C_i} - \tau_{C_i}) C_i - \tilde{\Delta}_k C_k$$

$C_i^o$ is the initial bundle of consumer goods on which the demand is conditioned for the Harberger approximation. $\tilde{\Delta}_k$ is the tax change (i.e., the $d\tau_{C_k}$ whose welfare loss is being measured). The task in interpreting demands is to characterize the properties of the uncompensated demand $\frac{\partial C_k}{\partial \tau_{C_k}}$ for this problem in relation to the pure substitution or Hicksian compensated effect. The Harberger demand, $C_k^{Ha}$, equals a Hicksian demand, $C_k^H$, at the equilibrium selections for the consumer choice problem. As a result we can use this to define the equivalent to the Irwin and Sims envelope condition for this problem

$$C_k^{Ha}(P_C - \tau_C,\ \tau_I,\ \tilde{\Delta}_k,\ C^o) = C_k^H(P_C - \tau_C,\ \tau_I,\ V(P_C - \tau_C,\ \tau_I,\ \sum_j \tau_{I_j} I_j^o - \sum_i (P_{C_i} - \tau_{C_i}) C_i^o - \tilde{\Delta}_k C_k^o))$$

$$\frac{\partial C_k^{Ha}}{\partial \tau_{C_k}} = \frac{\partial C_k^H}{\partial \tau_{C_k}} + (C_k^o - C_k^M) \frac{\partial C_k^M}{\partial y}$$

Thus the closer $C_k^M$ is to $C_k^o$, the closer will the Harberger demand approximate the pure substitution effect. When we introduce non-separable amenities with the feedback effect there is another argument in the two demand functions — $q$ — and it changes with $\tau_{C_k}$ because all $C_i$ change. As a result, both the pure substitution (i.e., $\frac{\partial C_k^H}{\partial \tau_{C_k}}$) and the approximate income substitution terms must change.

Their analysis maintains that a simplified treatment of the most important source of tax interactions — that due to labor market effects — is possible because average substitution offers a reasonable description of the substitution relationships among consumption goods. As we noted above, this assumption implies that the cross-price elasticity between leisure and the taxed good is approximately equal to the weighted average of the cross-price elasticities for all consumption goods. We suggested that separability between leisure and consumption goods implies this actually restricts consumption shares for the benchmark solution.

The second issue we raised concerned whether the size of these interactions was influenced by non-market effects – also an important source of distortionary wedges that affect consumer behavior when consumption goods, leisure, and amenities contribute to preferences in non-separable ways. These two conceptual issues motivate our empirical analysis.

Goulder and Williams (2003) consider two examples — a new tax on cigarettes and one associated with energy. In each example, the only important pre-existing distortion is in the labor market. We limit our attention to the impact of the same energy tax proposals in our model because this case is most likely to have relevance to environmental policy. The structure of their numerical model resembles the ones that Goulder and co-authors have used to evaluate the tax interaction effects arising from new environmental policies with pre-existing labor taxes (see Goulder, Parry and Burtraw (1997) and Goulder et al. (1999)). In these cases pollution's effects on households have been treated as separable and environmental policy is assumed to impose the equivalent of new virtual taxes on firms for their emissions.

Our model alters the focus to the interaction effects due to the implicit wedge between the virtual demand and supply prices for amenities. Interactions arise, as we noted, because pollution is assumed to affect air quality and air quality enters preferences in a non-separable form. Pollution (the sole determinant of air quality) is linked to output through various final and intermediate production activities within the economy, so there are a set of feedback effects that can result from a new energy tax. This modification implies our model has two pre-existing distortions — the labor tax leading to significant differences between the market determined demand and supply prices and the pollution externality with differences in the virtual prices.

The size of the labor supply response is determined through the calibration of elasticities of substitution between leisure, market goods, and the non-market amenity. GW resolved this interrelationship by calibrating the relevant elasticities to match estimates of the labor supply elasticity. When pollution's impact on amenities is introduced by assuming leisure and amenities enter preferences in a separable subfunction, this calibration will have implications for labor supply in the benchmark equilibrium. We discuss the issues in maintaining consistency with their logic as an adaptation to model calibration.

## A Preference Structures

The preferences of the representative agent in Goulder and Williams (2003) numerical model are assumed to be captured using a nested constant elasticity of substitution (NCES) utility function over leisure and consumption goods as in equation (11):

$$U(l, C_1, ..., C_n) = \left[ \alpha \left( \frac{l}{l_0} \right)^{\rho} + (1-\alpha) \left( \sum_{i=1}^{n} \delta_i \left( \frac{C_i}{C_{0i}} \right)^{\psi} \right)^{\rho/\psi} \right]^{1/\rho} \tag{11}$$

where $\alpha$ is the value share of leisure in the benchmark equilibrium. $l_0$ and $C_{0i}$ are benchmark levels of the choice variables, and $\delta_i$ are the benchmark value shares of consumption goods within the consumption nest. $\psi$ and $\rho$ are substitution elasticity parameters for the consumption nest and the overall utility function, respectively.[19]

The consumer chooses demands for $l$ and $C_i$ so as to maximize utility subject to a budget constraint:

$$w(1-\tau_L)T + g = w(1-\tau_L)l + \sum_{i=1}^{n} P_{C_i} \cdot C_i$$

in which $w$ and $P_{C_i}$ are the wage rate and equilibrium prices of consumptions goods, respectively. In the analytical model we assumed each consumption good was taxed. Here we drop these effects because they are not in the GW model or our empirical models. $\tau_L$ is the pre-existing labor tax, $g$ is tax revenue from the labor tax (returned to the consumer lump sum,) and $T$ is the total time endowment. Naturally, $g = w\tau_L(T-l)$.[20]

Our modification adds an air quality term, $a$, to the leisure contribution.[21]

$$U(l, a, C_1, ..., C_n) = \left[ \alpha \left( \gamma \left( \frac{l}{l_0} \right)^{\xi} + (1-\gamma) \left( \frac{a}{a_0} \right)^{\xi} \right)^{\rho/\xi} + (1-\alpha) \left( \sum_{i=1}^{n} \delta_i \left( \frac{C_i}{C_{0i}} \right)^{\psi} \right)^{\rho/\psi} \right]^{1/\rho} \tag{12}$$

[19] This representation is what Rutherford (2002) describes as the calibrated share form of the NCES. It is written in this form to simplify our discussion of the model's calibration.

[20] $g$ is exogenous from the perspective of the consumer's choice problem, however. This is the assumption that leads to the Harberger normalization discussed in section II.

[21] This is the specific non-market good for our example that serves as our example for $q$ in the analytical model.

such that

$$w(1-\tau_L)T + g = w(1-\tau_L)l + \sum_{i=1}^{n} P_{C_i} C_i$$

$a$ and $a_0$ refer to current and benchmark air quality levels, $\gamma$ is the benchmark value share of leisure in the new leisure-air quality nest, and $\xi$ is the elasticity parameter for the new nest.

Air quality in our model is inversely proportional to the level of pollution produced by the various sectors of the economy, hence

$$a = \frac{1}{\sum_i \beta_i C_i + \sum_j b_j I_j} \tag{13}$$

where $\beta_i$ is the exogenous pollution coefficient for final good sector $i$ and $b_j$ for the intermediate goods.

Using a representative agent model to describe an externality requires we treat air quality as quasi-fixed from the consumer's perspective.[22] The demand, indirect utility, and expenditure functions that normally follow from the consumer's optimization problems with NCES preferences to do not apply to (12). To our knowledge, no closed-form solutions exist.[23] Nonetheless, it is easy to verify that the marginal rate of substitution between leisure and consumption goods will depend on the level of air quality in this specification. The presence of a quasi-fixed good also implies non-homothetic income effects.

The specification of preferences in (12) represents the minimum modification necessary to introduce a non-separable, non-market good into the model. This change will also introduce deviations from the average substitution of consumption goods with leisure.

We also consider a more detailed preference specification where one consumption good (i.e. consumer services in the GW model) also enters the leisure bundle as part of a subnest with air quality. This formulation leads to a more explicit deviation from the average substitution condition and a model of preferences that would more closely approximate the idea of a use value for amenities — where market goods are consumed in conjunction with non-market goods to yield enhanced well being. In this

[22]Partial equilibrium models used to estimate individual willingness to pay for improvements in amenities often assume people can adjust to differential levels of amenities. The hedonic model, for example, relies on households recognizing site specific differences in amenities in adjusting their selections of homes in response to them. In a representative agent model treating pollution as an amenity requires that we ignore the general equilibrium effects as is done in the case of the lump sum return of tax revenue.

[23]To write down the corresponding indirect utility function in terms of prices is a simple task, as the NCES is self-dual in prices. The complication arises from the fact that the price of air quality is a function of the level of air quality, other prices, and income. Hence, an indirect utility function in prices (including the virtual price of air quality) is not a value function in the commonly understood sense.

specification, the expression $(1-\gamma)\left(\frac{a}{a_0}\right)^{\xi}$ from (12) is replaced by a third level subfunction

$$(1-\gamma)\left(\nu\left(\frac{a}{a_0}\right)^{\lambda}+(1-\nu)\left(\frac{C_{CSV}}{C_{CSV0}}\right)^{\lambda}\right)^{\xi/\lambda}$$

and the consumption good bundle no longer includes consumer services

$$\left(\sum_{i=1,\neq CSV}^{n}\delta_i\left(\frac{C_i}{C_{0i}}\right)^{\psi}\right)^{\rho/\psi}$$

## B Calibration

Preferences are calibrated to correspond as closely as possible to Goulder and Williams (2003). Specifically,

- We use the same benchmark dataset to calibrate the value share parameters for all final consumption demands ($\hat{\alpha},\ \gamma,\ \nu,\ \delta$), intermediate inputs, and intermediate labor demands.
- $\rho$ and $l_0$ (and therefore $T$) are calibrated to imply compensated labor supply elasticity of 0.25 and an uncompensated elasticity of 0.05 for assumed values of $\psi$, $\xi$, and $\lambda$. $\xi$ and $\lambda$ are chosen to yield the desired substitution and complementarity relationship between leisure and air quality and consumer services.

The details of the calibration are reported in appendices A - D. A few issues regarding the treatment of the air quality calibration warrant further discussion. Interpreting the coefficients in this function as value shares (as in (11)) requires that we augment income by exactly the expenditure necessary to purchase the benchmark level of air quality at its benchmark price. Hence,

$$\hat{\alpha}=\frac{w(1-\tau_L)l_0+P_{a_0}a_0}{w(1-\tau_L)\hat{T}+g+P_{a_0}a_0} \tag{14}$$

where $P_{a_0}$ is the benchmark marginal willingness to pay or virtual price for the air quality commodity. The numerator of (14) describes the benchmark value of the leisure-air quality bundle in (12) and the denominator is "virtual" benchmark income, as described above.

The introduction of non-separable amenities into CGE models raises several interesting issues about how to calibrate the model. We selected two approaches that are consistent with the past CGE literature - treating the benchmark share parameters as shares in virtual income with and without recognition of the impacts of feedback effects. Consider first the case associated with calibration ignoring pollution feedback effects. A virtual shares approach assumes at the benchmark the level of air quality is "optimal" given the benchmark virtual price and the virtual income. This formulation might seem to undercut our conceptual logic (e.g. the argument that there is a disparity between virtual demand and supply prices). It does not for two reasons. First and foremost, the benchmark supply price of air quality is *not* equal to the demand price. The former is determined by the marginal cost schedules for the production of pollution-intensive goods. Second, at the actual monetary income the consumer has a *different* virtual price for air quality. With an assumption that the amenity is exogenous from the perspective of the representative agent, this is the virtual price relevant for the Harberger non-market wedge due to pollution.

As we noted earlier, there is also an issue arising from the question of how one should calibrate the model to labor supply elasticities in the presence of the quasi-fixed air quality good. The complication arises because changes in the level of air quality are linked to the rest of the final demand surface through changes in the sectoral activity levels of the general equilibrium model. This linkage is what we referred to as the case with feedback effects. Our no-feedback calibration ignores the change in air quality in the calibration procedure, effectively treating air quality as fixed at the benchmark level when relative prices change. For example, in the case of the compensated labor supply elasticity this would suggest that we match the model response to the assumed elasticity ($\eta$) in the following way:

$$\eta = \frac{\partial L^C(u, w, P, a)}{\partial w} \frac{w_0}{L_0} \tag{15}$$

where $L^C$ represents the consumer's compensated labor supply and $u$ is the benchmark utility level. Here $a$ is treated as an exogenous argument in the compensated supply function in the same way that price and utility levels are in Hicksian compensated analysis.

Alternatively, we could embed the change in air quality that is implied by the change in the demand for consumption goods into the calculation:

$$\eta = \left[ \frac{\partial L^C(u, w, P, a(u, w, P))}{\partial w} + \frac{\partial L^C}{\partial a} \frac{\partial a(u, w, P)}{\partial w} \right] \frac{w_0}{L_0} \tag{16}$$

where:

$$\frac{\partial a(u, w, P)}{\partial w} = \sum_i \frac{\partial a}{\partial C_i} \cdot \frac{\partial C_i^C}{\partial w}$$

The distinction between the no-feedback and feedback calibrations lies in our interpretation of the benchmark parameterization. Without consideration of these feedback effects from consumption goods to pollution and air quality effects there would be inconsistency between the market outcomes and the non-market responses. The model parameterization would not reproduce the benchmark equilibrium. Of course, one could also argue that without the assumption that the agent has the virtual income implied by the monetized value of the benchmark air quality it would also not reproduce the benchmark conditions. On this second point, there are a wide array of alternative calibration approaches that could be considered. These are outside the scope of this paper. They represent new issues for CGE calibration. Their importance, in the end, will depend on how much the model calibrations are influenced by the ways we coordinate market and non-market conditions in the benchmark for general equilibrium calibration.

Current econometric estimates of labor supply responses are unlikely to reflect changes in environmental benefits such as we have included in the preference specifications used here. For an actual policy application these disparities could be important because they introduce a new source of error. However, in our case the objective is illustrating how pre-existing market wedges influence the performance of excess burden measures with pre-existing taxes.

Calculating the derivatives in (16) requires that we use the general description of the economy to compute the correct air quality responses. However, it also requires that we isolate the effects described by the Hicksian and Marshallian choice problems. Full, general equilibrium responses to a change in one price generally involve changes in the full price vector in the economy as well as changes in the value of the factor endowments that make up a representative agent's income. Both of these effects fall outside the description of a compensated or uncompensated price change. The computational technique we use to calibrate the labor supply response within the model involves strategically defining artificial sinks and sources for the change representative agent's income or utility that maintain the fiction of the particular price experiment within in general equilibrium structure. In the case of a Hicksian price change, a separable, perfectly inelastic demand for the representative agent's utility index is constructed which guarantees that a change in the wage does not move the model away from the benchmark indifference curve. For a Marshallian price change, the ownership of the labor endowment is re-assigned to a new, separable agent who absorbs the income effects associated with a change in the wage. The true representative agent is then assigned an alternative source of income that replicates benchmark labor income but is invariant to changes in the wage.[24]

[24] A full description of these issues and numerical methods for isolating compensated and uncompensated price experiments in CGE models are described in Carbone (2004).

## C Air Quality Data

Data on 1995 levels of $PM_{10}$ particulate matter concentrations in the United States are taken from the United States Environmental Protection Agency (1996) and measures of the marginal willingness to pay for reductions in $PM_{10}$ concentrations come from Smith and Huang (1995). To derive the virtual price of air quality used in our study, we simply make the conversion between pollution units and air quality units (based on (13)), convert a value at the low end of the range of adjusted estimates from the Smith-Huang summary of marginal willingness to pay for estimates for particular matter to 1995 dollars using the CPI, and multiply by one-hundred million to reflect the number of households in the U.S.[25] Table 1 shows benchmark $PM_{10}$ emission levels and intensities by sector. Sectoral intensities are computed as the level of physical emissions attributable to the sector divided by the sector's value of output.

Table 1: $PM_{10}$ Benchmark Emission Levels and Intensities by Sector

| | LEVEL OF EMISSIONS | % TOTAL EMISSIONS | INTENSITY |
|---|---|---|---|
| TRANSPORTATION | 29.5 | 69.2 | 0.2 |
| AGRICULTURE | 9.1 | 21.4 | 0.0 |
| MANUFACTURING | 1.0 | 2.2 | 20.7 |
| ENERGY | 0.7 | 1.5 | 1.7 |
| UTILITIES | 0.3 | 0.6 | 0.1 |
| NATURAL | 2.2 | 5.1 | |

LEVEL — Millions of Short Tons $PM_{10}$

INTENSITY — Short Tons $PM_{10}$ per 1995 U.S. $ of Output x $10^5$

Based on the EPA emission factors, the transportation sector is responsible almost seventy percent of total $PM_{10}$ emissions, followed by agriculture at just over twenty percent. Natural sources make up another five percent, while utilities, energy production, and manufacturing together account for the remaining five percent. The intensity values in table 1 correspond to the calibration of the $\beta$ terms from (13). Manufacturing is by far the most $PM_{10}$-intensive sector, with a $100,000 increase in the annual value of this sector leading to a 20.7 short-ton increase in $PM_{10}$. Energy production is roughly one tenth as intensive as manufacturing, and the remaining industries are less than a tenth as intensive as energy.

Table 2 shows the shares of the final consumption goods in total income (including the value of

[25]Some studies, instead of (or in addition to) measuring the marginal willingness to pay for air quality improvements measure total willingness to pay for a discrete change in air quality. Calibrating the model based on "totals" information of this sort would require that the analyst take into account income effects and is another of the calibration alternatives implicitly discussed in the text above. Comparison between these two methods will be the subject of future research.

Table 2: Final Consumption by % of Income and % Energy Inputs

| | % INCOME | % ENERGY DEMAND |
|---|---|---|
| CONSUMER MANUFACTURES | 34.2 | 0.4 |
| CONSUMER SERVICES | 20.7 | 0.0 |
| LEISURE | 20.0 | 0.0 |
| FOOD AND ALCOHOL | 18.7 | 0.0 |
| TRANSPORTATION | 3.2 | 35.3 |
| UTILITIES | 3.2 | 39.6 |

% INCOME — exclusive of virtual value of air quality.
% ENERGY — value of energy inputs to row sector as a percentage of total energy demand.

leisure) and the shares of factor intensity of energy in the production of each of these final consumption goods. Both measures provide a gauge of the magnitude of the effects that a new energy tax would have throughout the economy represented by the GW empirical model. As noted in section II, the GW measure of average substitution ($\theta$) depends on the shares of final consumption represented by the taxed sector. Extension of this analysis to the case of a tax on an intermediate sector such as energy is straightforward. In this case, average substitution is defined in terms of the shares of goods in final consumption weighted by the relative energy intensities of their respective production technologies (see GW, pp. 921-922). For example, consumer manufactures make up the single largest share (34%) of the representative agent's consumption bundle, a fact that would tend to make this good a stronger than average substitute for leisure in the CES framework we have adopted. However, the value of energy inputs to this good as a fraction of total energy used is relatively small. This effect works in favor of reducing the importance of tax interaction effects through this channel.[26]

Despite the fact that a significant fraction of the value that goes into producing transportation is energy, the intensity profile we have just described implies that the energy taxes that we consider in the simulations are rather blunt instruments to use for reductions in $PM_{10}$. In this respect, the air quality responses (and their welfare consequences) that we measure in our numerical analysis would represent an understatement of the responses one would expect to observe from a specifically designed environmental policy.

[26]Evaluating the implications of an assumption average substitution with intermediate goods requires consideration of both the direct and *indirect* value of energy used in the production of each good. For example, consumer manufactures are also produced using intermediate manufactures, to which energy is also input, so a full accounting would include these indirect sources of energy as well.

# V Results

Our evaluation of the energy tax alternatives follows GW in that we use the same variations in the energy tax and the same demand elasticities. We extend the set of alternatives considered by conducting sensitivity analyses with respect to key parameters likely to influence the non-market effects. Our results also report the same welfare and excess burden measures as in GW with three sets of supplementary information: the changes in leisure consumed and in air pollution generated; the true value of Hicksian equivalent variation ($EV$); and the GW measure of average substitution ($\theta$). The non-homotheticity of our preference specification implies that, even without consumption-induced changes in air quality, the $EV$ will be different from what GW measure as the true excess burden. In these cases, the difference between the two provides a gauge of the implications of the resulting income effects for the performance of the Harberger normalization. The GW $\theta$ measures the impact of our calibrated substitution or complementarity relationship specified for air quality and leisure or (with the second specification) for the composite of consumer services and air quality with leisure on the assumption of average substitution.[27] We are interested in both the overall welfare costs of the policies as well as the specific effect that the deviations from average substitution and non-market separability imply for errors in the simple Harberger and GW measures of excess burden.

In reporting our findings we use a distinction between "fixed" and "feedback" versions of the model. These labels refer to whether or not we have included the air quality feedbacks in the model. In the "fixed" runs, the benchmark level of air quality contributes to the agent's welfare both before and after the new tax is introduced (i.e. it is not a function of sectoral activity levels). Because we have calibrated the model to yield the assumed labor supply response in the benchmark, the demand system is *locally* identical to the model presented in Goulder and Williams (2003). The only effects that air quality has on the demand system in the "fixed" runs are through the non-homothetic income effects that the quasi-fixed good implies as the new tax moves the economy away from the benchmark equilibrium. When the feedback effects are included, air quality influences the labor supply response through these non-local effects (as before) as well as through deviations from average substitution implied by the air quality response to the new tax.

The fixed and feedback solutions have two effects on the way the analysis is undertaken. They imply

[27]The $\theta$ values presented in tables 3-6 are *approximate* measures, calculated using the difference between $EB$ and $EB^{GW}$, hence they will include some error associated with the linearization in the latter excess burden calculation. For tables 3 and 4, the calculations in all table rows are based on the smallest tax scenario (2.5%) in order to minimize this error. In tables 5 and 6, calculations are based on the middle tax.

some different parameters for the model, because the calibration to the benchmark values either ignores feedbacks or takes them into account. Equally important, in conducting the evaluation of the changes from the benchmark conditions, they are either ignored (fixed) or recognized (feedback) as part of the non-market effects on general equilibrium adjustments.

In the first description of preferences where air quality is the only source of non-separabilities, this distinction between "fixed" and "feedback" models allows us to decompose the importance of these different aspects of non-market effects. When we move to the more detailed description of the preferences, where we have both market and non-market induced non-separabilities, this same type of comparison allows us to separate the substitution effects in this dimension — when air quality is fixed, we are capturing only the effects of deviations from average substitution for market goods as well.

## A Non-Market Effects

Table 3 describes the central results from the first numerical model. Air quality is the only source of non-separabilities. We deliberately selected a calibration for its influence at the low end of a range of possibilities discussed below. The top half of the table describes model results when air quality is held fixed. The first two columns describe the different tax levels and different substitution relationships between leisure and air quality. The column $EV$ describes the exact equivalent variation of each tax policy calculated from the numerical model. In the "Fixed AQ" version of the model, this welfare measure appears to be equivalent to the true excess burden calculation ($EB$) down to the approximation error introduced by the linearization of the integral in the latter calculation. $EB^{H}$ and $EB^{GW}$ are applications of the simple Harberger and GW approximations of excess burden. The errors in these measures are taken as percentage differences from $EB$.

In the "Fixed AQ" runs of the model, the introduction of the air quality good has very little effect on the errors in the excess burden approximations. The Harberger and GW errors are comparable to the magnitudes reported in Goulder and Williams (2003). Because the model is calibrated to match assumed labor supply elasticities locally, the only effects we would expect to see in this version of the model would be due to the effect of the fixed air quality good on the relative elasticities of the leisure and consumption goods as we move away from the neighborhood of the benchmark equilibrium. Demand for goods that are stronger complements to air quality will become less elastic as we move away from the benchmark than those that are stronger substitutes.

Rows with a "C" in the second column of the table describe calibrations in which leisure and air quality

Table 3: Non-Market Implications of Energy Taxes

| | | $\%\Delta L$ | $\%\Delta PM_{10}$ | $EV$ | $EB$ | $EB^{H}$ | $EB^{GW}$ | $\%\epsilon^{H}$ | $\%\epsilon^{GW}$ | $\theta$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | *Fixed AQ* | | | | |
| L | C | -0.08 | - | 1.20 | 1.21 | 0.14 | 1.28 | -88.50 | 6.05 | -0.06 |
| L | S | -0.08 | - | 1.20 | 1.21 | 0.14 | 1.28 | -88.51 | 6.02 | -0.06 |
| M | C | -0.15 | - | 2.59 | 2.62 | 0.53 | 2.80 | -79.62 | 6.90 | -0.06 |
| M | S | -0.15 | - | 2.60 | 2.62 | 0.53 | 2.80 | -79.62 | 6.85 | -0.06 |
| H | C | -0.28 | - | 5.82 | 5.96 | 1.98 | 6.44 | -66.74 | 8.10 | -0.06 |
| H | S | -0.28 | - | 5.83 | 5.96 | 1.98 | 6.44 | -66.76 | 8.04 | -0.06 |
| | | | | | | *Feedback AQ* | | | | |
| L | C | -0.09 | -1.11 | 1.21 | 1.44 | 0.14 | 1.28 | -90.30 | -11.11 | 0.14 |
| L | S | -0.07 | -1.09 | 0.93 | 1.16 | 0.14 | 1.28 | -88.05 | 10.37 | -0.10 |
| M | C | -0.18 | -2.18 | 2.61 | 3.07 | 0.54 | 2.80 | -82.51 | -8.82 | 0.14 |
| M | S | -0.14 | -2.14 | 2.05 | 2.52 | 0.53 | 2.80 | -78.89 | 10.81 | -0.10 |
| H | C | -0.34 | -4.18 | 5.86 | 6.82 | 2.00 | 6.45 | -70.74 | -5.37 | 0.14 |
| H | S | -0.27 | -4.11 | 4.78 | 5.78 | 1.98 | 6.44 | -65.75 | 11.43 | -0.10 |

NOTE — $\%\Delta L$ — percent change in labor supply; $\%\Delta PM_{10}$ — percent change in pollution level; $EV$ — total cost measured as equivalent variation (billions 1995 US \$); $EB$ — total economic cost (billions 1995 US \$); $EB^{H}$ — Harberger approximation (billions 1995 US \$); $EB^{GW}$ — GW approximation (billions 1995 US \$); $\%\epsilon^{H}$ — percent difference between $EB$ and $EB^{H}$; $\%\epsilon^{GW}$ — percent difference between $EB$ and $EB^{GW}$; $\theta$ — average substitution measure.

are Hicksian complements, whereas an "S" denotes the assumption of Hicksian substitutes. Considering the errors on to excess burden approximations, we can see some evidence that the true excess burden is slightly larger when leisure and air quality are substitutes — $EB^{H}$ understates true excess burden slightly more, and $EB^{GW}$ overstates less compared to the complements case. This is because the overall effect of the policy is to decrease labor supply or, alternatively, to increase leisure demand. These effects are extremely small. When findings are reported to two digits, there is little difference in the percentage changes in leisure. The effects are seen through the percentage errors in the measures of excess burden. When leisure and the fixed air quality good are complements, leisure is to a greater extent anchored at the benchmark level because higher levels of leisure are less valuable when not accompanied by higher air quality. In the case where the goods are substitutes, leisure demand is more elastic, hence labor supply contracts more strongly in response to the energy tax in this scenario.

The scenarios in the bottom half of the table include the feedback effects due to the non-separable air quality responses to the energy taxes. In these cases the effects of adding non-market goods to the model start to be displayed. When air quality and leisure are complements ($C$), excess burden is higher because the labor response is stronger and the air quality improvement is larger. Increases in leisure (and decreases in labor) are more valuable when leisure and air quality are more complementary. Likewise, when leisure and air quality are substitutes, an increase in air quality means that consumers can more easily substitute out of leisure and into the consumption of market goods. The mechanism can be understood in terms of our discussion of the "fixed" model results — when the leisure and air quality are complements they must move together. However, because the policy implies higher air quality, the effect works in the opposite direction and the labor supply response is now stronger than in the substitutes case.

The implications for the comparative performance Harberger and GW measures of excess burden are also substantial. The model results indicate that in contrast to all of their scenarios, the substitution/complementarity assumption changes the *direction* of the error in their measure of excess burden. The GW measure tends to underestimate the burden associated with the tax when leisure and air quality are Hicksian complements and overestimate the burden when the goods are substitutes. Notice that these effects are large enough to change the sign for GW's measure of average substitution ($\theta$). Because the air quality feedbacks are derived from changes in the sectoral activity levels in the general equilibrium model, the magnitude of the leisure/labor response will depend on the relative intensities in final consumption goods of both the value of the taxed sector that each takes as an input as well as the value of all input sectors, scaled by their pollution impacts.

Introducing non-separable amenities also affects the welfare loss of policies that will (even if blunt in impacts) reduce pollution. This effect can be seen by comparing the equivalent variation ($EV$) and true excess burden ($EB$) measures of the welfare effects of the policy. The direct, non-market benefits of the policy are included in the former measure but neglected by the latter. The full welfare cost of the new policy is, naturally, smaller than the market-based costs because the increase in air quality leads to a welfare improvement. For the smallest taxes we consider (2.5%), the difference is on the order of $200,000,000. The size of the air quality improvement and the wedge between $EV$ and $EB$ grow with the size of the tax.

Considering the percentage change in the level of air quality across the different scenarios is also instructive. When air quality is a complement to leisure, the air quality response is larger. In this case, increases in the level of air quality make leisure more attractive, which in turn makes other consumption activities less attractive. This change forces final goods production to contract, which leads to higher air quality. Increases in air quality, in turn, make further substitution into leisure even more attractive, and the logic proceeds. Well behaved preferences assure there are limits to the extent of this substitution.

## B Market & Non-Market Effects

Table 4 reports the same experiments but with the second preference structure. Leisure trades off with a bundle composed of the air quality good (as before) and the consumer services in final consumption. By controlling values of the substitution elasticity parameters, this functional forms allows us to consider the implications of market goods that are not average substitutes for leisure and the interactions between market and non-market goods as determinants of excess burden and total welfare.

Table 4: Market & Non-Market Implications of Energy Taxes

| | | $\%\Delta L$ | $\%\Delta CSV$ | $\%\Delta PM_{10}$ | $EV$ | $EB$ | $EB^H$ | $EB^{GW}$ | $\%\epsilon^H$ | $\%\epsilon^{GW}$ | $\theta$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | *Fixed AQ* | | | | | | |
| L | C | -0.10 | 0.17 | - | 1.57 | 1.57 | 0.14 | 1.28 | -91.00 | -18.45 | 0.25 |
| L | S | -0.06 | 0.02 | - | 0.98 | 0.99 | 0.14 | 1.28 | -86.16 | 29.49 | -0.25 |
| M | C | -0.20 | 0.33 | - | 3.32 | 3.34 | 0.54 | 2.81 | -83.72 | -16.05 | 0.25 |
| M | S | -0.12 | 0.03 | - | 2.16 | 2.18 | 0.53 | 2.79 | -75.90 | 28.01 | -0.25 |
| H | C | -0.38 | 0.63 | - | 7.25 | 7.40 | 2.02 | 6.48 | -72.65 | -12.40 | 0.25 |
| H | S | -0.22 | 0.03 | - | 4.96 | 5.09 | 1.95 | 6.41 | -61.69 | 25.91 | -0.25 |
| | | | | | *Feedback AQ* | | | | | | |
| L | C | -0.10 | 0.16 | -1.15 | 1.36 | 1.60 | 0.14 | 1.28 | -91.16 | -19.94 | 0.28 |
| L | S | -0.06 | 0.01 | -1.05 | 0.75 | 0.98 | 0.14 | 1.28 | -86.01 | 30.95 | -0.26 |
| M | C | -0.20 | 0.31 | -2.25 | 2.91 | 3.40 | 0.54 | 2.81 | -83.99 | -17.46 | 0.28 |
| M | S | -0.12 | 0.02 | -2.06 | 1.71 | 2.16 | 0.52 | 2.79 | -75.67 | 29.29 | -0.26 |
| H | C | -0.39 | 0.60 | -4.32 | 6.45 | 7.51 | 2.02 | 6.48 | -73.04 | -13.68 | 0.28 |
| H | S | -0.22 | 0.02 | -3.96 | 4.09 | 5.05 | 1.95 | 6.41 | -61.39 | 26.95 | -0.26 |

As before, the top half of the table describes model results when air quality is held fixed at its benchmark level, so these results pertain to the effects of making consumer services either a stronger substitute or complement to leisure. As indicated in Table 2, consumer services are not particularly energy-intensive goods. Thus with consumer services as a closer complement to leisure, the more energy-intensive components of final demand (utilities and transportation) become stronger-than-average substitutes for leisure. This specification allows for a stronger labor supply response to the energy tax and a larger excess burden associated with the new policy. When leisure is a stronger substitute for consumer services ($CSV$), energy-intensive goods are stronger complements. Demands for these goods decline with the introduction of the tax, so substitution into leisure becomes less valuable and excess burden is smaller.

This change to the preferences has a substantial impact on the excess burden approximations because the benchmark value share of consumer services is relatively large. When the goods are complements,

$EB^{GW}$ understates the true burden of the policy by between 12 and 18%, and overstates it between 26 and 29% in the substitutes scenarios.

Turning to the case with feedback effects, we see that the air quality responses tend to multiply the effects implied by the consumer services good. In other words, when the average substitution assumption would tend to overstate excess burden, both market and non-market response work to increase this overstatement. When the bias is toward understatement, this understatement becomes more severe as well. These results follow because the demand for consumer services and the equilibrium level of the non-market good increase in response to the new tax. The combined market/non-market response adds approximately a percentage point to the size of the errors in $EB^{GW}$. The dominant effect remains due to the deviation from average substitution implied by the market goods rather than the air quality response. Of course, this response depends on the relative importance of the value share attributed to amenities, a point we return to below in considering a few sensitivity comparisons for our numerical models' calibrations.

While the market and non-market effects work in concert in the simulations shown here, a demand system with offsetting effects is also a possibility. For example, if consumer services were a strong substitute to leisure and air quality a strong complement, then the market effects would tend to decrease excess burden while the non-market effects would tend to increase it.

## VI Sensitivity Analysis

In this section, we evaluate how the results in Tables 3 and 4 respond to three key parameters — the energy demand elasticity, the labor supply elasticity, and the benchmark marginal value for air quality. We evaluate the first parameters using values 25% above and below their calibrated levels from the simulations presented in section V. The last parameter is varied in a different way. As a result, those findings are discussed at the end of the section. Table 5 summarizes the alternative parameterizations for the first preference specification, using the middle (5%) tax scenario for the feedback AQ model from Table 3.

The energy demand elasticity is altered by changing the substitution elasticity parameter of the model's CES production functions by 25% on either side of their benchmark value. When this parameter is smaller (-25% scenarios), the energy demand is less elastic. The most obvious effect of such a change is that direct excess burden associated with the change in the energy market is smaller when energy demand

Table 5: Sensitivity Results: Non-Market Implications

| | | $\%\Delta L$ | $\%\Delta PM_{10}$ | $EV$ | $EB$ | $EB^H$ | $EB^{GW}$ | $\%\epsilon^H$ | $\%\epsilon^{GW}$ | $\theta$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | *Energy Demand Elasticity* | | | | | |
| -25% | C | -0.18 | -2.16 | 2.54 | 3.00 | 0.45 | 2.72 | -85.08 | -9.32 | 0.12 |
| +25% | C | -0.18 | -2.19 | 2.68 | 3.15 | 0.63 | 2.88 | -80.09 | -8.35 | 0.11 |
| -25% | S | -0.14 | -2.12 | 1.99 | 2.45 | 0.44 | 2.71 | -81.96 | 10.62 | -0.11 |
| +25% | S | -0.14 | -2.16 | 2.12 | 2.59 | 0.62 | 2.88 | -76.02 | 11.00 | -0.12 |
| | | | | | *Labor Supply Elasticity* | | | | | |
| -25% | C | -0.15 | -2.15 | 2.16 | 2.61 | 0.53 | 2.26 | -79.59 | -13.42 | 0.20 |
| +25% | C | -0.21 | -2.21 | 3.03 | 3.49 | 0.54 | 3.32 | -84.52 | -5.03 | 0.06 |
| -25% | S | -0.11 | -2.11 | 1.58 | 2.04 | 0.53 | 2.26 | -74.06 | 10.87 | -0.13 |
| +25% | S | -0.17 | -2.17 | 2.51 | 2.98 | 0.54 | 3.31 | -82.01 | 11.15 | -0.12 |
| | | | | | *Benchmark AQ Value* | | | | | |
| 0.6% | C | -0.18 | -2.18 | 2.61 | 3.07 | 0.54 | 2.80 | -82.51 | -8.82 | 0.12 |
| 1.15% | C | -0.20 | -2.20 | 2.53 | 3.40 | 0.54 | 2.80 | -84.10 | -17.47 | 0.26 |
| 2% | C | -0.23 | -2.23 | 2.31 | 3.81 | 0.54 | 2.81 | -85.75 | -26.39 | 0.44 |
| 0.6% | S | -0.14 | -2.14 | 2.05 | 2.52 | 0.53 | 2.80 | -78.89 | 10.81 | -0.12 |
| 1.15% | S | -0.14 | -2.13 | 1.57 | 2.44 | 0.53 | 2.80 | -78.22 | 14.46 | -0.15 |
| 2% | S | -0.13 | -2.13 | 0.84 | 2.32 | 0.53 | 2.80 | -77.16 | 20.22 | -0.20 |

is less elastic, as we would expect. Thus all efficiency cost measures are smaller in these scenarios. The air quality response is also smaller, because demand for energy-intensive goods is also less elastic. The difference in the implied change in the labor supply response is quite small with this variation in the energy elasticity. Nonetheless, the excess burden approximations tend to understate the true cost of the policy slightly more when energy demand is relatively inelastic.

When labor supply is more elastic, the tax interaction effect is larger, and the policy is more costly. The interaction between leisure and the air quality is more pronounced when the two goods are complements. This outcome can be seen in both the relative magnitude of the errors in the burden approximations and the implied $\theta$ values. When labor supply is 25% less elastic and leisure and air quality are complements, the error in the $EB^{GW}$ approximation increases by about 50%.

Table 6 reports comparable sensitivity analysis for the second preference specification. The effects are qualitatively similar. Changes in the energy elasticity, reducing its absolute magnitude, reduce excess burden. The errors in the Harberger and GW measures respond comparably in terms of the increase or decrease in the percentage error with increases or decreases in either the energy or the labor elasticities. The size of the error in the Harberger measure is comparable (in percentage terms) with that measured for

Table 6: Sensitivity Results: Market & Non-Market Implications

| | | $\%\Delta L$ | $\%\Delta CSV$ | $\%\Delta PM_{10}$ | $EV$ | $EB$ | $EB^H$ | $EB^{GW}$ | $\%\epsilon^H$ | $\%\epsilon^{GW}$ | $\theta$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | *Energy Demand Elasticity* | | | | | | |
| -25% | C | -0.20 | 0.32 | -2.23 | 2.85 | 3.33 | 0.45 | 2.72 | -86.36 | -18.24 | 0.26 |
| +25% | C | -0.20 | 0.31 | -2.27 | 2.97 | 3.47 | 0.63 | 2.89 | -81.74 | -16.72 | 0.25 |
| -25% | S | -0.12 | 0.02 | -2.05 | 1.64 | 2.08 | 0.43 | 2.71 | -79.15 | 29.83 | -0.27 |
| +25% | S | -0.11 | 0.02 | -2.08 | 1.77 | 2.23 | 0.61 | 2.87 | -72.45 | 28.83 | -0.28 |
| | | | | | *Labor Supply Elasticity* | | | | | | |
| -25% | C | -0.17 | 0.40 | -2.23 | 2.45 | 2.94 | 0.54 | 2.27 | -81.54 | -22.63 | 0.38 |
| +25% | C | -0.23 | 0.25 | -2.27 | 3.34 | 3.84 | 0.55 | 3.32 | -85.73 | -13.34 | 0.18 |
| -25% | S | -0.08 | 0.02 | -2.02 | 1.23 | 1.67 | 0.52 | 2.25 | -68.85 | 34.81 | -0.33 |
| +25% | S | -0.15 | 0.01 | -2.10 | 2.16 | 2.62 | 0.53 | 3.31 | -79.79 | 26.30 | -0.24 |
| | | | | | *Benchmark AQ Value* | | | | | | |
| 0.6% | C | -0.20 | 0.31 | -2.25 | 2.91 | 3.40 | 0.54 | 2.81 | -83.99 | -17.46 | 0.26 |
| 1.15% | C | -0.21 | 0.30 | -2.25 | 2.52 | 3.44 | 0.54 | 2.81 | -84.16 | -18.33 | 0.27 |
| 2% | C | -0.21 | 0.27 | -2.25 | 1.92 | 3.49 | 0.54 | 2.81 | -84.41 | -19.59 | 0.30 |
| 0.6% | S | -0.12 | 0.02 | -2.06 | 1.71 | 2.16 | 0.52 | 2.79 | -75.67 | 29.29 | -0.27 |
| 1.15% | S | -0.12 | 0.02 | -2.06 | 1.31 | 2.15 | 0.52 | 2.79 | -75.53 | 30.02 | -0.28 |
| 2% | S | -0.11 | 0.02 | -2.06 | 0.69 | 2.13 | 0.52 | 2.79 | -75.35 | 31.06 | -0.29 |

specification one and the sensitivity to different energy and labor supply elasticities is about comparable — two to three percentage point changes up with decreases in the magnitude of the energy elasticity and down with increases. Variations in the supply reverses the direction of change — down with decreases and up with increases. There are somewhat larger effects for the cases involving the labor supply elasticity when it is a substitute; the error in the Harberger measure changes by nearly seven percentage points in this case.

The GW measure has large percentage errors with specification two but comparable sensitivity to variations in the energy demand elasticity as specification one. The sensitivity to changes in the labor supply elasticities are larger for the case of complementarity with both specifications and have about a four percentage points change with 25% alternations for the substitution case with specification two. They are smaller — less than one percentage point (for substitution cases) with specification one. Thus, as expected, the importance of the average substitution assumption depends on the labor supply elasticity.

The sensitivity analysis for the magnitude of the effect of air quality was designed differently. In this case, our benchmark analysis deliberately selected a low value for the importance of air quality — about 0.6% of virtual income at the benchmark solution. Two increases in the importance were considered.

The first uses the average estimate for incremental willingness to pay from Smith and Huang (1995)'s summary. This is almost twice the size of our benchmark case (i.e. 1.95 times). Finally we consider a situation where the value is set so benchmark amenities are two percent of virtual income.[28]

As expected, increases in the importance of air quality dramatically increase the errors in the GW revised measures for excess burden. This effect is especially pronounced with complementarity scenarios for preference specification one (where leisure and air quality subfunction is the only source of departures from average substitution). The absolute performance of the GW measure deteriorates with preference specification two but this record is not greatly affected by increasing the importance of amenities, suggesting it is largely due to the violation of average substitution effect with the specification of the consumer services and air quality subfunction.

Also, as expected, the indirect, positive effects of increases in energy taxes on air quality accentuate the size of the disparity between $EV$ and the $EB$ when the importance of air quality in preferences is increased. Both specifications display this pattern. However the overall magnitude is larger for the first preference specification where air quality's separate effects are experienced with leisure.

## VII Implications

Goulder and Williams have demonstrated there are practical ways to allow Harberger triangles to take account of *some* interaction effects (e.g. those associated with the largest source of pre-existing distortions). Our analysis does not change their conclusion that these revisions offer the potential for *dramatic* improvements in the performance Harberger own-market measure of the excess burden of new taxes. The prospect of improving upon the Harberger measure is important because the errors due to interaction effects can be quite large. They are, however, always in one direction — understating the importance of the distortions. In one respect they might be considered to offer a conservative measure of the distortionary effects.

Our analysis considered two issues — potentially important to the Goulder-Williams extension — average substitution and the absence (in their model) of non-separable, non-market policy interactions. Introducing either consideration was found to be important to the performance of the GW approximation. The GW measure *always* remains superior to the Harberger simple index when evaluated using the absolute value of the proportionate error. However, both the magnitude *and the direction* of the bias in their

[28]Sieg, Smith, Banzhaf and Walsh (2004) found the Hicksian willingness to pay for California households would be about two percent of their income for the improvements in anyone in the region from 1990 to 1995. These improvements in air quality would be substantially smaller than the total change implied by the benchmark valuation of air pollution.

measure are sensitive to changes in assumptions that would alter average substitution and non-market effects. In their empirical comparisons, their extended measure overstates the error by modest amount (e.g. one-tenth the size of the understatement found with Harberger). We find that complementarity between leisure and either air quality or a service/air quality composite can *reverse* the sign of the error. Moreover, the non-market effects can increase its magnitude by about three to four times. Non-market effects are also important to judging the distortionary effects of taxes. The error measure with GW's indexes are *solely* the result of the effects of substitution or complementarity relationships between *market* goods that are affected by non-separable amenities. There is a separate and important impact due to the improvements in air quality that can be induced by some tax policy. These are left out of both the Harberger and the GW excess burden measures.

Distortionary taxes continue to reduce welfare and pre-existing taxes compound this effect. Nonetheless, complementarity gains, outside markets, due to improvements in amenities, can have an appreciable effect on the size of these welfare losses. The assumption of separability and with it average substitution is *not neutral* to one's conclusions about the size or direction of the effects of tax interactions. Our analysis using the GW model demonstrates the source of this conclusion and estimates its potential empirical importance using measures of the willingness to pay for air quality taken from the literature. Finally, in the process of developing our alternative models to evaluate the robustness of the Goulder-Williams measure we believe a new set of issues for the use of CGE models in policy analysis has been identified. These issues relate to calibrating market and non-market outcomes consistently in a framework that recognizes non-separabilities provide the source of their interaction.

Nonseparable, non-market goods should not be assumed to be limited to environmental amenities. For example, Landefeld and McCulla (2000) found, based on preliminary estimates of satellite national income and product accounts, that the inclusion of household non-market services raised GDP by 24 percent in 1997. This adjustment primarily reflects non-priced household time. Including local public goods and other environmental amenities – each with potential non-market interaction effects can be expected to further enhance the importance of the issues raised here.

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# A Excess Burden Derivations

Consider the effect of introducing a tax, $\tau_{C_k}$, on the consumption of final good $k$. The total welfare change from the new tax may be written:

$$dU = \sum_{i=1}^{M} \frac{\partial U}{\partial C_i} \frac{\partial C_i}{\partial \tau_{C_k}} d\tau_{C_k} + \frac{\partial U}{\partial l} \frac{\partial l}{\partial \tau_{C_k}} d\tau_{C_k} + \frac{\partial U}{\partial q} \sum_{i=1}^{M} \frac{\partial q}{\partial C_i} \frac{\partial C_i}{\partial \tau_{C_k}} d\tau_{C_k} \quad \text{(A1)}$$

And substituting in the first-order conditions from the consumer's maximization problem ($U_{C_i} = \lambda \, P_{C_i}$, $U_l = \lambda \, (1 - \tau_L)$) we have

$$\frac{1}{\lambda} \frac{dU}{d\tau_{C_k}} = \sum_{i=1}^{M} P_{C_i} \frac{\partial C_i}{\partial \tau_{C_k}} + (1 - \tau_L) \frac{\partial l}{\partial \tau_{C_k}} + \frac{1}{\lambda} \frac{\partial U}{\partial q} \sum_{i=1}^{M} \frac{\partial q}{\partial C_i} \frac{\partial C_i}{\partial \tau_{C_k}} \quad \text{(A2)}$$

Changes in $C_i$ are ultimately linked to the production side of the economy, hence

$$\frac{\partial C_i}{\partial \tau_{C_k}} = \frac{\partial F_i}{\partial L_{C_i}} \frac{\partial L_{C_i}}{\partial \tau_{C_k}} + \sum_{j=1}^{N} \frac{\partial F_i}{\partial I_{ji}} \frac{\partial I_{ji}}{\partial \tau_{C_k}} \quad \text{(A3)}$$

where $L_{C_i}$ and $I_{ji}$ are respectively the input demands for labor and intermediate goods in final good sector $i$. The first-order conditions for firms in sector $i$ are:

$$\frac{\partial F_i}{\partial L_{C_i}} = \frac{1}{P_{C_i} - \tau_{C_i}} \quad \text{(A4)}$$

$$\frac{\partial F_i}{\partial I_{ji}} = \frac{P_{I_j}}{P_{C_i} - \tau_{C_i}} \quad \text{(A5)}$$

And combining these three elements yields:

$$P_{C_i} \frac{\partial C_i}{\partial \tau_{C_k}} = \tau_{C_i} \frac{\partial C_i}{\partial \tau_{C_k}} + \frac{\partial L_{C_i}}{\partial \tau_{C_k}} + \sum_{j=1}^{N} P_{I_j} \frac{\partial I_{ji}}{\partial \tau_{C_k}} \quad \text{(A6)}$$

The market clearing condition for labor and leisure is:

$$T = L + l = \sum_{i=1}^{M} L_{C_i} + \sum_{j=1}^{N} L_{I_j} + l \quad \text{(A7)}$$

where $L_{I_j}$ is the demand for labor in intermediate goods production. Differentiating this equation with respect to the tax we have

$$\frac{\partial l}{\partial \tau_{C_k}} + \sum_{i=1}^{M} \frac{\partial L_{C_i}}{\partial \tau_{C_k}} + \sum_{j}^{N} \frac{\partial L_{I_j}}{\partial \tau_{C_k}} = 0 \quad \text{(A8)}$$

Subtract (A8) from (A2) and substitute in (A6) to derive an expression familiar in the literature on tax interactions and revenue recycling.

$$\frac{1}{\lambda}\frac{dU}{d\tau_{C_k}} = \underbrace{\tau_{C_k}\frac{\partial C_k}{\partial \tau_{C_k}}}_{dW_D} + \underbrace{\sum_{i\neq k}\tau_{C_i}\frac{\partial C_i}{\partial \tau_{C_k}} + \sum_j \tau_{i_j}\frac{\partial I_j}{\partial \tau_{C_k}} - \tau_L\frac{\partial l}{\partial \tau_{C_k}}}_{dW_I} + \underbrace{\frac{1}{\lambda}\frac{\partial U}{\partial q}\sum_{i=1}^{M}\frac{\partial q}{\partial C_i}\frac{\partial C_i}{\partial \tau_{C_k}}}_{dW_N} \tag{A9}$$

The first term in the expression in (A9) describes the direct effect of the new tax on the sector to which it is applied. The second term describes that indirect martket effects of the tax in other sectors of the economy. Finally, the third term describes the change in the level of nonmarket goods due to the new tax.

For small price changes, we can treat income effects as negligible, hence

$$\frac{1}{\lambda}\frac{dU}{d\tau_{C_k}} \approx \tau_{C_k}\frac{\partial C_k^C}{\partial \tau_{C_k}} - \frac{\tau_L L}{P_{c_k}}\frac{\partial l^C}{\partial \tau_L}\frac{(1-\tau_l)}{l}\frac{P_{c_k}C_k}{y}\theta + \frac{1}{\lambda}\frac{\partial U}{\partial q}\sum_{i=1}^{M}\frac{\partial q}{\partial C_i}\frac{\partial C_i^C}{\partial \tau_{C_k}} \tag{A10}$$

For larger taxes, however, the income effects due to the taxes must be taken into account. GW use the Slutsky equation (A11) to describe the link between compensated and uncompensated adjustments with this part of the problem.

$$\frac{\partial C_i}{\partial \tau_{C_k}} = \frac{\partial C_i^C}{\partial \tau_{C_k}} - (C_k - \frac{dG}{d\tau_{C_k}})\frac{\partial C_i}{\partial Y_G} \tag{A11}$$

where $\frac{dG}{d\tau_{C_k}}$ describes the income loss due to the tax policy.

Substituting (A11) into (A9) we have (A12)

$$\frac{1}{\lambda}\frac{dU}{d\tau_{C_k}} = \tau_{C_k}\frac{\partial C_k^C}{\partial \tau_{C_k}} + \sum_{i\neq k}\tau_{C_i}\frac{\partial C_i^C}{\partial \tau_{C_k}} + \sum_j \tau_{i_j}\frac{\partial I_j^C}{\partial \tau_{C_k}} - \tau_L\frac{\partial l^C}{\partial \tau_{C_k}} + \frac{1}{\lambda}\frac{\partial U}{\partial q}\sum_{i=1}^{M}\frac{\partial q}{\partial C_i}\frac{\partial C_i^C}{\partial \tau_{C_k}} \tag{A12}$$

$$+\left[\tau_{C_k}\frac{\partial C_k}{\partial Y_G} + \sum_{i\neq k}\tau_{C_i}\frac{\partial C_i}{\partial Y_G} + \sum_j \tau_{i_j}\frac{\partial I_j}{\partial Y_G} - \tau_L\frac{\partial l}{\partial Y_G} + \frac{1}{\lambda}\frac{\partial U}{\partial q}\sum_{i=1}^{M}\frac{\partial q}{\partial C_i}\frac{\partial C_i}{\partial Y_G}\right]\left(C_k - \frac{dG}{d\tau_{C_k}}\right)$$

where the second line of (A12) describes income effects. By definition

$$\frac{1}{\lambda}\frac{dU}{d\tau_{C_k}} = \left(C_k - \frac{dG}{d\tau_{C_k}}\right) \tag{A13}$$

As a result we can simplify and reorganize terms as in (A14)

$$\frac{1}{\lambda}\frac{dU}{d\tau_{C_k}} = \frac{\tau_{C_k}\frac{\partial C_k^C}{\partial \tau_{C_k}} + \sum_{i\neq k}\tau_{C_i}\frac{\partial C_i^C}{\partial \tau_{C_k}} + \sum_j \tau_{i_j}\frac{\partial I_j^C}{\partial \tau_{C_k}} - \tau_L\frac{\partial l^C}{\partial \tau_{C_k}} + \frac{1}{\lambda}\frac{\partial U}{\partial q}\sum_{i=1}^M \frac{\partial q}{\partial C_i}\frac{\partial C_i^C}{\partial \tau_{C_k}}}{1 - \left[\tau_{C_k}\frac{\partial C_k}{\partial Y_G} + \sum_{i\neq k}\tau_{C_i}\frac{\partial C_i}{\partial Y_G} + \sum_j \tau_{i_j}\frac{\partial I_j}{\partial Y_G} - \tau_L\frac{\partial l}{\partial Y_G} + \frac{1}{\lambda}\frac{\partial U}{\partial q}\sum_{i=1}^M \frac{\partial q}{\partial C_i}\frac{\partial C_i}{\partial Y_G}\right]} \tag{A14}$$

For a discrete change with the labor tax as the only important source of distorton in the pre-existing economy, then we can summarize (A14) as (A15):

$$\frac{1}{\lambda}\Delta U \approx s_k y\left[\frac{\frac{1}{2}\left(\frac{\tau_{C_k}}{P_{C_k}}\right)^2\epsilon_{C_k} - \left(\frac{\tau_L\tau_{C_k}}{P_{C_k}}\right)\epsilon_L(\theta+1) + \tau_{C_k}\frac{1}{\lambda}\frac{\partial U}{\partial q}\sum_{i=1}^M \frac{\partial q}{\partial C_i}\frac{\partial C_i^C}{\partial \tau_{C_k}}}{1-\tau_L\epsilon_{Ly}}\right] \tag{A15}$$

$$\theta = \frac{\epsilon_{C_k L}}{\sum_i s_i\epsilon_{C_i L} + \sum_i \tilde{s}_i\epsilon_{C_i L}}$$

The expression for $\theta$ is derived by exploiting the Slutsky matrix to describe the labor supply effect in terms of its substitution relationship with other goods. That is, for a compensated change in the price of leisure, we have

$$U_l\frac{\partial l^C}{\partial(1-\tau_L)} + \sum_i U_{C_i}\frac{\partial C_i^C}{\partial(1-\tau_L)} + \frac{\partial U}{\partial q}\frac{\partial q}{\partial C_i}\frac{\partial C_i^C}{\partial(1-\tau_L)} = 0 \tag{A16}$$

and substituting in the first-order conditions gives us

$$-(1-\tau_L)\lambda\frac{\partial l^C}{\partial(1-\tau_L)} = \lambda\sum_i P_{C_i}\frac{\partial C_i^C}{\partial(1-\tau_L)} + \frac{\partial U}{\partial q}\sum_i\frac{\partial q}{\partial C_i}\frac{\partial C_i^C}{\partial(1-\tau_L)} \tag{A17}$$

Slutsky symmetry implies that

$$\frac{\partial l^C}{\partial P_{C_i}} = \frac{\partial C_i^C}{\partial(1-\tau_L)} \tag{A18}$$

Using the ratio of (A17) and (A18) we have:

$$\frac{\partial l^C}{\partial P_{C_k}} = \frac{\partial l^C}{\partial \tau_L}(1-\tau_L)\frac{C_k}{y}\left[\frac{\frac{(1-\tau_L)}{C_k}\frac{\partial C_i^C}{\partial(1-\tau_L)}}{\sum_i\left(\frac{P_{C_i}C_i}{y}\right)\left(\frac{1-\tau_L}{C_i}\right)\frac{\partial C_i^C}{\partial(1-\tau_L)} + \sum_i\frac{1}{\lambda}\frac{\partial U}{\partial q}\frac{\partial q}{\partial C_i}\frac{C_i}{y}\frac{(1-\tau_L)}{C_i}\frac{\partial C_i^C}{\partial(1-\tau_L)}}\right] \tag{A19}$$

and re-writing this expression in elasticity terms we have:

$$\frac{\partial l^C}{\partial P_{C_k}} = \frac{\partial L^C}{\partial \tau_L}(1-\tau_L)\frac{C_k}{y}\frac{\epsilon_{C_k L}}{\sum_i s_i\epsilon_{C_i L} + \sum_i \tilde{s}_i\epsilon_{C_i L}} \tag{A20}$$

where

$$s_i = \frac{P_{C_i} C_i}{y} \tag{A21}$$

are value shares for market commodities and

$$\tilde{s}_i = \frac{1}{\lambda} \frac{\partial U}{\partial q} \frac{\partial q}{\partial C_i} \frac{C_i}{y} \tag{A22}$$

are value shares of the *nonmarket contribution of each consumption good i* and with

$$y = \sum_i P_{C_i} C_i + \frac{1}{\lambda} \frac{\partial U}{\partial q} \frac{\partial q}{\partial C_i} C_i \tag{A23}$$

is the consumer's virtual income, which include the value of the benchmark value of nonmarket commodities.

# B Elements of the Numerical Model

Table B1 lists the dimensions of the economic model. The model describes a general equilibrium in sectors of the economy and primary factors.

Table B1: Elements of the Model

| | |
|---|---|
| | *Primary Factors* |
| LAB | Labor |
| | *Intermediate Sectors* |
| ENE | Energy |
| SVC | Services |
| AGR | Agriculture |
| MNF | Manufactures |
| | *Final Consumption Sectors* |
| FDA | Food and Alcohol |
| CSV | Consumer Services |
| CMN | Consumer Manufactures |
| TRN | Transportation |
| UTL | Utilities |

Benchmark data on quantities, prices, and elasticities provide the calibration point for the production and utility functions that describe the economy.

Key assumptions and notation:

- The model is identical to that used in Goulder and Williams (2003) except in the form of the utility function. Whenever possible we maintain the same calibration as Goulder and Williams (2003).
- All goods are produced via constant elasticity of substitution (CES) production functions. This implies constant returns to scale technology in all sectors.
- The representative agent's welfare is produced through the consumption of consumer goods, leisure, and air quality, subject to time endowment and income constraints. The utility function is a nested CES function.

Table B2: Intermediate Production Benchmark Values

| | ENERGY | SERVICES | AGRICULTURE | MANUFACTURES |
|---|---|---|---|---|
| ENERGY | 253,800.3 | 35,748.4 | 12,135.2 | 83,751.8 |
| SERVICES | 55,608.3 | 1,182,177.2 | 48,378.1 | 753,981.8 |
| AGRICULTURE | 174.6 | 109,776.9 | 353,617.4 | 32,591.6 |
| MANUFACTURES | 108,723.6 | 537,487.8 | 58,516.9 | 2,017,510.8 |
| LABOR | 79,221.2 | 2,239,303.1 | 55,472.4 | 1,143,765.5 |
| TOTAL | 497,528.0 | 4,104,493.4 | 528,120.0 | 4,031,601.6 |

SOURCE – Reproduced from Table B2 in Goulder and Williams (2003).

NOTE – All figures in millions of US 1995 $.

Table B3: Final Consumption Production Benchmark Values

| | FOOD & ALCOHOL | CONSUMER SERVICES | CONSUMER MANUFACTURES | TRANSPORTATION | UTILITIES |
|---|---|---|---|---|---|
| ENERGY | 297.6 | 34.6 | 5,571.4 | 50,320.6 | 55,868.1 |
| SERVICES | 480,375.7 | 835,116.3 | 571,872.7 | 92,237.5 | 84,745.9 |
| AGRICULTURE | 24,721.9 | 105.5 | 7,131.1 | 0.5 | 0.5 |
| MANUFACTURES | 315,431.3 | 75,867.5 | 917,510.0 | 0.5 | 553.2 |
| TOTAL | 820,826.4 | 911,123.9 | 1,502,085.1 | 142,559.1 | 141,167.7 |

SOURCE – Reproduced from Table B3 in Goulder and Williams (2003).

NOTE – All figures in millions of US 1995 $.

Table B4: Model Notation and Parameter Values

| | | |
|---|---|---|
| | *Sets* | |
| $C$ | Final Consumption Goods | {FDA,CSV,CMN,TRN,UTL} |
| $I$ | Intermediate Goods | {ENE, SVC, AGR, MNF} |
| | *Parameters* | |
| $\tau_{ene}$ | Per unit tax rate on energy sector | {0.025, 0.05, 0.1} |
| $\tau_L$ | Ad valorem labor tax rate | 0.4 |
| $T$ | Aggregate time endowment | $\sim \eta_{\text{LAB}} = 0.05,\ \eta^h_{\text{LAB}} = 0.25$ |
| $\sigma_j$ | Substitution between inputs in intermediate and final sectors | $\sim \epsilon_{\text{ENE}} = 0.9$ |
| $\sigma_U$ | Substitution between leisure and other consumption | $\sim \eta_{\text{LAB}} = 0.05,\ \eta^h_{\text{LAB}} = 0.25$ |
| $\sigma_C$ | Substitution between consumer goods in consumption nest | 0.85 |
| $\sigma_{AQ}$ | Substitution between leisure and air quality (Pref. #1) | {0.2,1.5} |
| | Substitution between leisure and air quality/services bundle (Pref. #2) | {0.5,0.9} |
| $\sigma_{CSV}$ | Substitution between consumer services and air quality | 0.9 |

$\sim$ reads "calibrated to imply".
$\eta_{\text{LAB}}$ and $\eta^h_{\text{LAB}}$ denote the uncompensated and compensated labor supply elasticities, respectively.
$\epsilon_{\text{ENE}}$ denotes the own-price demand elasticity of energy.

# C Non-Market Sector

The estimates for air pollution are derived from the U.S. Environmental Protection Agency report *National Air Quality and Emission Trends Report for 1995.* Tables A6 and A7 report estimates for emissions of $PM_{10}$ by sector from 1986 to 1995. We selected the reports for 1995 and aggregated the reported thousands of short tons of particulate matter as indicated in table B5.

Table B5: Definitions for Mapping Emission Rates to GW Sector

| | |
|---|---|
| ENERGY | Fuel combustion for electric utilities (including coal, oil, gas, and internal combustion), industrial (including coal, oil, gas, and internal combustion), and residential wood. |
| MANUFACTURING | Chemical and allied products manufacturing, metal processing, petroleum and related industries, other industrial processes, solvent utilization, storage and transport, and waste disposal and recycling. |
| TRANSPORTATION | On-road vehicles and non-road sources. |
| AGRICULTURE | Agriculture and forestry. |
| NATURAL SOURCES | Combustion — wildfires, managed burning and other; Fugitive dust and wind erosion. |

Using the estimates for $PM_{10}$ emissions by sector, we constructed the emission coefficients per unit of output (measured in dollars). In addition, the aggregate annual $PM_{10}$ emissions in thousands of short tons (42) together with the 1995 annual arithmetic mean of $PM_{10}$ (25, in micrograms per cubic meter) were used to convert emissions factors to measures the ambient concentration. We use the EPA rate to convert estimates of the marginal willingness to pay to reduce particulate matter (measured as TSP) into the marginal willingness to pay for $PM_{10}$.

The process begins with MWTP from Smith and Huang [1995] in 1982-84 dollars and converts it to 1995 dollars:

$$\underbrace{MWTP}_{\$/TSP}\ \underbrace{(1.524)}_{CPI}\ \underbrace{\left(\frac{1}{.55}\right)}_{PM_{10}/TSP}\ \underbrace{(100)}_{millions\ of\ households}\ \left(\frac{25}{42}\right) = AMWTP$$

Three sets of estimates are developed: the middle estimate from the Smith-Huang meta analyses of hedonic estimates (i.e. adjusting for the characteristics of the hedonic studies used to develop these measures); the average of the unadjusted hedonic estimates included in the Smith-Huang study; and a marginal willingness to pay that implies a value of air quality that is two percent of virtual income in the benchmark equilibrium. The mapping of the values from in Smith-Huang to the implied aggregate MWTP measures in our study are shown in table B6.

Table B6: Aggregate MWTP Estimates for $PM_{10}$ Reductions

| | Smith-Huang (1982-84 $/TSP) | AMWTP (millions of 1995 $) |
|---|---|---|
| Middle of Meta Analysis | $102.49 | $9,273 |
| Average of Hedonic Estimates | $199.82 | $18,079 |
| AMWTP/Virtual Income = 2% | $333.81 | $30,202 |

# D Production Structure

The following figures give a graphical description of the various production technologies in the model. The top level in each figure represents the output, while all subsequent levels of the tree structure describe the nesting structure of the inputs in the nested constant elasticity of substitution production functions. The substitution patterns for each nest are listed in italics at each node of the tree.

Figure D1: Nesting in Household Consumption (Specification #1)

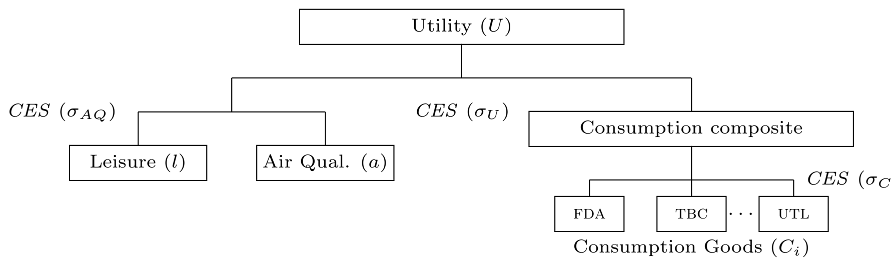


Figure D2: Nesting in Household Consumption (Specification #2)

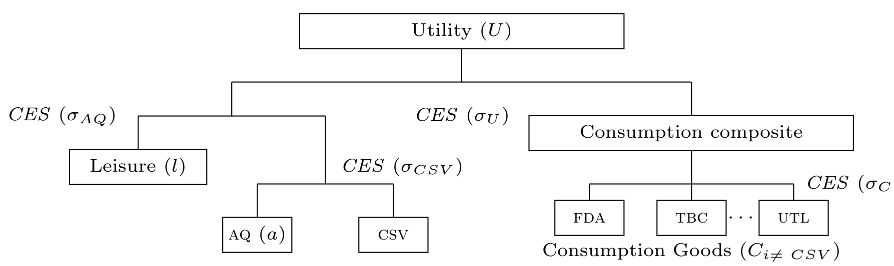

Figure D3: Intermediate Goods

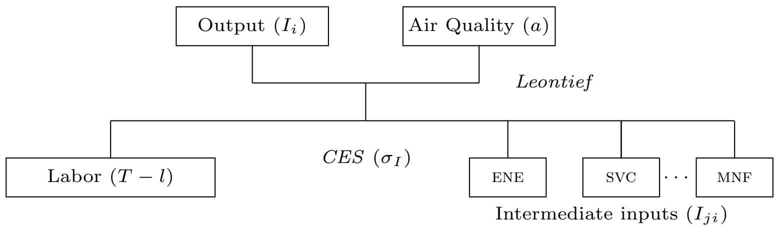


Figure D4: Final Goods