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Can pollution tax rebates protect low-wage earners?

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ABSTRACT

Pollution taxes are believed to burden low-income households that spend a greater than average share of income on pollution-intensive goods. Some proposals offset that effect by returning revenue to low-income workers via reduced labor tax. We build analytical general equilibrium models with both high-skilled and low-skilled labor, and we solve for the change in real net wage of each group. Decomposition shows the separate effects of the tax rebate, higher product prices, and the changes in relative wage rates. We also include numerical examples. Even though the pollution tax injures both types of labor, in most cases we find that returning all of the revenue to low-skilled workers is still not enough to offset higher product prices. Changes in relative wage rates may further hurt low-skilled labor. Protecting low-income workers is possible in this model only if they are defined as those below a relatively low wage threshold, but we discuss many possible elaborations of this model that could affect those results.

1. Introduction

Market-based pollution policies can efficiently address environmental problems and save overall costs, but policymakers may also want to know distributional effects. These effects also depend on what is done with any revenue. Permits allocated freely to firms do not generate revenue, but pollution taxes or auctioned permits do. Government use of this revenue helps determine the final incidence of the policy.

A common argument against pollution taxes is that they tend to raise prices of pollution-intensive goods that constitute a high fraction of spending by low-income households. However, a pollution tax may affect relative wage rates as well as output prices. To consider both the uses side and the sources side of income, this paper employs new analytical general equilibrium models in the spirit of Harberger (1962) to solve for the incidence of a pollution tax when government has a revenue neutrality requirement. Unlike the standard Harberger model with labor and capital, however, our simple model assumes firms use high-skilled and low-skilled labor. A change in the pollution tax can alter demand for one relative to the other and thus affect relative wage rates. We assume that low-income low-skilled workers spend a higher fraction of income on the polluting good, and that government tries to offset this effect by using the new revenue to reduce pre-existing labor taxes on low-income workers. Then we solve for effects on each wage rate to determine the net burdens. We show that generally the rebate is not enough to offset higher prices for polluting goods such as gasoline, electricity, and home heating oil. Moreover, changes in factor prices can further burden low-income families.

Related to this topic is the "double dividend" claim that a pollution tax can clean up the environment and generate revenue to cut distortionary taxes.[1] This literature uses analytical and computational equilibrium models to study revenue-neutral

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[1] See Bovenberg and de Mooij (1994a, 1994b, 1998), Bovenberg and van der Ploeg (1994), Parry (1995), Goulder (1995), Bovenberg and Goulder (1997), Parry et al. (1999), and Fullerton and Metcalf (2001).

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environmental policy reform, but they address questions about economic efficiency rather than about distributional effects. Some of these studies solve for the change in wage rate, but not relative burdens. They do not report whether the real low-skilled wage rises or falls.

A few papers do use computational models to consider the distributional side of an environmental tax swap. Metcalf (1999, 2009) uses data on the carbon content of different products and on purchases across different income groups to show that the use of new pollution tax revenue to reduce taxes for low-income households can make the overall reform less regressive or even progressive. Burtraw et al. (2009) also calculate incidence based on product price increases (without factor price changes). Dinan and Rogers (2002) use a computational general equilibrium (CGE) model with labor and capital but do not show distributional effects on the sources side.[2] West and Williams III (2004) estimate the uses-side incidence of a gasoline tax in several scenarios, one of which is using tax revenue to decrease the tax on labor. They find a gain in efficiency and a decrease in regressivity, but the gas tax is still not progressive. Hassett et al. (2009) emphasize redistribution on a lifetime basis and by region. Rausch et al. (2010) use a computational model with tax shifting to labor and capital.

This computational literature asks if a return of pollution tax revenue can make the tax swap progressive (so that net burden is a higher fraction of income for those with more income). It finds the answer is yes. Here we use analytical models, and we ask instead whether the tax swap can avoid placing *any* burden on low-income families. We find the answer in our model is usually no. Even if all the pollution tax revenue is used to cut the labor tax on low-skilled workers, their real net wage usually still falls. As explained below, some burden is still felt by both low-skilled and high-skilled workers.

To our knowledge, no paper employs analytical models to analyze distributional effects on both the uses side and sources side from a pollution tax swap, with revenue used to reduce an existing tax such as the payroll tax. A limitation of computational models is that specific results depend on assumptions about parameter values. Since our analytical solutions hold for any parameter values, we can show general conditions under which the relative real wage ratio rises or falls. We also use plausible parameter values to illustrate numerical burdens on each type of labor.

Whereas Harberger (1962) had two sectors, two factors, and one representative consumer ($2\times2\times1$), Fullerton and Heutel (2007) add pollution as a factor of production ($2\times3\times1$). Like Harberger, they assume the government uses the pollution tax revenue to purchase the two commodities in the same proportion as do households. Here, we keep two sectors and three factors, but we make three contributions. First, we distinguish two types of household, each with its own utility function and preferences ($2\times3\times2$). Second, we solve for the new low-skilled labor tax rate that returns new pollution tax revenue to balance the budget. These changes increase our dimensionality from 10 equations to 16. Third, we consider low-skilled labor and high-skilled labor as separate factors of production.[3] In contrast, all prior general equilibrium incidence studies mentioned above consider labor to be one homogenous input.[4]

Other studies have shown effects on rising wage inequality from other exogenous shocks. Increased demand for high-skilled relative to other labor may occur with changes over time in technology, globalization, trade patterns, labor force composition, and other exogenous changes.[5] Similarly, a pollution tax could increase the relative demand for high-skilled labor and raise their wage rate, if firms substitute from pollution into high-skilled labor. Conversely, it could increase the low-skilled wage if firms substitute more into low-skilled labor. Which is more likely? These cross-price substitution parameters have never been estimated, but one possibility is that major environmental policy reform could spur sophisticated abatement technologies that favor high-skilled labor.

Given the generality of our model, the pollution tax need not raise the price of the dirty good, or even reduce pollution.[6] Yet such possibilities do not just confirm the idea that “anything can happen.” To avoid that trap, we carefully categorize those perverse cases and show that they require extreme parameter values that are highly unlikely. Our paper is not about perverse cases. Even without perverse cases, however, we demonstrate multiple ways in which low-income workers might suffer despite receiving all the tax rebate. We say nothing about whether low-income families “ought” to be protected; we only ask whether they *can* be protected from a fall in their real net wage rate.

We decompose the change in their real net wage into the effect of their gross wage, of the tax rebate, and of product prices. Both groups face higher product prices, and yet we find that the return of *all* additional pollution tax revenue just to the low-income group in this model is still usually not enough to offset the decline of their real net wage. One reason is that

[2] They assume that government can use permit revenue to cut corporate taxes, to cut payroll taxes, or to give households lump-sum rebates. The last scenario is the only one that might not be regressive.

[3] We started our model with one type of labor and capital, just as in many other papers back to Harberger (1962), but we soon realized that those two factors do not clearly delineate who has high or low income. In the Consumer Expenditure Survey, using annual data, the ratio of capital income to labor income plotted against total income reveals a U-shaped pattern, primarily because low-income retirees may have no labor income. A lifecycle model is way beyond the scope of this paper. Instead, our two types of labor clearly identify who has high or low income. High-skilled labor differs from low-skilled labor, the ratio of their use may differ by industry, and either one might be a better substitute for pollution.

[4] In these prior models, some individuals may have a larger endowment of effective labor units, but every labor unit earns the same wage rate. Therefore, individuals at all income levels with different endowments are affected the same way when the single wage rate changes in response to an environmental tax.

[5] Several papers focus on the role of high-skill-biased-technical-change and the effect on relative high-skilled and low-skilled wages, including Bound and Johnson (1992), Katz and Murphy (1991), and Berman et al. (1994). Hanson and Harrison (1999) consider trade liberalization as an explanation for rising wage inequality, and Autor et al. (2008) evaluate the effect of shifts in labor force composition.

[6] Such possibilities were shown in Bovenberg and de Mooij (1998) and in Fullerton and Heutel (2007).

burdens on the two groups exceed pollution tax revenue (because of excess burden). This effect is not captured in papers mentioned above that focus just on product prices and return of revenue. Moreover, changes in relative wage rates may offset or exacerbate that burden on low-skilled workers.

Our illustrations use data on carbon-intensity and impose a carbon tax. In most of our calculations, the use of all revenue to cut the labor tax on low-skilled workers is not enough to protect them. But we do not claim this result is general. We only mean to point out the difficulties of trying to protect low-income families, and to point out the conditions under which it might be more feasible. Other extensions to the model would certainly affect these results. But in our model, as shown below, low-skilled labor can only be protected from a fall in their real net wage when (1) low-skilled labor is better than high-skilled labor as a substitute for pollution, (2) the dirty sector is high-skilled intensive, and (3) the low-skilled labor group is defined sufficiently narrowly that the use of all pollution tax revenue can compensate this smaller group.

2. The analytical model

Note that we do not provide the most thorough estimates of all burdens from a pollution tax. That task would undoubtedly require a multi-sector, multi-factor CGE model. Instead, simple models are solved analytically to gain intuition about how each parameter affects each result. We omit many possible channels of incidence, in order to focus on how a pollution tax affects the real net wage of low-skilled workers compared to that of high-skilled workers. For that purpose, our model is similar to one in Fullerton and Heutel (2007), with the addition of three features: we consider two household types instead of one, we solve for the labor tax reduction that exactly rebates the extra pollution tax revenue, and we distinguish low-skilled from high-skilled labor.

One type of household supplies high-wage high-skilled labor, while the other type supplies low-wage low-skilled labor. The low-income families spend a relatively high fraction of income on pollution-intensive products like gasoline, electricity, and heating oil (Metcalf, 1999, 2009). We assume that government tries to offset their added burden on the uses side by using the extra pollution tax revenue to lessen the payroll tax, a pre-existing tax on the labor of low-wage families. The incidence of the new tax system on the sources side is characterized by the proportional changes in the two wage rates, in response to a small exogenous increase in the pollution tax.

The setting for the model is a perfectly competitive two-sector economy, with production of a "clean" good, denoted by X with price p_X, and a "dirty" good, denoted by Y with price p_Y. High-skilled and low-skilled labor are used to produce both goods, and pollution is also an input in the dirty sector. Constant returns to scale (CRS) production functions are $X=X(L_X, H_X)$ and $Y=Y(L_Y, H_Y, Z)$, where L is low-skilled labor with wage w, H is high-skilled labor with wage h, and Z is pollution.[7] All inputs have positive but declining marginal products. The price of pollution is simply its unit tax rate, τ_Z. Both types of labor are mobile between the two sectors, with fixed total amounts of each ($\overline{L}$ and $\overline{H}$). Resource constraints for these two inputs are $L_X+L_Y=\overline{L}$ and $H_X+H_Y=\overline{H}$. Totally differentiation yields:

$$\hat{H}_X\lambda_{HX}+\hat{H}_Y\lambda_{HY}=0 \tag{1}$$

$$\hat{L}_X\lambda_{LX}+\hat{L}_Y\lambda_{LY}=0 \tag{2}$$

where a hat indicates a proportional change (e.g., $\hat{H}_X=dH_X/H_X$), and λ_{ij} is sector j's share of input i (e.g., $\lambda_{HX}=H_X/\overline{H}$). These two equations contain four of the unknowns (with hats); we proceed to collect more equations to solve for all unknowns.

Producers of X can substitute between high- and low-skilled labor according to an elasticity of substitution, σ_X. Rearranging the definition of σ_X provides a behavioral equation showing how they respond to any change in input prices, p_L and p_H, namely $\hat{H}_X-\hat{L}_X=\sigma_X(\hat{p}_L-\hat{p}_H)$. These two input prices are the costs that producers face and are gross-of-tax, so $p_L=w(1+\tau_L)$ and $p_H=h(1+\tau_H)$. We assume that the increased pollution tax τ_Z generates revenue used to lower τ_L, the wage tax on low-skilled labor. For simplicity, all other tax rates are assumed to stay constant. Thus, the proportional change in the price of low-skilled labor is $\hat{p}_L=\hat{w}+\hat{\tau}_L$ where $\hat{w}\equiv dw/w$, but where we define $\hat{\tau}_L$ as $d\tau_L/(1+\tau_L)$. Since τ_H does not change, $\hat{p}_H=\hat{h}$. Thus we have:

$$\hat{H}_X-\hat{L}_X=\sigma_X(\hat{w}+\hat{\tau}_L-\hat{h}). \tag{3}$$

Because the dirty sector uses three factors of production, it has slightly more complicated responses. The firms' input demands are functions of all input prices and output. Following Mieszkowski (1972), differentiate these demand functions to get:

$$\begin{aligned}\hat{H}_Y&=a_{HH}\hat{p}_H+a_{HL}\hat{p}_L+a_{HZ}\hat{p}_Z+\hat{Y}\\ \hat{L}_Y&=a_{LH}\hat{p}_H+a_{LL}\hat{p}_L+a_{LZ}\hat{p}_Z+\hat{Y}\\ \hat{Z}&=a_{ZH}\hat{p}_H+a_{ZL}\hat{p}_L+a_{ZZ}\hat{p}_Z+\hat{Y}\end{aligned}$$

where a_{ij} is the elasticity of demand for factor i with respect to the price of factor j. Define θ_{Yj} as the share of sales revenue from Y used to purchase factor j (e.g., $\theta_{YH}=h(1+\tau_H)H_Y/p_YY$). Then $a_{ij}=e_{ij}\theta_{Yj}$, where e_{ij} is the Allen elasticity of substitution

[7] Production of Y is CRS with respect to all three inputs (a given percentage increase in output can be achieved by the same percentage increase in all three: high-skilled labor, low-skilled labor, and pollution).

between inputs i and j (Allen, 1938), which is negative when the two inputs are complements and positive for substitutes.[8] In the case where a tax per unit of pollution is its only price, then $p_Z=\tau_Z$ and $\hat{p}_Z=\hat{\tau}_Z$ (where $\hat{p}_Z \equiv dp_Z/p_Z$ and $\hat{\tau}_Z \equiv d\tau_Z/\tau_Z$). Substitute the Allen elasticities and the proportional price changes into the differentiated factor demands above, and subtract the third equation from the first two:

$$\hat{H}_Y-\hat{Z}=\theta_{YH}(e_{HH}-e_{ZH})\hat{h}+\theta_{YL}(e_{HL}-e_{ZL})(\hat{w}+\hat{\tau}_L)+\theta_{YZ}(e_{HZ}-e_{ZZ})\hat{\tau}_Z \tag{4}$$

$$\hat{L}_Y-\hat{Z}=\theta_{YH}(e_{LH}-e_{ZH})\hat{h}+\theta_{YL}(e_{LL}-e_{ZL})(\hat{w}+\hat{\tau}_L)+\theta_{YZ}(e_{LZ}-e_{ZZ})\hat{\tau}_Z \tag{5}$$

These two equations represent how producers of Y react to changes in prices and tax rates that are attributable to an exogenous increase in the pollution tax, τ_Z.

Perfect competition and CRS imply that sales revenue in each sector equals the sum of payments to factors. Differentiate the zero profit conditions to get:

$$\hat{X}+\hat{p}_X=\theta_{XH}(\hat{h}+\hat{H}_X)+\theta_{XL}(\hat{w}+\hat{\tau}_L+\hat{L}_X) \tag{6}$$

$$\hat{Y}+\hat{p}_Y=\theta_{YH}(\hat{h}+\hat{H}_Y)+\theta_{YL}(\hat{w}+\hat{\tau}_L+\hat{L}_Y)+\theta_{YZ}(\hat{\tau}_Z+\hat{Z}). \tag{7}$$

Then, differentiate each sector's production function to describe how output quantities change with input variations:

$$\hat{X}=\theta_{XH}\hat{H}_X+\theta_{XL}\hat{L}_X \tag{8}$$

$$\hat{Y}=\theta_{YH}\hat{H}_Y+\theta_{YL}\hat{L}_Y+\theta_{YZ}\hat{Z}. \tag{9}$$

In order to discuss the distribution of net burdens in the simplest possible way, we assume that the economy has two types of consumers, low-skilled and high-skilled laborers, where subscripts L and H denote these groups (e.g. X_L is the amount of good X consumed by low-skilled workers). These two groups may spend on X and Y in different proportions, but they have the same elasticity of substitution in utility, σ_U, between X and Y. This simplifying assumption makes the model easier to solve, and yet does not detract from the purpose of the paper to find effects on these two groups. The elasticity of substitution has major impacts on economic efficiency, but it has only second-order effects on burdens.[9] The first-order impact of $\hat{p}_X$ and $\hat{p}_Y$ on the relative burden of each group is the major pre-existing difference in the fraction of income that each group spends on Y. Rearranging the definition of σ_U yields behavioral equations that show how the two consumers' demands respond to changes in output prices:

$$\hat{X}_L-\hat{Y}_L=\sigma_U(\hat{p}_Y-\hat{p}_X) \tag{10}$$

$$\hat{X}_H-\hat{Y}_H=\sigma_U(\hat{p}_Y-\hat{p}_X) \tag{11}$$

The two goods are purchased by both types of workers. The total quantity of good X can then be expressed as $X=X_L+X_H$, and similarly $Y=Y_L+Y_H$. Differentiating these equations yields:

$$\hat{X}=\hat{X}_L\frac{X_L}{X}+\hat{X}_H\frac{X_H}{X} \tag{12}$$

$$\hat{Y}=\hat{Y}_L\frac{Y_L}{Y}+\hat{Y}_H\frac{Y_H}{Y}. \tag{13}$$

The government budget constraint requires a fixed amount, G, matched by tax revenue:

$$G=\tau_Z Z+h\tau_H H+w\tau_L L.$$

Rather than specify direct government spending on X and Y, we say that the fixed revenue G is returned to the two groups (δG to the high-income group, and $(1-\delta)G$ to the low-income group). Since G is fixed, these lump-sum transfers are fixed and do not affect our results. Only the *increase* in pollution tax revenue is used to cut τ_L (leaving G fixed). With the revenue neutrality condition ($dG=0$) and the assumption that only tax rates τ_Z and τ_L can change, we differentiate the government budget constraint and rearrange to solve for the change in the labor tax:

$$\hat{\tau}_L=\frac{1}{\overline{L}p_L}\left[-Z\tau_Z(\hat{\tau}_Z+\hat{Z})-\overline{H}h\tau_H\hat{h}-\tau_L\hat{w}\right]. \tag{14}$$

[8] Also, Allen (1938) shows that e_{ii} (and thus a_{ii}) are negative, and $a_{iH}+a_{iL}+a_{iZ}=0$. Thus, at most one of the two cross-price elasticities can be negative. Given symmetry ($e_{ij}=e_{ji}$) this result means either that all three cross-price elasticities are positive or that one is negative and the other two are positive.

[9] The choice of σ_U determines the demand elasticity for Y (or vice versa). In a partial equilibrium diagram with a small increase in p_Y, any variation in that demand elasticity would have first order effects on the size of the deadweight loss (DWL) triangle, but not on the size of the consumer surplus loss trapezoid. DWL is well studied, while here we focus on distributional effects. The price increase adds a narrow strip to the height of the burden trapezoid, the size of which is virtually unaffected by the slope of demand.

The two consumer groups allocate spending on the two goods according to their preferences and budget constraints.[10] For example, the budget constraint for high-skilled labor is $p_X X_H + p_Y Y_H = h(H_X + H_Y) + \delta G$. Of the two spending equations, only one is independent. The second can be derived from the first, using Eqs. (6) and (7). Therefore, only one consumer group budget constraint is necessary, and differentiation of the high-skilled labor budget constraint yields:

$$p_X X_H(\hat{p}_X + \hat{X}_H) + p_Y Y_H(\hat{p}_Y + \hat{Y}_H) = h(H_X + H_Y)\hat{h}. \tag{15}$$

Eqs. (1)–(15) are fifteen linear equations in sixteen unknowns: $\hat{H}_X, \hat{H}_Y, \hat{L}_X, \hat{L}_Y, \hat{w}, \hat{h}, \hat{p}_X, \hat{X}, \hat{X}_L, \hat{X}_H, \hat{p}_Y, \hat{Y}, \hat{Y}_L, \hat{Y}_H, \hat{Z}$, and $\hat{\tau}_L$. Good X is chosen as numeraire, so that $\hat{p}_X = 0$. The model can be solved through successive substitution to obtain equations for each of the remaining fifteen endogenous variables in terms of exogenous parameters and the exogenous change in the pollution tax, $\hat{\tau}_Z$.

3. Analytical results

The variables of most interest are the price changes, to determine the relative incidence on high-skilled and low-skilled labor. Eqs. (16a)–(16e) are solutions for these selected variables and the change in pollution, $\hat{Z}$. The expressions for $\hat{p}_H$ and $\hat{p}_L$ are "closed form" solutions, because they contain only parameters and the exogenous policy shock ($\hat{\tau}_Z$), but the expression for $\hat{w}$ contains $\hat{\tau}_L$ (which is endogenous). All of these solutions *can* be expressed just in terms of exogenous parameters and $\hat{\tau}_Z$, but that would make the expressions much longer. For example, a closed-form solution for $\hat{Z}$ can be obtained by substituting expressions for $\hat{h}$ and $\hat{w} + \hat{\tau}_L$ into the $\hat{Z}$ expression, and that $\hat{Z}$ can be used to obtain closed-form expressions for $\hat{\tau}_L$ and $\hat{w}$.

$$\hat{h} = \hat{p}_H = \frac{\theta_{XL}\theta_{YZ}}{D}\left[A(e_{HZ} - e_{ZZ}) - B(e_{LZ} - e_{ZZ}) - (\gamma_H - \gamma_L)(\sigma_U N + J)\right]\hat{\tau}_Z \tag{16a}$$

$$\hat{w} = \hat{p}_L - \hat{\tau}_L = \frac{\theta_{XH}\theta_{YZ}}{D}\left[A(e_{ZZ} - e_{HZ}) - B(e_{ZZ} - e_{LZ}) + (\gamma_H - \gamma_L)(\sigma_U N + J)\right]\hat{\tau}_Z - \hat{\tau}_L \tag{16b}$$

$$\hat{p}_Y = \frac{(\theta_{YL}\theta_{XH} - \theta_{YH}\theta_{XL})}{D}\theta_{YZ}\left[A(e_{ZZ} - e_{HZ}) - B(e_{ZZ} - e_{LZ}) + (\gamma_H - \gamma_L)(\sigma_U N + J)\right]\hat{\tau}_Z + \theta_{YZ}\hat{\tau}_Z \tag{16c}$$

$$\begin{aligned}\hat{Z} = -\frac{1}{C}\Bigg[&\theta_{YH}\left[\beta_H(e_{HH} - e_{ZH}) + \beta_L(e_{LH} - e_{ZH}) + \sigma_U N + J\right] - \frac{1}{C_H}h\overline{H}\left(\frac{Y_H}{Y_L} - \frac{X_H}{X_L}\right)\Bigg]\hat{h}\\ &+ \theta_{YL}[\beta_H(e_{HL} - e_{ZL}) + \beta_L(e_{LL} - e_{ZL}) + \sigma_U N + J](\hat{w} + \hat{\tau}_L)\\ &+ \theta_{YZ}[\beta_H(e_{HZ} - e_{ZZ}) + \beta_L(e_{LZ} - e_{ZZ}) + \sigma_U N + J]\hat{\tau}_Z]\end{aligned} \tag{16d}$$

$$\hat{\tau}_L = \left[\frac{1 + \tau_L}{\overline{L}p_L}\right]\left[-Z\tau_Z(\hat{Z} + \hat{\tau}_Z) + (-\overline{H}\tau_H h + M\overline{L}p_L)\hat{h}\right] \tag{16e}$$

To simplify, parameters are combined into definitions (see Box 1). That is, γ_H and γ_L are relative factor intensities. In our data below, the two sectors have similar factor intensities ($\gamma_L \cong \gamma_H$), but here we analyze the general case where they may differ. The constants A and B are difficult to interpret, but they are weights on the terms involving the Allen elasticities (e_{ij}). In Eq. (16), these terms represent "substitution effects" and indicate how producers of Y substitute among inputs when pollution becomes more expensive. The constant C partly determines the change in pollution ($\hat{Z}$) in (16d). The constants A, B, and C are all positive, but the denominator D cannot be signed in general. The terms N and J summarize the relative consumption of the two goods by the two consumer groups. While N can be shown to be positive, the sign of J is ambiguous without additional assumptions (discussed below).

Two effects appear in (16a)–(16c) that are comparable to effects identified by Mieszkowski (1967) and discussed by Fullerton and Heutel. (2007). The "substitution effect" is the term $[A(e_{HZ} – e_{ZZ}) – B(e_{LZ} – e_{ZZ})]$. Through this term, the higher pollution tax ($\hat{\tau}_Z > 0$) tends to help high-skilled labor ($\hat{h} > 0$) whenever e_{HZ} is larger than e_{LZ}, that is, when H is a better substitute for pollution than is L. Second, the "output effect" is represented here by the term $(\gamma_H - \gamma_L)(\sigma_U N + J)$. Basically, the N and J terms show how expenditure patterns affect demands for X and Y, and thus demands for L and H, with effects on the sources side (on $\hat{h}$ vs. $\hat{w}$). Suppose L is used more intensively in the dirty sector, so that $(\gamma_H - \gamma_L) < 0$. Because σ_U and N are both positive, then the first part of this term, $(\gamma_H - \gamma_L)\sigma_U N$, is negative. A higher tax on emissions, $\hat{\tau}_Z$, reduces the dirty output in a way that depends on consumer preferences represented by σ_U, and therefore reduces demand for L relative to H (reducing w and raising h). It places more burden on the factor intensively employed in the dirty sector.

The additional term J means that this effect on factor prices also depends on the relative consumption by the two groups. For concreteness, assume that low-skilled consumers spend a greater proportion of income on the dirty good than do high-skilled consumers. In other words, assume Y_L/X_L exceeds Y_H/X_H, which makes J negative. The additional J term does not

[10] We assume utility is homothetic, ignoring the possibility that additional income to poor families might not be spent in the same proportions as was their initial income. This simplification might be a problem, except that we rebate revenue to the low-income group to minimize any change in their real net income.

Box 1–Further definitions of terms.

$$\gamma_H \equiv \frac{\lambda_{HY}}{\lambda_{HX}} = \frac{H_Y}{H_X}, \quad \gamma_L \equiv \frac{\lambda_{LY}}{\lambda_{LX}} = \frac{L_Y}{L_X}, \quad \beta_H \equiv \tfrac{X}{X_L}\theta_{XH}\gamma_H + \tfrac{Y}{Y_L}\theta_{YH}, \quad \beta_L \equiv \tfrac{X}{X_L}\theta_{XL}\gamma_L + \tfrac{Y}{Y_L}\theta_{YL},$$

$$A \equiv \gamma_L\beta_H + \gamma_H(\beta_L + \tfrac{Y}{Y_L}\theta_{YZ}), \quad B \equiv \gamma_H\beta_L + \gamma_L(\beta_H + \tfrac{Y}{Y_L}\theta_{YZ}), \quad C \equiv \beta_H + \beta_L + \tfrac{Y}{Y_L}\theta_{YZ},$$

$$D \equiv C\sigma_X + A[\theta_{XH}\theta_{YL}(e_{HL} - e_{LZ}) - \theta_{XL}\theta_{XH}(e_{HH} - e_{HZ})] - B[\theta_{XH}\theta_{YL}(e_{LL} - e_{LZ}) - \theta_{XL}\theta_{YH}(e_{HL} - e_{HZ})]$$
$$- (\gamma_H - \gamma_L)(\sigma_U N + J)(\theta_{XH}\theta_{YL} - \theta_{XL}\theta_{YH}) - (\gamma_H - \gamma_L)\frac{1}{C_H}h\overline{H}\left(\frac{Y_H}{Y_L} - \frac{X_H}{X_L}\right),$$

$$M \equiv \frac{\tau_L \quad \theta_{XH}}{1 + \tau_L\theta_{XL}}, \quad N \equiv \frac{X}{X_L} + (1 - \alpha_H)\left(\frac{Y_H}{Y_L} - \frac{X_H}{X_L}\right), \quad J \equiv \alpha_H\left(\frac{Y_H}{Y_L} - \frac{X_H}{X_L}\right),$$

$$C_H \equiv p_X X_H + p_Y Y_H, \text{ and } \alpha_H \equiv \frac{p_Y Y_H}{p_X X_H + p_Y Y_H}$$

appear in results of Fullerton and Heutel (2007) because they assume government spends the tax revenue in the same way as the one consumer. Here, the extra tax revenue is rebated to low-skilled labor, with relatively more spending on the dirty good, so this particular use of the revenue increases purchases of Y. This J term helps the factor used intensively in Y, offsetting part of the usual output effect.

Because the solutions for these variables are complicated, with offsetting effects, the determination of the overall sign of each is difficult. In this general case, the tax on pollution might even reduce the price of the dirty good, or increase pollution. Therefore, we employ special cases to simplify the expressions and add intuition. The rest of this section focuses on the sources side of income, and a later section focuses on the uses side.

3.1. Special Case 1: equal factor intensities ($\gamma_H = \gamma_L = \gamma$)

For the first special case, suppose that the two sectors have the same ratio of high-skilled to low-skilled labor ($H_Y/H_X = L_Y/L_X$). This condition eliminates the output effect, $(\gamma_H - \gamma_L)(\sigma_U N + J)$ and leaves the sign of each price change to depend only on the substitution effects – the e_{ij} parameters. In this simple case, the solutions are:

$$\hat{p}_Y = \theta_{YZ}\hat{\tau}_Z \tag{17a}$$

$$\hat{h} = \hat{p}_H = \frac{\theta_{XL}\theta_{YZ}\gamma(e_{HZ} - e_{LZ})}{D_1}\hat{\tau}_Z \tag{17b}$$

$$\hat{w} = \hat{p}_L - \hat{\tau}_L = \frac{-\theta_{XH}\theta_{YZ}\gamma(e_{HZ} - e_{LZ})}{D_1}\hat{\tau}_Z - \hat{\tau}_L \tag{17c}$$

where $D_1 = (\sigma_X - \theta_{XL}\theta_{YH}\gamma e_{HH} - \theta_{XH}\theta_{YL}\gamma e_{LL}) + \gamma(\theta_{XL}\theta_{YH} + \theta_{XH}\theta_{YL})e_{HL}$. In this case, $\hat{p}_Y$ in (17a) is clearly positive, since θ_{YZ} is positive, and because the pollution tax is increased ($\hat{\tau}_Z > 0$). The sign of $\hat{h}$ depends on whether $e_{HZ} > e_{LZ}$ and $D_1 > 0$. To put a sign on this denominator, define

$$\text{Condition 1}: e_{HL} > \frac{-\sigma_X + \theta_{XL}\theta_{YH}\gamma e_{HH} + \theta_{XH}\theta_{YL}\gamma e_{LL}}{\gamma(\theta_{XL}\theta_{YH} + \theta_{XH}\theta_{YL})}.$$

The denominator D_1 is positive if and only if Condition 1 holds. Since $e_{HH} < 0$, $e_{LL} < 0$, and all other terms are positive, the ratio on the right side of the inequality is strictly negative. For this condition to hold, it is sufficient that $e_{HL} > 0$, which means that low-skilled labor and high-skilled labor are substitutes for each other. Generally, Condition 1 may still hold if low-skilled and high-skilled labors are not too complementary.

If that condition holds, and high-skilled labor is better than low-skilled labor as a substitute for pollution ($e_{HZ} > e_{LZ}$), then the pollution tax raises the high-skilled wage ($\hat{h} > 0$). If Condition 1 fails, and the two types of labor are "too" complementary, then $\hat{h}$ is negative.[11] Less unlikely is that Condition 1 holds but low-skilled labor is a better substitute for pollution, where again $\hat{h}$ is negative.[12]

The sign of $\hat{w}$ depends on $\hat{\tau}_L$ and on the $\hat{p}_L$ term (with sign opposite to that of $\hat{h} = \hat{p}_H$). The extra pollution tax revenue is used to reduce τ_L, so $\hat{\tau}_L$ is negative.[13] The reduction in this tax rate has a powerful, positive impact on $\hat{w}$ in (17c), since the

[11] Intuition is difficult for this perverse case. How could the tax hurt high-skilled labor, even though H is a better substitute for pollution ($e_{HZ} > e_{LZ}$)? The higher price of pollution induces substitution into H, but if L and H are sufficiently complementary, then the firm wants to employ more L, which raises w relative to h.

[12] If *both* conditions fail, so that $D_1 < 0$ *and* $e_{HZ} < e_{LZ}$, then h would rise.

[13] We assume that the pollution tax rate is on the normal side of the Laffer curve, so that increasing the rate yields additional revenue that can be used to cut τ_L.

Box 2–Changes in w and h for Special Case 1 (equal factor intensities).

If high-skilled labor and low-skilled labor are not too complementary ($D_1 > 0$):	$\hat{h}$	$\hat{w}$
(1) $e_{HZ} < e_{LZ}$ (*low-skilled labor is a better substitute for pollution*)	< 0	> 0
(2) $e_{HZ} > e_{LZ}$ and $\hat{\tau}_L > \frac{-\theta_{XH}\theta_{YZ}\gamma(e_{HZ}-e_{LZ})}{D_1}\hat{\tau}_Z$	> 0	< 0
(3) $e_{HZ} > e_{LZ}$ and $\hat{\tau}_L < \frac{-\theta_{XH}\theta_{YZ}\gamma(e_{HZ}-e_{LZ})}{D_1}\hat{\tau}_Z$	> 0	> 0

goal of the tax swap is to raise the *net* wage for low-income families. If low-skilled labor is a better substitute for pollution than is high-skilled labor ($e_{LZ} > e_{HZ}$), then the $\hat{p}_L$ term in (17c) is positive, as long as D_1 is positive. In that case $\hat{w}$ is unambiguously positive. The positive effect of $\hat{\tau}_L$ on $\hat{w}$ can be overwhelmed, however, if low-skilled labor is enough less of a substitute for pollution ($e_{HZ} \gg e_{LZ}$), so that a reduction in Z leads to a large reduction in demand for L. Then the net low-skilled wage may fall.

Box 2 summarizes these results and conditions.[14] In the first row, $e_{HZ} < e_{LZ}$, so L is a better substitute for pollution, and the increased pollution tax definitely raises the net low-skilled labor wage (even before accounting for $\hat{\tau}_L < 0$).[15] In the next two rows of Box 2, high-skilled labor is a better substitute for pollution than low-skilled labor, a situation that tends to help high-skilled labor and reduce the low-skilled wage. In the second row, the decrease in τ_L is *not* enough to overcome this injury, so the net-of-tax low-skilled wage falls. In the third row, however, the decrease in τ_L is large enough to offset this burden, so that the low-skilled wage rises. The intuition for the sign of $\hat{h}$ is similar and depends on whether low-skilled labor or high-skilled labor is a better substitute for pollution. Since the high-skilled labor tax rate does not change, though, any burden on the high-skilled wage cannot be offset by tax changes.

3.2. Special Case 2: equal factor intensities and $e_{HZ} = e_{LZ}$

This case is a subset of Special Case 1 with equal factor intensities ($\gamma_H = \gamma_L = \gamma$), with the additional requirement that low-skilled labor and high-skilled labor are equally substitutable for pollution. In this most simple case, the solutions are now just:

$$\hat{p}_Y = \theta_{YZ}\hat{\tau}_Z > 0, \quad \hat{w} = -\hat{\tau}_L > 0, \quad \hat{h} = 0 \tag{18}$$

The change in p_Y is the same as in Special Case 1 and is positive. Whereas equal factor intensities removes the output effect, setting $e_{HZ} = e_{LZ}$ removes the substitution effect. Now relative wage rates do not change at all ($\hat{p}_L = \hat{p}_H = 0$), but pollution tax revenue is used to cut the low-skilled labor tax ($\hat{\tau}_L < 0$, so $\hat{w} > 0$). These simplifying assumptions remove factor price effects and leave only the product price effects analyzed by Metcalf (1999, 2009) and Burtraw et al. (2009). The remaining question, analyzed below, is whether the rebate is enough to overcome the burden from $\hat{p}_Y > 0$.

3.3. Special Case 3: fixed input proportions ($e_{ij} = 0$)

In this case, all the elasticities are set to zero, so that the substitution effects disappear, and only the output effects remain. Now results are driven by whether sector Y is high-skilled labor intensive or low-skilled labor intensive. The solutions are:

$$\hat{p}_Y = \frac{[C\sigma_X - (\gamma_H - \gamma_L)1/C_H h\overline{H}(Y_H/Y_L - X_H/X_L)]\theta_{YZ}}{D_3}\hat{\tau}_Z \tag{191}$$

$$\hat{h} = \hat{p}_H = -\frac{\theta_{XL}\theta_{YZ}(\gamma_H - \gamma_L)(\sigma_U N + J)}{D_3}\hat{\tau}_Z \tag{19b}$$

$$\hat{w} = \hat{p}_L - \hat{\tau}_L = \frac{\theta_{XH}\theta_{YZ}(\gamma_H - \gamma_L)(\sigma_U N + J)}{D_3}\hat{\tau}_Z - \hat{\tau}_L \tag{19c}$$

[14] The $\hat{\tau}_L$ term is endogenous. The three conditions in Box 2 can be expressed in terms of exogenous parameters only, but these conditions would then be longer and more complicated.

[15] But even this case does not guarantee that L is held harmless, because this analysis does not yet account for the effect on L from spending disproportionately on Y when $\hat{p}_Y > 0$. So far, we discuss only the sources side ($\hat{w}$ and $\hat{h}$), but later we discuss effects on the two groups from the uses side ($\hat{p}_Y > 0$).

where

$$D_3 = C\sigma_X - (\gamma_H - \gamma_L)(\sigma_U N + J)(\theta_{XH}\theta_{YL} - \theta_{XL}\theta_{YH}) - (\gamma_H - \gamma_L)\frac{1}{C_H} h\overline{H}\left(\frac{Y_H}{Y_L} - \frac{X_H}{X_L}\right).$$

The denominator D_3 can be positive or negative, depending on whether the dirty sector is low-skilled or high-skilled labor intensive, as well as on other parameters. Even with the removal of the substitution effects, the results are still complicated and difficult to sign. An additional simplification is that the elasticity of substitution in consumption between X and Y, σ_U, is equal to unity (the value used in the numerical section of Fullerton and Heutel (2007)). This simplifying assumption means that the term $(\sigma_U N + J)$ is now unambiguously positive, and it allows us to sign the results based on factor intensities in the dirty industry and several other conditions. The Appendix contains a diagram of these sub-cases and shows the signs of $\hat{p}_Y$, $\hat{h}$, and $\hat{w}$.

When the dirty sector is high-skilled intensive ($\gamma_H > \gamma_L$), the results are definitive: p_Y increases, h decreases, and w increases. These results are consistent with the intuition stated earlier that the output effect places more of the burden on the factor used intensively in the dirty sector. When the dirty industry is low-skilled intensive ($\gamma_H < \gamma_L$), the situation is more complicated. In this case, low-skilled labor might be hurt despite their tax cut. Also, the dirty good's price could actually decrease. When the industries have very different factor intensities, so that γ_L is much larger than γ_H, then w likely decreases. The output effect hurts intensively-used low-skilled labor, which can overtake the opposing decrease in the tax on low-skilled labor. A full categorization of results for Special Case 3 is provided in the Appendix.

4. Effects on the uses side

Thus far, we have discussed the effect of a pollution tax swap on the sources side of income for both types of workers. We next consider the uses side, and we define the *real* net low-skilled wage as $\omega \equiv w/p_Q^L$, where $p_Q^L \equiv \alpha_L p_Y + (1-\alpha_L)p_X$ is a price index.[16] The former yields $\hat{\omega} = \hat{w} - \hat{p}_Q^L$, and the latter yields $\hat{p}_Q^L = \alpha_L \hat{p}_Y$. We showed above that $\hat{p}_L = \hat{w} + \hat{\tau}_L$, so the change in the real net low-skilled wage is

$$\hat{\omega} = \hat{p}_L - \hat{\tau}_L - \hat{p}_Q^L \tag{20}$$

This equation nicely decomposes the effect on the real net wage into three components: the change in the gross wage, the change in the tax rate, and the change from product prices. Similarly, define the real net wage for high-skilled labor as $\psi \equiv h/p_Q^H$, with analogous definitions of p_Q^H and α_H. Since τ_H is fixed, we have

$$\hat{\psi} = \hat{p}_H - \hat{p}_Q^H \tag{21}$$

In Special Case 1 with equal factor intensities, we show above that $\hat{p}_Y > 0$, so $\hat{w}$ may be positive or negative. Thus $\hat{\omega}$ is definitely negative when $\hat{w} < 0$; in particular, when high-skilled and low-skilled labor are not too complementary, and low-skilled labor is relatively complementary with pollution, then the real low-skilled wage falls. For $\hat{w} > 0$, it is more likely that the real net wage increases if α_L is small, that is, if low-skilled laborers do not spend too much more than others on good Y. Special Case 2 simplifies the analysis even more, with the additional assumption that high-skilled labor and low-skilled labor are equally substitutable for pollution. In this case $\hat{p}_Y > 0$, and the real wage increases if $-\hat{\tau}_L > \alpha_L \hat{p}_Y$. Thus, if the wage tax cut is very large, or if low-skilled workers do not spend too much on Y, then their real wage is likely to rise.

Special Case 3 is unique because $\hat{p}_Y$ may be positive or negative. Therefore, $\hat{\omega}$ is definitely positive when $\hat{w} > 0$ and $\hat{p}_Y < 0$. Otherwise, as before, $\hat{\omega}$ may still be positive as long as low-skilled labor's expenditure share on Y is not too large. It is also possible that $\hat{\omega} > 0$ in the perverse case where both the net wage and p_Y fall.

We now summarize all our analytical results. Ignoring unlikely perverse cases where p_Y may fall or Z may rise, we have identified several reasons that the real net wage of low-income workers (ω) may fall, even when all pollution tax revenue is used to cut their labor tax rate. First, ω may fall if H is better than L as a substitute for pollution. Second, ω may fall if the dirty sector is low-skill intensive. Third, ω may fall if low-skill labor spends a higher fraction of income on the dirty good.

5. Caveats and limitations

The most glaring omission from our model might be the absence of capital, as the incidence on capital is important. We contemplated simple ways to account for capital, but we decided those approaches would be unsatisfying. We also contemplated a full model of capital as a fourth factor of production, but that model would have more equations, more complications, and less intuition.[17] Instead, in our model, "three" represents "many", as the point is to gain intuition for how results are affected by patterns of substitution and factor intensities. Substitution effects would still depend on which of the

[16] The weight α_L is low-skilled labor's expenditure share on Y (using initial values, so α_L is a fixed parameter). Thus, $\alpha_L \equiv p_Y Y_L/(p_X X_L + p_Y Y_L)$. We set initial prices to 1.0, so $\alpha_L \equiv Y_L/(Y_L + X_L)$.

[17] The analytical model of Fullerton and Heutel (2007) has three inputs in the dirty sector (labor, capital, and pollution); it requires three own-price and three cross-price elasticities, a total of six parameters not yet estimated. That sector could be extended to four inputs (e.g. high-skilled labor, low-skilled labor, capital, and pollution). But then results would depend on four own-price and six cross-price elasticities, for a total of ten unknown parameters. The result would not be a more accurate calculation of incidence. Turning to a large CGE model does not provide a more accurate calculation of incidence either,

multiple factors are better substitutes for pollution, and the output effect would still depend on which factors are intensively used in the dirty sector. Finally, we contemplated turning to numerical simulation. Even with a capital stock, however, our model could not compete with existing CGE models that consider multiple regions of the world, dozens of outputs, multiple factors, input–output matrices, and many other features. Moreover, nobody has estimated the ten elasticities needed for the four-factor model just mentioned, so simulation of this model would not obtain any additional accuracy. We still would not know the incidence of the pollution tax.

Moreover, consideration of capital is only one of many possible improvements, so it would not satisfy readers who want realistic estimates of incidence. It would not yet address effects of a carbon tax on the normal return to capital as opposed to supernormal returns, or on scarcity rents from ownership of natural resources. We do not try to address such questions; instead our goal is simply to introduce study of a new channel, namely, the effect of a carbon tax on the real net wage of high- vs. low-skilled workers.

The model has other limitations as well. First, we assume fixed labor supplies. Clearly variable labor supply would be necessary to account for actual effects on each wage rate from the deadweight loss of taxation, and to calculate efficiency effects of this tax swap to a carbon tax from the payroll tax. But those topics are well studied already. Our expressions are complicated, and adding that additional behavior to the model would make analytical solutions intractable. Yet even with fixed labor supplies, our model is fully able to focus on our intended topic, the effects on relative wage rates from firm substitution among inputs and from differences in factor intensities.

Second, we also ignore government transfers, which may accrue to the poorest members of society. Rausch et al. (2010) show that indexing of social security and other transfers can help protect those poor recipients from the way that a carbon tax might raise product prices, so the concern here is for low-skilled workers with no such protection.[18]

Third, the model is missing many other features such as imperfect competition, international trade, the export of tax burden to other countries, limited mobility of factors, the use of intermediate inputs, technology, and growth. Many such features are available in CGE models, which could provide more realistic calculations, but we have no intent of trying to compete with those models. Instead, we provide analytical expressions that demonstrate effects on relative wage rates. We use numerical illustrations to help understand the analytical expressions, not to predict actual equilibrium outcomes.

6. Numerical illustrations

Because the general model's results are complicated and sometimes difficult to sign, we now assign plausible parameter values and solve numerically for changes in wage rates and other variables. We then can change certain parameter values for a sensitivity analysis. This section provides only an illustration of plausible magnitudes in the analytical model, however, not a fully detailed numerical simulation of the pollution tax reform (particularly since we omit capital and changes in returns to capital).

We use several data sources. First, we define clean and dirty sectors by carbon intensity.[19] No industry is perfectly "clean", since every industry uses electricity and fuel as intermediate inputs – ignored here. We just separate the industries that emit the most CO_2 relative to output. The industries we put in the dirty sector are electricity generation, transportation, and petroleum refining. The clean sector is all remaining industries. Then the dirty sector represents about 6.5% of income.[20]

Next, to identify factor income shares for each sector, we use data from the 2010 Occupational Employment Statistics (OES) survey (http://www.bls.gov/data). The OES has data on employment and average wages for each of over 800 occupations, grouped by NAICS industry code.[21] We initially classify high-skilled labor to include any occupation with mean annual wage of at least $50,000. The share of the clean sector's compensation to low-skilled workers is about 48%, and the

(*footnote continued*)
because those models also do not account for cross-price elasticities that still have not been estimated. Instead, they generally assume a nested production structure that effectively sets the cross-price elasticities by default.

[18] We note that adding transfers and capital income might reduce the share of income to low-skilled labor, which might reduce the amount of tax revenue needed to protect them from loss.

[19] These initial steps follow Fullerton and Heutel (2010), but with more recent data. In 2010, total U.S. CO_2 emissions were 5706.4 million metric tons, of which 84% was from fossil fuel combustion in the electricity, transportation, and industrial sectors. The largest source of greenhouse gas emissions in the transportation sector was passenger cars, which accounted for 43% of those emissions. Among industrial sectors, the highest carbon emitter per value of output was primary metals, but that output is used by all other industries and not by consumers. The petroleum refining industry emitted the largest absolute amount of CO_2 of all the industrial sectors in 2010 (183 million metric tons), and it was the second highest carbon emitter per value of output. We include petroleum refining in our dirty sector because the burning of petroleum products such as gasoline is part of our dirty output (via the transportation sector). Data on CO_2 emissions is available from http://ghgdata.epa.gov/ghgp/main.do (the EPA's Greenhouse Gas Reporting Program) and http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html.

[20] Data on GDP by industry is available from: http://www.bea.gov/industry/gdpbyind_data.htm. The BEA uses industry definitions that are not perfectly consistent with EPA data on emissions. We add up the value added as a percentage of GDP for the broader industry categories utilities, petroleum and coal products, and transportation to get an estimate of 6.5% of GDP for the value added of our dirty industry. The utilities industry (NAICS code 22) includes electricity generation as well as natural gas distribution and water, sewer, and other systems. Because more detailed industry level data are not available, this method slightly overstates the dirty industry's share of GDP. The petroleum and coal products industry (NAICS code 324) includes petroleum refineries as well as firms that further process petroleum and coal products.

[21] For each industry, we multiply employment in each high-skilled occupation by the mean annual wage for that occupation, and take a sum to calculate total compensation to high-skilled labor. Similarly, for low-skilled labor, we take employment in each occupation times the mean wage for each, and sum.

share of the dirty sector's compensation to low-skilled workers is about 49%, indicating that the two sectors have nearly equal factor intensities. Later, we vary the $50,000 threshold; when low-skilled workers are defined as those with less than $25,000, then the dirty good is high-skill intensive.

For the clean sector this information implies $\theta_{XL}=0.485$ and $\theta_{XH}=0.515$, but for the dirty sector we also need the fraction of sales revenue attributable to pollution. Following Hassett et al. (2009) and Fullerton and Heutel (2010), we choose a price on CO_2 of $15 per metric ton.[22] The implied value of θ_{YZ} is 0.072, and the remaining 92.8% of sales revenue is paid to labor – of which 49% is paid to low-skilled labor (so $\theta_{YL}=0.459$ and $\theta_{YH}=0.469$). We define a unit of each input or output so that all initial prices are one ($w=h=p_X=p_Y=1$). Also, perfect competition and CRS implies zero profits, so initial $X=(1+\tau_H)H_X+(1+\tau_L)L_X$ and $Y=(1+\tau_H)H_Y+(1+\tau_L)L_Y+\tau_Z Z$. Defining total factor income to equal one as well means that $X+Y=1$. We can then solve for all initial factor shares and parameters shown in the top part of Table 1.

We also need numerical values for the tax rates (τ_H and τ_L), expenditure shares (α_H and α_L), the fraction of initial tax revenue returned to high-skilled labor (δ), and elasticities. First, we choose 10% as the tax rate on low-skilled labor to represent the current U.S. payroll tax, and 40% as the tax rate on high-skilled labor to represent the average of their marginal tax rates from payroll and personal income taxes.

We approximate the expenditure shares for each group of workers using data from the 2010 Consumer Expenditure Survey (CEX).[23] For initial results, we define consumer units with pre-tax income below $50,000 as our low-skilled workers and those above $50,000 as high-skilled workers. To obtain an approximate fraction of income spent on the "dirty" good, for each group of workers, we add expenditures on natural gas, electricity, home heating oil, and gasoline.[24] This procedure yields $\alpha_L=12\%$ (so 0.88 is the fraction spent on the clean good by low-skilled workers) and $\alpha_H=5\%$ (so 0.95 is the fraction spent on the clean good by high-skilled workers).[25] We assume that initial government revenue is simply distributed in proportion to each group's initial income, so $\delta=44\%$ (but this parameter has no effect on results, as seen in Eqs. (16a)–(16e)).

We use an elasticity of substitution in production for the clean sector of one, and an elasticity of substitution in utility of one (following Fullerton and Heutel, 2007, 2010). No study has estimated which factors of production are better substitutes for pollution, especially for our two factors (high-skilled and low-skilled labor). The point here is to see how much these Allen cross-price elasticities matter, so we use values ranging from –1 to 1. These then determine the own-price elasticities. We are now able to solve for the relevant magnitudes of changes from the initial equilibrium.

7. Numerical results

Table 2 shows results for relevant changes of interest, assuming the carbon tax rate increases by 10%. The different rows show results when the elasticities e_{HZ} and e_{LZ} are varied, while holding constant the value of $e_{HL}=1$ (so high-skilled and low-skilled labor are substitutes).[26] For all feasible combinations of parameters, the increase in the pollution tax always reduces pollution ($\hat{Z}<0$ in column 3), by an amount that varies with elasticities. Otherwise, the table shows each component of the overall impact on the real net wage in Eq. (20): $\hat{\omega}=\hat{p}_L-\hat{\tau}_L-\hat{p}_Q^L$.

The first term ($\hat{p}_L$ in column 4) may be slightly positive or negative, but the second term ($\hat{\tau}_L$ in column 5) always helps low-skilled labor. Interestingly, the amount of that rebate varies, because it depends on the revenue from the pollution tax increase. That revenue is small when abatement is relatively easy, so the rebate is small when *both* types of labor are good substitutes for pollution (rows 1 and 4). The final component is the effect of product prices ($-\hat{p}_Q^L$), which always reduces the real net wage. That component does not have a column in the table, because it is always the same amount. The price of the dirty good always rises by 0.72%.[27] Low-income families' spending on the dirty good as a fraction of income is more than twice that of high-income families ($\alpha_L=0.12$ and $\alpha_H=0.05$), so the amount subtracted to get their *real* net wage is more than twice as large ($\hat{p}_Q^L=\alpha_L\hat{p}_Y$ is 0.089%, while $\hat{p}_Q^H=\alpha_H\hat{p}_Y$ is 0.035%).

[22] The actual national carbon tax rate in the U.S. is zero, of course, but private firms do face some positive opportunity cost per ton of carbon emissions (from state or regional permit prices and because credits are available for voluntary carbon reductions). If we used a small positive price in our model, then the carbon share would be quite small and the effect of raising the carbon price would be quite small. Instead, we consider a hypothetical initial equilibrium with a $15/ton price, in order to discuss effects of raising that price. In 2010, U.S. GDP was $14.5 trillion, so the dirty sector is $0.943 trillion, and the value of its 4.527 billion metric tons of CO_2 emissions is $67.9 billion – accounting for 7% of the value of the dirty sector.

[23] Our simple static model has no savings or investment, but effects would be similar if investment goods were constructed from both X and Y, that is, just as clean or dirty as other spending.

[24] Because the dirty industry produces some outputs that are used as inputs in the clean sector, any definition of the dirty consumption good will not precisely reflect the dirty production sector without the use of input–output matrices. However, consumption of the dirty goods in our simplified model involves fossil fuel combustion by households and industries, and the overall fraction of income spent on the dirty good by all workers (6.5%) is close to our dirty sector's share of the economy.

[25] We use the interview portion of the Consumer Expenditure Survey public-use micro-data to allocate each consumer unit to the low-skilled or high-skilled group based on pre-tax income, and then for each group calculate the percent of income spent on natural gas, electricity, home heating oil, and gasoline. About 55% of consumer units fall into the low-skilled group when defined by pre-tax income up to $50,000.

[26] In the table, e_{HZ} and e_{LZ} can each take five different values (–1, –0.5, 0.0, +0.5, or +1), for a total of 25 combinations, but footnote 8 above notes that $e_{ij}=e_{ji}$, $e_{ii}<0$, and $e_{iH}\theta_{YH}+e_{iL}\theta_{YL}+e_{iZ}\theta_{YZ}=0$. These conditions rule out four cases where both e_{HZ} and e_{LZ} are negative (e.g. –1 and –0.5). Eight other cases are ruled out because the implied e_{ZZ} is positive. And the case with $e_{HL}=e_{HZ}=e_{LZ}=1$ is ruled out because the pollution tax does not raise additional revenue (is on the wrong side of the Laffer curve).

[27] In our data, factor intensities are nearly equal, where Case 1 above yields $\hat{p}_Y=\theta_{YZ}\hat{\tau}_Z$ (and $\theta_{YZ}=0.072$).

Table 1
Summary of parameters.

$H_Y=0.022$	$L_Y=0.027$	$\theta_{YZ}=0.072$
$H_X=0.344$	$L_X=0.412$	$\tau_H=40\%$
$\lambda_{HY}=0.060$	$\lambda_{LY}=0.062$	$\tau_L=10\%$
$\lambda_{HX}=0.940$	$\lambda_{LX}=0.938$	$\tau_Z=\$15/\text{ton}$
$\gamma_H=0.064$	$\gamma_L=0.066$	$\alpha_H=0.049$
$\theta_{XH}=0.515$	$\theta_{XL}=0.485$	$\alpha_L=0.123$
$\theta_{YH}=0.469$	$\theta_{YL}=0.459$	$\delta=0.454$

Table 2
A 10% increase in carbon tax, effects on emissions and wage rates, all in % changes.

Row	(1) e_{LZ}	(2) e_{HZ}	(3) Pollution $\hat{Z}$	(4) Factor price $\hat{p}_L$	(5) Tax rebate $\hat{\tau}_L$	(6) Low-skill wage $\hat{w}=\hat{p}_L-\hat{\tau}_L$	(7) Real net wage[a] $\hat{\omega}$	(8) Factor price $\hat{p}_H$	(9) Real net wage[b] $\hat{\psi}$
1	1	0.5	−7.899	0.011	−0.022	0.033	−0.056	−0.010	−0.045
2	1	0	−5.521	0.022	−0.047	0.069	−0.020	−0.021	−0.056
3	1	−0.5	−3.137	0.033	−0.072	0.105	0.017	−0.031	−0.066
4	0.5	1	−7.960	−0.012	−0.027	0.015	−0.074	0.011	−0.024
5	0.5	0.5	−5.591	−0.001	−0.052	0.051	−0.038	0.001	−0.034
6	0.5	0	−3.218	0.010	−0.077	0.087	−0.001	−0.010	−0.045
7	0	1	−5.641	−0.023	−0.057	0.034	−0.055	0.022	−0.013
8	0	0.5	−3.278	−0.012	−0.082	0.070	−0.019	0.011	−0.024
9	0	0	−0.910	−0.001	−0.107	0.106	0.017	0.001	−0.034
10	−0.5	1	−3.318	−0.035	−0.087	0.052	−0.037	0.033	−0.002
11	−0.5	0.5	−0.960	−0.024	−0.112	0.088	−0.001	0.022	−0.013
12	−1	1	−0.989	−0.046	−0.117	0.071	−0.018	0.044	0.008

[a] For low-skill labor, real net wage change is $\hat{\omega}=\hat{p}_L-\hat{\tau}_L-\hat{p}_Q^L$, where $\hat{p}_Q^L$ is 0.089% in all cases.
[b] For high-skill labor, $\hat{\psi}=\hat{p}_H-\hat{p}_Q^H$, where $\hat{p}_Q^H$ is 0.035% in all cases.

Because the two sectors have nearly the same labor ratios, the signs of factor price changes depend only on substitution effects (as discussed in Special Case 1 above). The gross wage for low-skilled workers (p_L) rises in the first three rows, because firms want to substitute more into low-skilled than into high-skilled labor ($e_{LZ}>e_{HZ}$). In the first row ($e_{LZ}=1$ and $e_{HZ}=0.5$), substitution away from pollution is easy, and Z falls by 7.9%. As a result, the tax hike raises relatively little revenue, and the low-skilled wage tax can only be cut by 0.022%. Those workers get a higher wage ($\hat{p}_L$is $+0.011\%$) *and* a tax cut ($\hat{\tau}_L$ is –0.022%), so their net wage rises ($\hat{w}=\hat{p}_L-\hat{\tau}_L=0.033\%$). But higher prices ($\hat{p}_Q^L=0.089\%$) still mean that their *real* net wage falls by a relatively large 0.056%.[28]

In fact, low-skill labor's real net wage falls in ten of the twelve rows of Table 2. Our decomposition can address *why* it falls. The rebate always offsets any fall in the gross wage, $\hat{p}_L$, so it always increases the net wage $\hat{w}$. But it's rarely enough to offset the effect of product prices ($\hat{p}_Q^L=0.089\%$). This result seems somewhat remarkable, since the pollution tax places some burden on high-skilled labor as well as on low-skilled labor, and yet all of the pollution tax revenue is given as a rebate just to low-skilled labor.

One of the exceptions is row 3, where low-skilled labor is *much* better than high-skilled labor as substitute for pollution ($e_{LZ}=1$ and $e_{HZ}=$–0.5), so the gross wage rises by the largest amount in the table (0.033%). Pollution falls by less than in the first two rows, so the rebate is larger (0.072%). Those sum to $\hat{w}=0.105\%$, enough to withstand the effect of higher prices ($\hat{p}_Q^L=0.089\%$). The real net wage rises by 0.017% (the difference, except for rounding). The other exception is row 9, for a different reason. In this case, both e_{LZ} and e_{HZ} are zero, so abatement is difficult. Pollution falls by the least amount in the table, so the rebate is relatively large, enough to offset higher prices.

In other words, using all new pollution tax revenue to cut the labor tax only of low-skilled workers is generally not enough in this model to offset the effect on them from higher prices of carbon-intensive goods. It might be enough if low-skilled labor is much better than high-skilled labor as a substitute for pollution and thus is in increased demand and receives a substantially higher gross wage, or if the increase in pollution tax achieves little abatement, thus raising enough more revenue for the rebate.

Table 2 also shows small changes in the high-skilled wage ($\hat{p}_H=\hat{h}$, in column 8). Through the substitution effect, the pollution tax tends to raise the high-skilled wage when $e_{HZ}>e_{LZ}$ (rows 4, 7, 8, 10, 11, and 12). It reduces that wage when $e_{LZ}>e_{HZ}$ (rows 1, 2, 3, and 6). In rows 5 and 9 where $e_{LZ}=e_{HZ}$, the substitution effect is eliminated as in Special Case 3 above, so the only effect on factor prices is from the output effect. The dirty sector is slightly low-skill intensive, so $\hat{p}_L$ is only –

[28] These changes are small in order to ensure that our linear approximation method is valid. The carbon tax rises by only 10%, where carbon is only 7.2% of the value of the dirty good (which itself is only 6.5% of GDP). Wage rates are driven primarily by the clean sector, which employs 93.5% of labor. The point is to look at *relative* changes, *i.e.* whether a tax cut (such as –0.022%) can offset higher prices (0.089%).

0.001% and $\hat{p}_H$ is 0.001%. As shown in Special Case 2 above, the tax has *no* effect on *relative* wage rates when factor intensities are the same in the two sectors and substitution parameters are equal.

The gross wage may rise or fall ($\hat{p}_H$ in column 8), but high-skilled labor gets no rebate in this tax swap. The effect of higher product prices ($\hat{p}_Q^H = 0.035\%$) nearly always swamps any positive effect on the skilled workers' wage rate, however, so their real net wage falls in all but a single case wage ($\hat{\psi}$ in column 9). In Table 2, *both* real net wage rates nearly always fall. In this model, because of excess burden, consumers lose more than the revenue from the tax, especially in cases where abatement is easy (where e_{LZ} and e_{HZ} are both positive, and revenue is small, as in rows 1 and 4).

In summary, the rebate of the entire tax to low-income families is not generally enough in this model to protect them from the effects of higher prices for electricity, heating fuel, and gasoline. This problem is even worse when factor prices also change to hurt low-skilled labor, especially where H is better than L as a substitute for pollution. Other extensions of the model that could affect these results are discussed in Section 4.

8. Further sensitivity analysis

In our analysis above, the high-skilled labor group is defined by occupations with average annual wages of at least \$50,000 per year. We now vary that threshold from \$25,000 to \$60,000, which changes the size of each group and factor intensity of each industry.[29] For low values of that threshold, the dirty sector is high-skilled intensive. We also vary the initial carbon tax rate, from \$5/ton to \$25/ton. The increase is still 10%.

Fig. 1 shows effects on real net wage rates in the case of row 7, Table 2 (where $e_{LZ}=0$ and $e_{HZ}=1$, so high-skilled labor is better as a substitute for pollution). The black lines show effects on low-skilled workers ($\hat{\omega}$), while the gray lines show effects on high-skilled workers ($\hat{\psi}$). Look first at the dashed black line showing $\hat{\omega}$ when the initial carbon tax is \$15/ton as in the previous section (so its value at the \$50,000 threshold is the result from Table 2 where $\hat{\omega} = -0.055\%$). If the threshold is only \$25,000 per year, then the more narrowly-defined low-wage group might be easier to protect using carbon tax revenue. Yet that dashed black line shows that giving that smaller group *all* of the pollution tax revenue is still not enough to protect them from harm ($\hat{\omega} = -0.13\%$).

Still in Fig. 1, the three gray lines show that the effect on the real net wage of the high-skilled group is almost always negative (even though the case in Fig. 1 is the case where high-skilled labor is better than low-skilled labor as a substitute for pollution). The effect on the high high-skilled wage is even more negative with small values of the wage threshold used to separate low-skilled from high-skilled labor. When that threshold is small, the dirty sector is high-skill intensive, and so the increased pollution tax hurts those high-skilled workers through the “output effect”.

Finally, Fig. 1 makes clear that both groups lose more when the initial carbon tax is higher (such as the two dotted lines where the initial rate is \$25/ton). Deadweight loss from the carbon tax is essentially the “cost of abatement” in this model. This DWL increases more than proportionately with the initial carbon tax rate (so the marginal cost of abatement is increasing with abatement).[30]

As an alternative, Fig. 2 shows all the same results for the case where low-skilled labor is better than high-skilled labor as a substitute for pollution ($e_{LZ}=1$ and $e_{HZ}=0$, where the value of e_{HL} remains 1 in both figures). At the \$50,000 threshold, the two dashed lines show the result in row 2 of Table 2, where both real net wage rates fall ($\hat{\omega} = -0.020\%$ and $\hat{\psi} = -0.056\%$). As shown in Fig. 2, however, a low choice of threshold makes more of a difference in this case. The figure shows three effects. First, because low-skilled labor is better than high-skilled labor as a substitute for pollution, the substitution effect tends to help low-skilled labor when the tax on pollution is raised. Second, a low threshold means that the dirty sector is H-intensive, so the output effect also helps L. Third, the low threshold means that the low-skilled group is smaller, so the use of all carbon tax revenue to cut the low-skilled labor tax rate has more effect on that labor tax rate and thus more effect on the real net wage.

This combination of circumstances represents the major caveat to our general conclusion about the difficulty of protecting low-wage workers. Fig. 2 shows that low-wage workers can experience higher real wage rates in this model, but only if (1) low-skilled labor is better than high-skilled labor as a substitute for pollution, (2) the dirty industry is high-skill intensive, and (3) the protected group is narrowly defined. Then the use of all tax revenue *can* be enough to protect this smaller set, those with the lowest wages. Other extensions discussed in Section 4 might also affect this conclusion.

For policy reasons, it is important to understand that any intended protection of low-skilled labor may not be realized. We have shown that even when the low-skilled wage increases, higher product prices mean that low-skilled labor may still bear a burden. Still, low-skilled labor in these cases could be hurt even more without the rebate.

[29] If the cutoff is \$50,000, then 70% of workers are in the low-skilled group, where they earn 54.6% of labor income. If the cutoff is \$25,000, then 23% are in that group earning 13.7% of labor income.

[30] Our model looks only at small changes, so it cannot be used to calculate *total* DWL from the pre-existing carbon tax. We choose not to calculate a measure of the *change* in these costs, for several reasons. First, any such measure would require a social welfare function to add the costs over two different groups. Second, DWL here arises only from the carbon tax. Labor supply is fixed in this simple model, and so any measure of DWL would not include labor distortions. Third, no overall measure is necessary in Fig. 1 to see that *both* groups are injured from an increase in the carbon tax. Any overall measure would therefore be negative and would become more negative with higher values of the initial carbon tax. Finally, the necessary derivations would be lengthy enough to sidetrack the paper. Efficiency effects are well-studied, and we wish here to focus on distributional effects.

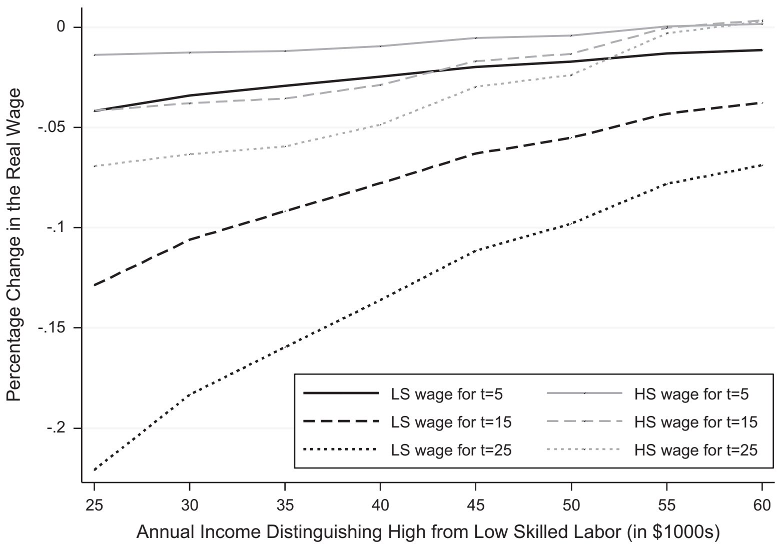

Fig. 1. Real net wage effects depend on the initial carbon tax rate and on the cutoff between high- and low-skilled income ($e_{LZ}=0$, $e_{HZ}=1$, and $e_{HL}=1$).

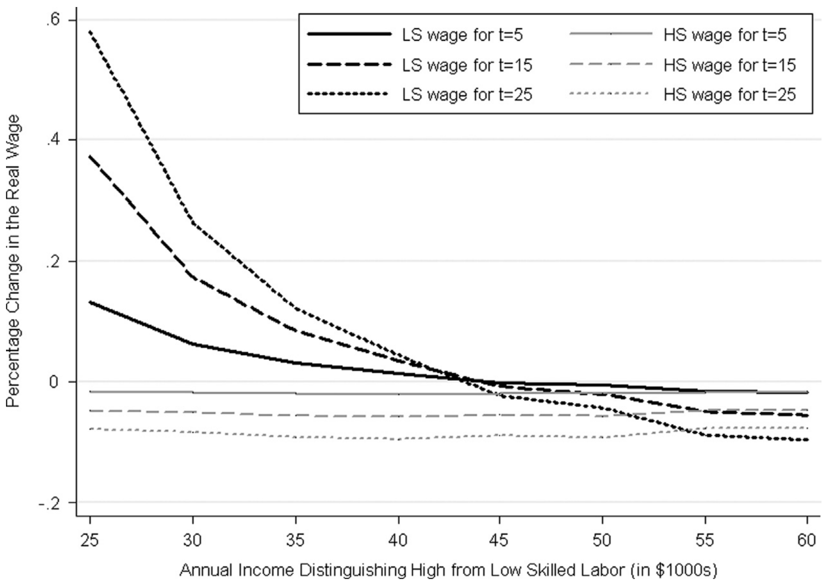

Fig. 2. Real net wage changes depend on the initial carbon tax rate and on the cutoff between high- and low-skilled income ($e_{LZ}=1$, $e_{HZ}=0$, and $e_{HL}=1$).

9. Conclusion

To evaluate different policies, it is important to understand not only efficiency costs but also distributional effects. Using pollution tax revenue to reduce pre-existing labor taxes can help protect low-income families, and that might make a pollution tax more politically viable. While the double dividend literature has focused on the efficiency side of this tax swap, this paper considers distributional effects and the circumstances under which real net wages may rise or fall. The model developed here is simple but can provide key insights into effects of the tax swap on low-skilled and high-skilled workers.

Using a general equilibrium model, we derive closed-form solutions for changes in relative wage rates, the price of the dirty good, the amount of pollution, and the labor tax cut made possible by the use of pollution tax revenue. The tax cut for low-skilled workers certainly has a positive impact on their net wage, but for three reasons this effect may not be enough to overcome the effect of higher product prices on their real net wage. First, their wage may fall if high-skilled labor is better than low-skilled labor as a substitute for pollution. Second, the low-skilled wage may fall if the dirty sector makes intensive use of that factor. And third, of course, the ability to protect low-income workers depends on how broadly that group is defined.

Our numerical calculations do not provide definitive results for the incidence of this tax swap, and other extensions would affect these results. But they do indicate what parameters need better estimation, and what values of those parameters make policy unable to offset the adverse effects of pollution taxes on low-income families.

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Appendix

Condition 2 (low-skilled labor does not spend too disproportionately on Y) Fig. A1:

$$(\sigma_U N+J)(\theta_{XH}\theta_{YL}-\theta_{XL}\theta_{YH})+\frac{1}{C_H}h\overline{H}\left(\frac{Y_H}{Y_L}-\frac{X_H}{X_L}\right)>0$$

Condition 3 (similar enough factor intensities): $\gamma_L-\gamma_H<C\sigma_X C_H/h\overline{H}(X_H/X_L-Y_H/Y_L)$

Condition 4 (different enough factor intensities):

$$\gamma_L-\gamma_H>\frac{-C\sigma_X}{(\sigma_U N+J)(\theta_{XH}\theta_{YL}-\theta_{XL}\theta_{YH})+\frac{1}{C_H}h\overline{H}(Y_H/Y_L-X_H/X_L)}$$

Condition 5 (similar enough factor intensities): $\theta_{XH}\theta_{YZ}/D_3(\gamma_L-\gamma_H)(\sigma_U N+J)\hat{\tau}_Z<-\hat{\tau}_L$.

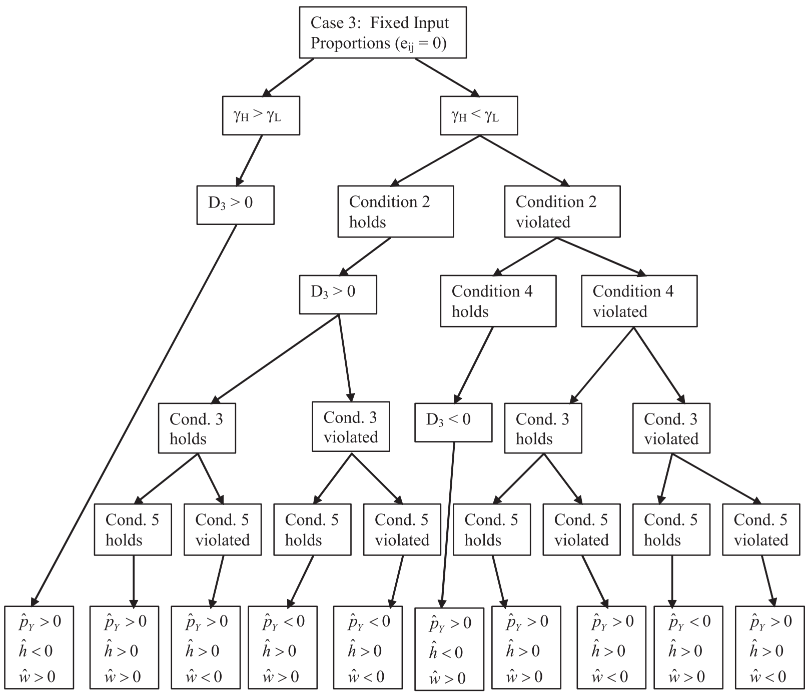

Fig. A1. Results for Special Case 3.

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