Hettich, Frank

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Frank Hettich

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Abstract

This paper analyses tax policy measures within a two sector endogenously growing economy with elastic labour supply. Pollution is modelled as a side product of physical capital stock used as a primary production factor in the final good sector. The framework allows to analyse consequences of isolated tax changes or of a revenue neutral environmental tax reform for economic growth. Although pollution does not affect directly production processes, it can be shown that a higher pollution tax or a revenue neutral environmental tax reform boosts economic growth, whereas a tax on capital, consumption or labour reduces the long term growth rate of the economy.

JEL classification: E62, Q28, O41, D62.
Keywords: Endogenous growth, environmental externalities, environmental tax reform, elastic labour supply, optimal taxation.

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†Mailing Address: Sonderforschungsbereich 178, Box D 133, D–78457 Konstanz, Germany. E-mail: frank.hettich@uni–konstanz.de

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1. Introduction

The consequences of fiscal policy for economic growth are a controversial issue. How taxes affect the long term growth rate in an economic model crucially depends on its specification.[1] This is also true for efficient instruments like a Pigouvian tax that internalizes environmental externalities. This paper concentrates on the growth effects of a higher pollution tax or of a revenue neutral environmental tax reform by incorporating aspects of public finance and environmental economics in a two sector human capital endogenous growth model. It is shown that there might exist a *double growth dividend* accompanied by a better environmental quality.

In the literature on endogenous growth with human capital it is shown that a tighter environmental policy might have a stimulating growth effect.[2] [7] Gradus & Smulders (1993) find in their basic two sector model without leisure that the optimal growth rate is independent of environmental care. Only by assuming that pollution negatively affects the efficiency in the human capital sector they detect positive growth effects in a model variant. [4] Bovenberg & Smulders (1995) model a two sector economy consisting of a consumption/capital good and a R&D sector which generates knowledge about pollution–augmenting techniques. Since better environmental quality improves factor productivity in the consumption good sector, positive growth effects of a tighter environmental policy are possible. In a pure human–capital variant of the two sector Lucas model, [6] Ewijk & Wijnbergen (1995) find positive growth effects of a tighter environmental policy also by assuming that pollution negatively affects the production process. Hence, the existing literature can only explain positive growth effects of a tighter environmental policy by assuming direct positive productivity effects – positive environmental externality in production – either in the education or in the consumption good sector.

In contrast to the existing literature it is shown in this paper that a higher pollution tax might boost long term economic growth even if direct positive productivity effects of a cleaner environment are not considered.[3] Pollution is modelled as

[1] Decisive are the assumptions concerning production technologies like substitution possibilities, the existence of spillovers or the influence of public goods, but also those concerning preferences. For a survey of the consequences of fiscal policy for growth, see e.g. [22] Xu (1994).

[2] Other contributions in different types of endogenous growth models (one sector Rebelo (AK) and Barro models) analysing the impact of environmental policy on economic growth are e.g. [7] Gradus & Smulders (1993), [10] Ligthart & Ploeg (1994).

[3] This paper is solely concerned with long term growth effects, i.e. effects along a balanced growth path. Inherent adaptation processes of the model are hence neglected. For a descrip-

an inevitable side product of the physical capital stock used in the final good production, and it is assumed to affect individuals' utility only. By means of private abatement activities pollution can be reduced without lowering production. The pollution tax lowers leisure, increases studying time and hence boosts growth. The reason is that a higher pollution tax creates the incentive for increased abatement activities by the firms. This in turn reduces the households consumption share of total output. By decreasing leisure time, households increase their marginal utility of leisure. Reduced leisure is used to increase studying time to compensate for reduced consumption which finally boosts growth. Hence, already an improvement of the environment by means of a pollution tax leads to a positive growth effect. This is the *first* growth dividend.

A tax on consumption, capital or labour income increases the demand for leisure at the expense of studying time and therefore reduces growth. These results have been already shown by [12] Lucas (1990) in a model similar to this paper, but without environment. [5] Devereux & Love (1994) and [13] Milesi–Ferretti & Roubini (1995) confirm Lucas' results in more general models, but also without environment.[4]

The consequences of an environmental tax reform where green taxes partly replace other taxes have been already analysed by [3] Bovenberg & de Mooij (1997) within a modified Barro model. They find that a tighter environmental policy may enhance growth if there exists a positive environmental externality in production or if the substitution elasticity between pollution and other input factors is rather low. Again the former effect is caused by a positive productivity effect of the environment. In the latter case, the environmental tax almost possesses the characteristics of a lump sum tax because its tax base is rather inelastic. A revenue neutral environmental tax reform would shift the tax burden away from the net return on investment toward profits and hence stimulate growth.[5]

Without the assumption of an inelastic substitution elasticity it is shown in this paper that a revenue neutral environmental tax reform yields a *second* growth

tion of transitional dynamics in two sector human capital endogenous growth models see e.g. [9] Jones et al. (1993), [14] Mulligan & Sala–i–Martin (1993), [16] Pecorino (1993), [5] Devereux & Love (1994), and [8] Hettich (1995) for a model extended by environmental aspects.

[4]Both papers assume not only human capital but also physical capital as an input factor in the studying sector. Additionally, Milesi–Ferretti & Roubini (1995) distinguish between different specification of leisure like raw time – used in this paper –, quality time, and home production.

[5]Also in a modified Barro model where the labour market is distorted by unions [15] Nielsen et al. (1995) find positive employment effects but no positive growth effects for an environmental tax reform.

dividend. A higher pollution tax stimulates growth, and by using the additional tax revenue for cutting non–environmental taxes an additional positive growth effects arises. This is because all non–environmental taxes reduce growth, thus lowering one of those tax rates yield a positive growth effect. In the last few years an academic debate emerged on environmental taxes. It is suggested that they allow for a double dividend.[6] The second dividend can be seen in analogy to the second growth dividend since both dividends arise from the use of the additional revenue.

The results concerning both growth dividends are driven by the consideration of endogenous labour supply. This aspect has been neglected so far in the literature of endogenous growth in connection with environmental economics, despite its strong influence on the results. In endogenous growth models with human capital the growth rate is finally determined in the education sector, i.e. this sector is the engine of growth. Via the households' leisure–studying choice, different taxes affect the education sector positively or negatively, therefore endogenous labour supply is important to consider.

The paper is structured as follows: In section 2 the general model is laid out and both market and central planner solutions are derived. Optimal tax rates of all taxes in a first best setting are derived in section 3.1. Section 3.2 determines the effects of isolated tax and parameter changes on growth, both for the case of elastic and inelastic labour supply, and section 3.3 finally derives growth effects of a revenue neutral tax reform. Section 4 summarizes the results and concludes.

2. The Analytical Framework

We assume a two sector endogenous growth model of a closed economy. It is basically the Uzawa–Lucas–Model extended by elastic labour supply and by a technological environmental externality.[7] The first sector produces one universal good, which can be used for consumption, abatement activities and investment in the physical capital stock. The second sector is the education sector where human capital is accumulated. In the presumed economy growth in output is sustainable

[6] The first dividend is the reduced environmental damage, the second dividend is reaped by using the revenue of the pollution tax for cutting other already existing distortionary taxes, thus, reducing the deadweight loss of taxation. For a survey concerning a double dividend in static frameworks, see [2] Bovenberg (1997).

[7] See [7] Gradus & Smulders (1993), for the same specification of the environmental externality.

in a environmental sense, because it is consistent with a fixed level of pollution.

2.1. Technology

In the first sector, the final good Y is produced with a Cobb–Douglas technology that possesses constant returns to scale with respect to physical capital K and effective labour (uH) but diminishing returns to factors separately:

$$Y_t = A\ K_t^{\alpha}\left(u_t H_t\right)^{1-\alpha} \tag{2.1}$$

Effective labour is defined as the product of u – the fraction of time that is devoted to production of the final good –, and human capital H. α and $1-\alpha$ $(0<\alpha<1)$ are the exogenous shares of physical capital and effective labour, respectively, and A reflects the exogenously given level of the technology. Both inputs H and K can be accumulated infinitively. Therefore, falling marginal products to one factor can be avoided and unlimited growth is in principle possible. The flow resource constraint of the economy is given by:[8]

$$Y_t = C_t + \dot{K}_t + Z_t + \delta_K K \tag{2.2}$$

Final output Y can be used either for consumption C, for net investment in the physical capital stock $\dot{K}$, for private abatement activities Z, or to prevent current physical capital stock from depreciation $\delta_K K$, $(\delta_K \geqslant 0)$.

In the education sector, human capital is produced with a constant returns to scale technology which utilizes human capital whereas physical capital is negligible:[9]

$$\dot{H}_t = \left(Bv_t - \delta_H\right) H_t \tag{2.3}$$

B (>0) is the exogenous studying productivity parameter, v is the fraction of time devoted to education, and δ_H $(\geqslant 0)$ is the depreciation rate of human capital. The maximum growth rate of human capital is given by $B-\delta_H$, for $v=1$ where the whole time budget is devoted to studying.

The capital stock K used in production causes a negative environmental externality as a side product. Pollution is modelled as an 'output' not as an input

[8] A variable with a dot denotes the derivative with respect to time while a variable with a hat stands for growth rate and a variable with a subscript describes the partial derivative.

[9] This technology is studied by [21] Uzawa (1965) and [11] Lucas (1988).

factor.[10] The externality is assumed to affect individual's utility only, but does not harm the production processes, i.e. there are no positive spillover of a better environment to production of goods or human capital. Of course it is conceivable pollution directly affects the productivity in the final good or the education sector, an aspect not being analysed in this paper. Aggregated pollution P is a public 'bad' which can be reduced by means of private abatement activities Z which consume a part of output, in line with the flow resource constraint (2.2). Both P and Z are modelled as flow quantities. This simplification is justified as long as we are solely interested in results along a balanced growth path. There, qualitative results do not change, if a stock rather than a flow determines the external damage. If Z increases, the whole physical capital stock pollutes less, no matter if old or new. One can think of some end of pipe technology, e.g. filters, being used up within one period. Therefore, abatement activities have to be launched in each period again. The net pollution function P has the functional form:

$$P_t = \left(\frac{K_t}{Z_t}\right)^{\chi} \tag{2.4}$$

where χ (> 0) is the exogenous elasticity of P with respect to $\frac{K}{Z}$ and $P_K > 0$ and $P_Z < 0$.

2.2. Households

We assume identical, atomistic agents with perfect foresight over an infinite time horizon. The instantaneous utility function is additively separable in consumption C, leisure l, and net pollution P:[11]

$$U_t = \log C_t + \eta_l \log l_t - \eta_P P_t \tag{2.5}$$

The exogenous parameters η_l (> 0) and η_P (> 0) represent the weight of leisure and pollution in utility. $U_C > 0, U_{CC} < 0, U_l > 0, U_{ll} < 0, U_P < 0$ and $U_{PP} = 0$.

[10] For other literature where pollution is modelled as an output factor, see e.g. [17] Van der Ploeg & Withagen (1991), [7] Gradus & Smulders (1993) and [10] Ligthart & Ploeg (1994). For pollution as an input factor see e.g. [15] Nielsen et al. (1995) and [3] Bovenberg & de Mooij (1997). Both modelling approaches are equivalent, see [19] Siebert et al. (1980).

[11] Preferences must be restricted to ensure that leisure and all other time allocations are constant along a balanced growth path. For a discussion, see [18] Rebelo (1991).
Leisure is modelled as raw time. For other specifications, like quality time or home production, see e.g. [13] Milesi–Ferretti & Roubini (1995).
For simplicity, it is assumed that U is linear in P. However, the qualitative results do not change if U_{PP} is larger or smaller than zero.

Economic agents allocate their unit time budget in every period between leisure l, production time u, and studying time v.[12] They rent human and physical capital to firms. Consumption and the allocation of time are chosen in order to maximise life time utility, given by the discounted integral of instantaneous utility:

$$U_0 = \int_{t=0}^{\infty} \left(\log C_t + \eta_l \log l_t - \eta_P P_t\right) e^{-\rho t} dt \tag{2.6}$$

subject to the human capital accumulation constraint (2.3) and the flow budget constraint

$$\left(1 - \tau_t^K\right) r_t K_t + \left(1 - \tau_t^H\right) w_t \left(u_t H_t\right) + L_t = \left(1 + \tau_t^C\right) C_t + \dot{K}_t + \delta_K K \tag{2.7}$$

ρ is the exogenous rate of time preference. w_t, and r_t, are the gross–of–tax returns of effective labour, and physical capital. $\tau_t^C, \tau_t^H, \tau_t^K$ are and the tax rates on consumption, labour income, and capital income, respectively, and L is a lump sum transfer[13] of the government. The left hand side of equation (2.7) represents the different sources of income, the right hand side the uses of income. Since pollution is a public 'bad' economic agents ignore it in their individual maximisation problem.

2.3. Firms

The economy consists of a large number of identical and competitive firms. They rent capital and hire effective labour from the households at the interest rate r and the wage rate w. They use these input factors to produce final goods with the technology described by equation (2.1). Firms must pay a pollution tax τ^P according to their net pollution P. The level of pollution and hence the amount of pollution tax payment depends on the capital–labour–ratio as well as on the abatement level Z. Abatement is assumed to be a private good, which enables firms in principle to increase output without causing more pollution.[14] In a model where abatement activities are not available the capital income tax would serve as an adequate pollution tax, because there would be a direct relation between

[12] Allocation of time: $(1 = l + u + v)$

[13] In section 3.2 it is assumed that the tax revenue is redistributed in a lump sum fashion.

[14] However, e.g. [10] Ligthart & Ploeg (1994) and [15] Nielsen et al. (1995) regard abatement as a public good.

the physical capital stock and pollution, and gross pollution would be equal to net pollution.

Cash flow π in every period is given by:

$$\pi_t = Y_t - w_t (u_t H_t) - Z_t - \tau_t^P P_t - I_t, \tag{2.8}$$

where $I = \dot{K}$. Firms are assumed to maximise their market value V_0, which is equal to the present value of future cash flows to the firms owners:

$$V_0 = \int_0^\infty \left[Y_t - w_t (u_t H_t) - Z_t - \tau_t^P P_t - I_t\right] \exp\left[-\int_0^t r_s ds\right] dt \tag{2.9}$$

The first order conditions of the maximisation problem are given by:

$$r_t = \alpha A \left(\frac{K_t}{u_t H_t}\right)^{\alpha-1} - \frac{Z_t}{K_t} \tag{2.10}$$

$$w_t = (1-\alpha) A \left(\frac{K_t}{u_t H_t}\right)^{\alpha} \tag{2.11}$$

$$\frac{\tau_t^P}{K_t} = \chi^{-1} \left(\frac{Z_t}{K_t}\right)^{1+\chi} \tag{2.12}$$

Firms hire effective labour up to the point at which marginal product equals its marginal costs. They rent physical capital up to the point where its marginal costs equates marginal product of capital minus marginal costs of capital, which in turn is determined by the pollution tax in equation (2.12). Equation (2.12) in turn shows a relation between the pollution tax normalized by the capital stock and environmental quality. Without a pollution tax $\left(\tau^P = 0\right)$, firms would neglect the negative side product of physical capital in the production process and abatement activities would be zero.

2.4. Government

The government is introduced in a minimal fashion, its task is solely to correct the market failure caused by the environmental externality. At this stage we assume no real government spending, all revenue are transferred lump sum to households. When we analyse growth effects of a revenue neutral environmental tax reform in section 3.3, we extend the role of the state and impose an exogenously given government revenue requirement, which has to be financed solely by taxing consumption, labour, capital, or pollution, because the government does not issue public debt.

2.5. The Market Solution

Agents maximise life time utility (2.6), choosing the path of C, H, K, u, and v subject to the human capital accumulation constraint (2.3) and the flow budget constraint (2.7), given the time paths of r, w, and $\tau^C, \tau^H, \tau^K, \tau^P$. After eliminating the shadow prices for physical and human capital and replacing r and w by equation (2.10) and (2.11) the first order conditions are given by the following equations:[15]

$$\frac{\eta_L C}{l} = \frac{\left(1-\tau^H\right)}{\left(1+\tau^C\right)}\left(1-\alpha\right) A \left(\frac{K}{uH}\right)^{\alpha} H \tag{2.13}$$

$$\hat{C} = \left(1-\tau^K\right)\left[\alpha A \left(\frac{K}{uH}\right)^{\alpha-1} - \frac{Z}{K}\right] - \delta_K - \rho \tag{2.14}$$

$$\hat{H} + \hat{l} = B\left(u+v\right) - \delta_H - \rho \tag{2.15}$$

$$\hat{K} = A\left(\frac{K}{uH}\right)^{\alpha-1} - \frac{C}{K} - \frac{Z}{K} - \delta_K \tag{2.16}$$

$$\hat{H} = Bv - \delta_H \tag{2.17}$$

and by equation (2.12) which determines the ratio $\frac{Z}{K}$.

Equation (2.13) equates the marginal rate of substitution between consumption and leisure to the real wage, adjusted for consumption and labour taxes. Equations (2.14) and (2.15) are the Euler conditions determining the optimal accumulation of physical and human capital. Equations (2.16) and (2.17) are the resource constraints of the economy and the human capital accumulation constraint, respectively.

It is obvious that all taxes have effects on the economy. The consumption and labour taxes create a wedge between the marginal rate of substitution of consumption for leisure, see equation (2.13). Both, the capital and the pollution tax affect the intertemporal incentive to invest in physical capital, described in equation (2.14) in connection with (2.12).

2.6. The Central Planner Solution

In contrast to a market solution, a central planner who maximises the utility of the representative economic agent takes the negative side effects of production

[15] In the following time indices of variables are neglected, where unnecessary.

into account. The central planner maximises life time utility (2.6) by choosing the time path of C, H, K, Z, u, and v subject to the flow resource constraint of the economy (2.2) and the human capital accumulation constraint (2.3). After the elimination of the shadow prices, the first order conditions of the central planner solution are given by equations (2.18) – (2.23).

$$\left(\frac{Z}{K}\right)^{1+\chi} = \eta_P \chi \frac{C}{K} \tag{2.18}$$

$$\frac{\eta_L C}{l} = (1-\alpha) A \left(\frac{K}{uH}\right)^{\alpha} H \tag{2.19}$$

$$\hat{C} = \alpha A \left(\frac{K}{uH}\right)^{\alpha-1} - \frac{Z}{K} - \delta_K - \rho \tag{2.20}$$

$$\hat{H} + \hat{l} = B(u+v) - \delta_H - \rho \tag{2.21}$$

$$\hat{K} = A \left(\frac{K}{uH}\right)^{\alpha-1} - \frac{C}{K} - \frac{Z}{K} - \delta_K \tag{2.22}$$

$$\hat{H} = Bv - \delta_H \tag{2.23}$$

Neglecting the consumption, labour, and capital tax, the central planner solution differs from the market solution only in equation (2.18). Equation (2.18) shows that for an optimal solution, marginal utility of consumption and pollution must be equalised. If we replace $A\ [K/(uH)]^{\alpha-1}$ by $\frac{Y}{K}$ in the first Euler condition (2.20), it reduces to a more familiar expression:

$$\hat{C} = \alpha Y/K - Z/K - \delta_K - \rho \tag{2.24}$$

This condition is also known as the Keynes–Ramsey–Rule describing the optimal consumption path over time. The right hand side consists of the private marginal product of physical capital, corrected by the term $\frac{Z}{K}$, the depreciation rate of the physical capital stock and the rate of time preference. There is a wedge between private and social return to physical capital. The first two terms can be seen as the social return of physical capital, where solely $\frac{Z}{K}$ corresponds to the marginal damage of the physical capital.

The equilibrium in a decentralised economy without government intervention is not Pareto optimal. Because of the pure public 'bad' character of pollution, economic agents ignore the negative environmental effects arising from the use of physical capital in production: Private marginal return of physical capital is higher than its social return. The government can in principle correct the market failure and internalize the externality by raising private costs up to the level of social costs by means of efficient instruments such as Pigouvian taxes or auctioned permits.[16] Equation (2.12) shows that the ratio $\frac{Z}{K}$ in the market solution is solely determined by the pollution tax. For example, if τ^P would be zero, $\frac{Z}{K}$ would be zero as well. In that case the negative externality is totally neglected and the marginal productivity of private physical capital is therefore too low.

Taking into account the negative externality, the private marginal product of physical capital must be higher in order to attain the same growth rate of consumption than without this externality. Consumption grows, remains constant, or declines if the corrected private marginal product of physical capital is larger, equal, or smaller than the sum of the rate of depreciation δ_K and the rate of time preference ρ.

In the following we derive in section 3.1 the optimal tax rates of all taxes in a first best setting. Section 3.2 determines the effects of isolated tax and parameter changes on growth, both for the case of elastic and inelastic labour supply, and section 3.3 finally derives growth effects of a revenue neutral tax reform.

3. Balanced Growth Path Results

On a balanced growth path the variables C, H, K, Y, Z grow at the same constant rate g, whereas l, u, v are constant over time.[17]

$$\begin{aligned} g &\equiv \dot{C}/C = \dot{H}/H = \dot{K}/K = \dot{Y}/Y = \dot{Z}/Z \\ 0 &= \dot{l} = \dot{u} = \dot{v} \end{aligned} \tag{3.1}$$

Because of condition (3.1), the ratios $\frac{C}{K}, \frac{K}{H}$ or $\frac{Z}{K}$ are constant, and therefore, net pollution P is constant on a balanced growth path as well. A constant level of P is in accord with sustainable environmental development.[18] If one tax rate is greater than zero, the lump sum transfers L growth with the rate g as well.

[16] Both instruments are appropriate to reach a first best solution, see e.g. [1] Baumol & Oates (1988), part I.

[17] For a formal proof, see section A.1 in the appendix.

[18] For a survey how sustainable development can be achieved within endogenous growth models, see [20] Smulders (1995).

3.1. Optimal Tax Rates

To figure out first best tax rates, we compare the first order conditions of the market solution, equations (2.12) – (2.14) with the corresponding first order conditions of the central planner solution, equations (2.18) – (2.20). By comparing (2.12) with (2.18) we can compute the optimal pollution tax rule:

$$\tau_t^{P^{opt}} = K_t \eta_P \left(\frac{C_t}{K_t} \right)^{CPS} \tag{3.2}$$

The optimal environmental tax $\tau^{P^{opt}}$ must be equal to the product of the current physical capital stock times the weight of pollution in the utility function η_P times the optimal consumption–capital ratio of the central planner solution denoted by the superscript ^{CPS}. Ratio $\frac{C}{K}$ is constant along a balanced growth path and η_P is a parameter. But K increases over time. For that reason the Pigouvian tax rate must increase over time with the growth rate of the economy. This results becomes intuitive by remembering that P must be constant along a balanced growth path. To keep the level of P constant, the pollution tax must rise over time, because the physical capital stock, which is responsible for the pollution, accumulates over time. Firms only increase abatement activities over time if they have the incentive via an increasing pollution tax. For further analysis it is useful to separate trend and level of the pollution tax. Therefore we normalize it by the physical capital stock and define $\tilde{\tau}^P \equiv \tau^P / K$, which is constant along a balanced growth path.

Additionally, comparing (2.13) with (2.19) and (2.14) with (2.20) we see that for tax rates of consumption, labour, and capital equal to zero a first best solution is attained. Because pollution is the only distortion in the economy, a first best solution in a decentralised economy is reached solely by setting the Pigouvian according to the taxation rule (3.2). Later on we will expand this analysis by assuming an exogenously given government budget constraint which must be financed by tax revenue.

However, there is a special case: If $\tau^C = -\tau^H$, the tax rates cancel out in equation (2.13). Considering the whole time horizon, the consumption tax base equals the tax bases of labour and the returns of the physical capital stock. So basically a consumption tax corresponds to a equivalent labour income tax plus a tax on the initial capital stock. Obviously the magnitude of the consumption tax base is larger than that of the labour income tax. By taxing consumption and subsidising labour according to the mentioned rule, the government could realize a lump sum tax. This tax–subsidy–combination implies a tax on the initial physical capital endowment which is assumed to be exogenously, inelastically given and therefore constitutes the ideal tax base for a lump sum tax. In the following we assume no subsidies and therefore leave out the possibility of a lump sum taxation.

3.2. The Effects of Isolated Tax Changes on Growth

In this section we analyse the long term consequences of isolated tax changes for economic growth. In addition, we show how parameter variations affect growth. On the balanced growth path, the differential equations of the market solution (2.14) – (2.17), can be rewritten by using equation (2.12) and condition (3.1) to:

$$g = \overbrace{\left(1-\tau^K\right)\left[\alpha A\left(\frac{K}{uH}\right)^{\alpha-1} - \left(\chi\bar{\tau}^P\right)^{1/(1+\chi)}\right] - \delta_K}^{\equiv R} - \rho \tag{3.3}$$

$$g = B\left(u+v\right) - \delta_H - \rho \tag{3.4}$$

$$g = A\left(\frac{K}{uH}\right)^{\alpha-1} - \frac{C}{K} - \left(\chi\bar{\tau}^P\right)^{1/(1+\chi)} - \delta_K \tag{3.5}$$

$$g = Bv - \delta_H \tag{3.6}$$

whereas equation (2.13) is unchanged. For further analysis it is useful to define R as the real marginal product of capital net of tax.

By using the first order conditions along a balanced growth path (2.13) and (3.3) – (3.6) we can implicitly define the growth rate by the following function N.

$$N \equiv 0 = B - g - \delta_H - \rho + \left[\frac{1+\tau^C}{1-\tau^H}\frac{\eta_l\rho}{1-\alpha}\right] \left[\frac{(\alpha-1)\left(1-\tau^K\right)\left(\chi\bar{\tau}^P\right)^{1/(1+\chi)} + \left[\alpha\left(1-\tau^K\right)-1\right]\left(g+\delta_K\right) - \rho}{g+\delta_K+\rho+\left(1-\tau^K\right)\left(\chi\bar{\tau}^P\right)^{1/(1+\chi)}}\right] \tag{3.7}$$

Apart from the endogenous variable g, the reduced form N consists solely of exogenous parameters and tax rates.[19] By using the implicit function rule we can derive the partial derivatives of g. Signs of the partial derivatives are summarised in table 3.1.[20]

[19] Solving explicitly the second order function of g is very toilsome and not appropriate to sign the partial derivatives $\frac{\partial g}{\partial *}$.

[20] The complete derivatives are shown in section A.2 in the appendix.

g with respect to	τ^C	τ^H	τ^K	$\bar{\tau}^P$	α	A	B	η_l	η_P	ρ	δ_H	δ_K
sign	$-$	$-$	$-$	$+$	$-$	0	$+$	$-$	0	$-$	$-$	?

Table 3.1: Partial derivatives $\frac{\partial g}{\partial *}$ of the reduced form

Whereas a higher tax on consumption, labour or capital *reduces* the long term growth rate, a higher pollution tax *boosts,* ceteris paribus, economic growth. For explanation we also derive the reduced form of u and $\frac{K}{H}$. Inserting equation (3.6) in (3.4) shows that the fraction of total available time devoted to production u is independent of any tax rates:[21]

$$u = \frac{\rho}{B} \tag{3.8}$$

The implicit form of the ratio $\frac{K}{H}$ and how this ratio is affected by tax rates is derived in the appendix A.3. Because all taxes affect economic growth, it is clear from equation (3.4) or (3.6) that all taxes also affect the leisure/studying choice l/v. Since the education sector is the engine of growth obviously all changes in v finally affect the long term growth rate.[22] A higher tax on consumption, labour, or capital increases leisure, whereas a higher pollution tax decrease leisure.

By means of the first order conditions (2.13) and (3.3) – (3.6), the reduced form of u (3.8) and results of (A.13), it can be shown through which channels taxes affect long term economic growth:

- Due to a higher labour income tax τ^H final good production becomes more capital intensive and raises the capital/labour ratio $\frac{K}{uH}$, where ratio $\frac{Z}{K}$ is solely determined by the normalized pollution tax and hence unchanged. From (3.3) we see that this reduce net real interest rate of capital R which lowers growth. In addition, from equations (2.10) and (2.11) we know that a higher capital/labour ratio lowers the gross return to capital r and increases wage rate w, respectively.

- Because a consumption tax basically consists of an income tax and a lump sum tax (see page 13) it has the same effects as an income tax.

[21] Furthermore, from equation (3.8) it can be stated that $B \geqslant \rho$ is a necessary condition for stability, because total available time is normalized to unity, hence u must be smaller than 1.

[22] According to the constant returns to scale in the final good sector, both capital stocks has to grow with the same rate along a balanced growth path. However, the growth rate of human capital stock is determined in the education sector. Therefore, human capital is the engine of growth in the Uzawa–Lucas model.

- A higher capital income tax τ^K reduces the net real interest rate R for a given capital/labour ratio $\frac{K}{uH}$ and a given abatement/capital ratio $\frac{Z}{K}$. From equation (3.3) we know that this single effect reduces growth. Again the ratio $\frac{Z}{K}$ is unchanged, but due to the capital tax final good production becomes more human capital intensive and ratio $\frac{K}{uH}$ decreases. Hence ceteris paribus the *gross* real interest rate increases. This has a positive effect on growth (see equation (3.3)). Why the negative growth effect dominates the positive can be explained by considering the household decision: An increased capital income tax rises the consumption share of total output. Households increase leisure l to lower their marginal utility of leisure and reduce their studying time v which lowers output growth. However, a reduction of labour time u would reduce output only temporarily and is therefore not appropriate to counteract the increased consumption share of total output permanently. From equation (3.6) it can be seen that a lower v harms growth.

- A higher pollution tax reduces the capital/labour ratio $\frac{K}{uH}$, because the dirty input factor K is substituted by the clean input factor H. Ceteris paribus, net real interest rate R increases (see equation (3.3)), and therefore boosts growth. But there is also an effect in the opposite direction: A higher pollution tax increases the ratio $\frac{Z}{K}$, which reduces R and lowers growth. In contrast to a capital tax a higher pollution tax reduces the households consumption share of total output. Due to the increased pollution tax, firms increase their abatement activities, which reduces final output net of abatement at the expense of households consumption. Households increase their marginal utility of leisure by reducing leisure time. At the same time they increase studying time to counteract reduced consumption. From equation (3.6) it can be seen that a higher v enhances growth. This growth stimulating effect is the first growth dividend accompanied by a better environmental quality.

The negative growth effects of taxes on capital income, labour income and consumption have been already shown by [5] Devereux & Love (1994) in a more general model version.[23] However they do not consider an environmental externality. In the following it is explained how certain parameter changes affect economic growth:

[23] In this model not only human capital but also physical capital is an input factor in the studying sector.

- A higher studying efficiency parameter B increases the productivity of the education sector. Increased human capital accumulation leads to a higher growth rate.

- A higher depreciation rate of human capital stock works exactly in the opposite direction. It reduces the productivity of human capital accumulation and lowers growth.

- In case of a higher η_l, individuals value leisure compared to consumption and pollution relatively higher, therefore they reduce v, while holding u constant – see equation (3.8). A stronger preference for leisure increases voluntary unemployment and reduces long term growth.

- When ρ increases, individuals value future utility less and consumption rises at the expense of capital accumulation. As a consequence, both time devoted to production – see equation (3.8) – and time spent on studying is reduced. Leisure increases which in turn lowers growth.

- A change in A does not affect long term growth because it does not change permanently the productivity of the final good sector.

- A change of η_P does not affect long term growth as long as the pollution tax is not adjusted to this change – an optimal pollution tax is a positive function of η_P. The reason is that the public 'bad' pollution is ignored in the individual maximisation problem.

- Finally, the influence of δ_K can not be signed.

It is important to note that welfare maximisation is not equivalent to growth maximisation. As shown in section 3.1, a Pareto optimum is reached for capital, consumption, labour taxes equal to zero and for the pollution tax scheme described by condition (3.2). Starting from a suboptimal pollution level, a tighter environmental policy improves environmental quality and step by step corrects the distorted leisure/studying time decision, thus reducing voluntary unemployment and boosting economic growth. Both effects lead to higher welfare W as long as the pollution tax is below the Pigouvian level. If the pollution tax is above the Pigouvian level, a tighter environmental policy would still increase environmental quality and boost growth further but decrease welfare, because growth rises at the expense of leisure, and leisure would be at a suboptimal low level. The relation

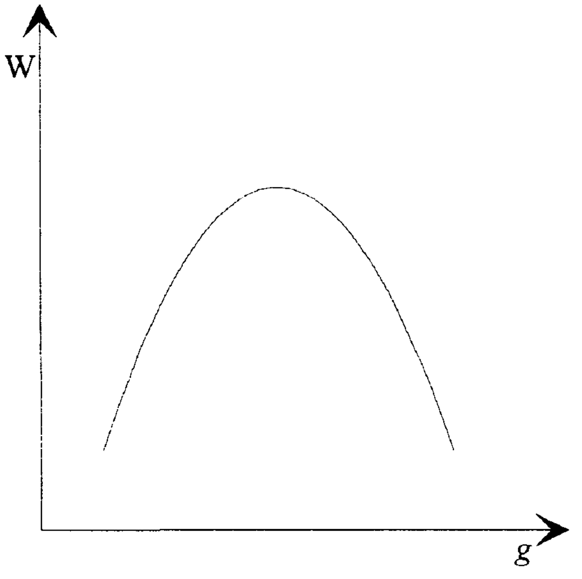

Figure 3.1: Relation between welfare and growth

between welfare and growth is illustrated in figure 3.1 in a stylized way.[24] For the pollution tax equal to the Pigouvian tax the schedule is maximal. This is equivalent to the central planner solution.

Before we proceed our analysis by deriving the growth effects of an environmental tax reform we show the growth effects of isolated tax changes in a model with inelastic labour supply. This is just a special case of the former setup and can be demonstrated by setting η_l equal to zero. Function N (3.7) can now be solved for g explicitly.

$$g = B - \rho - \delta_H \tag{3.9}$$

which corresponds to equation (3.4) since $u + v = 1$.[25] By use of equation (3.6) and (3.9) we get the familiar result that $u = \frac{\rho}{B}$, which is identical to equation (3.8). It can be seen that all taxes neither affect long term economic growth nor the fraction of time devoted to production. Studying productivity parameter B influences growth positively, the rate of time preference ρ and the depreciation rate of human capital stock δ_H negatively. In such a setting, taxes on consumption

[24] The actual shape of the graph depends on the parameter specification. However, the graph has always only one maximum.

[25] Without leisure the unit–time–budget reduces to $1 = u + v$.

or labour posses even the characteristics of a lump sum tax since they not affect the first order conditions at all. Distortions created by a pollution or capital tax does not affect long term economic growth. But due to a higher tax on pollution or capital, final good production becomes more labour intensive, reflected by a reduced capital/labour ratio $\frac{K}{uH}$. Ceteris paribus, net real interest rate R increases (see equation (3.3)), and hence boosts growth. But there is also an effect in the opposite direction. A higher pollution tax increases the ratio $\frac{Z}{K}$, a higher capital tax reduces $\left(1-\tau^K\right)$, for a given capital/labour ratio this lowers R and affects growth negatively. The positive and negative growth effects neutralize each other such that R is unchanged. The non–interference of long term economic growth due to a change of the pollution tax replicates the result of [7] Gradus & Smulders (1993). For a central planned economy they have shown by varying the weight factor of pollution in the utility function that environmental care does not influence optimal long term growth. Here we get the same result in a similar setup for a decentralised economy by explicitly modelling households and firms decisions. This digression shows how crucially the results in endogenous growth models depend not only on the assumptions concerning production technologies but also for those concerning the utility function.

3.3. Growth Effects of a Revenue Neutral Tax Reform

In the preceding section we analysed isolated consequences of various taxes for economic growth. We now assume that the government's task is to provide a public good which must be supplied in a certain proportion to the physical capital stock. One can think of some kind of infrastructure which is required as a complement to the current stock of physical capital in the economy. Since the physical capital stock grows over time, government revenue must grow with the same rate to keep the level of the public good constant. Government revenue can be financed by taxes on consumption, capital, labour or pollution. By dividing the flow government constraint by K we yield

$$\frac{G}{K} \equiv \bar{G} = \tau^C \frac{C}{K} + \tau^H \left(\frac{K}{uH}\right)^{-1} w + \tau^K r + \bar{\tau}^P P \tag{3.10}$$

$\bar{G}$ can be directly regarded as the public good, which must be constant over time. The public good has not been modelled in the former setup. Formally this could be done by adding an additive term to the production function. This would be the easiest way, since it does not change the first order conditions of the market solution. Furthermore, for simplicity it is assumed that the government automatically supplies a constant amount – which is not necessarily the optimal amount – of the public good. In addition to the growth effects of every single tax, analysed in the previous section 3.2 we must know whether a tax rate change increases the government revenue or not. To show this, in (3.10) we replace the ratios $\frac{C}{K}$, $\frac{K}{uH}$, pollution P, the wage rate w and interest rate r by the first order conditions such that $\bar{G}$ is solely a function of parameters, tax rates and g. This is done in the appendix A.4. It is shown that $\frac{\partial \bar{L}}{\partial \tau^P} > 0$, whereas $\frac{\partial \bar{L}}{\partial \tau^C}, \frac{\partial \bar{L}}{\partial \tau^H}, \frac{\partial \bar{L}}{\partial \tau^K}$ can not be signed. Hence, a higher pollution unambiguously raises ceteris paribus government revenue. A revenue neutral tax reform implies that $\bar{G}$ is unchanged. For analysing the growth effects of a revenue neutral environmental tax reform, where a consumption, or capital, or labour tax can be replaced by a pollution tax it is therefore necessary to distinguish two cases:

1. If $\frac{\partial \bar{L}}{\partial \tau^C}, \frac{\partial \bar{L}}{\partial \tau^H}, \frac{\partial \bar{L}}{\partial \tau^K} > 0$ means that all tax measures available to government increase the government revenue. In that case, a revenue neutral environmental tax reform would improve environmental quality and enhance growth for two reasons: An increased pollution tax will boost growth, at the same time due to increased tax revenue from the pollution tax other taxes could be reduced – holding the level of $\bar{G}$ constant – which enhance growth further.

2. $\frac{\partial \bar{L}}{\partial \tau^C}, \frac{\partial \bar{L}}{\partial \tau^H}, \frac{\partial \bar{L}}{\partial \tau^K} < 0$ implies that the government is confronted with the falling branch of the Laffer–curve in case of non–environmental taxes. Already a reduction of one of those tax rates would boost growth and enhance government revenue. A higher pollution tax would increase the revenue in addition. Tax revenue in excess of $\bar{G}$ could be transferred lump sum to households. Again the reform would have a stimulating growth effect for two reasons: The increased pollution tax and the reduced non–environmental tax would stimulate growth. However, the case of a falling Laffer curve seems to be unlikely for all tax rates of non–environmental taxes. For small tax rates the Laffer–curve should be positive. A rational government would choose the Laffer–efficient part of the Laffer–curve i.e. the positive branch since it gets the same revenue with lower tax rates and a higher growth rate. Hence, by assuming a rational government we can rule out the case of the falling branch of the Laffer–curve.

This section has been shown that a revenue neutral environmental tax reform, where non–environmental taxes are substituted by a pollution tax is accompanied with a double growth dividend.

4. Conclusion

We have investigated the interactions between endogenous growth, environmental economics and public finance in a decentralised economy. We showed that without government intervention the decentralised outcome is inefficient. There is too much pollution, too little abatement, and final good production is too capital intensive. The government could in principle reach a first best solution by setting the optimal pollution tax according to the derived taxation rule and by setting all other taxes equal to zero. The optimal pollution tax must rise over time because the pollution–causing input factor K accumulates over time. Firms are willing to increase their abatement activities, which is necessary to keep the level of pollution constant, by accommodating to an increasing pollution tax.

If we allow subsidies, it was shown that for $\tau^C = -\tau^H$ there is a possibility for the government to generate lump sum revenue. A consumption tax is equivalent to a labour income tax plus a tax on the initial capital stock. By taxing consumption and subsidising labour according to the mentioned rule, the government effectively taxes the initial physical capital stock which is assumed to be exogenously, inelastically given. Therefore the tax base is totally inelastic and this tax–subsidy–combination is a lump sum tax.

It was shown that a higher pollution tax boosts the long term economic growth rate, whereas taxes on consumption, capital and labour reduce it. This stimulating growth is the first growth dividend of a tighter environmental policy. However it is important to note that growth maximisation is not equivalent to welfare maximisation although it is possible to increase environmental quality and economic growth at the same time. The reason is the distorted leisure/studying time decision: Starting from a suboptimal pollution level, a tighter environmental policy would improve environmental quality and step by step correct the distorted leisure/studying time decision and boost economic growth. Both effects lead to higher welfare as long as the pollution tax is below the Pigouvian level. If the pollution tax is above the Pigouvian level, a tighter environmental policy would still increase environmental quality and boost growth, but decrease welfare because growth rises at the expense of leisure.

For the special case of an totally inelastic labour supply it was shown that non of the taxes influence long term economic growth.

Finally, we analysed growth effects of a revenue neutral environmental tax reform. It was assumed that the government's task is to provide a public good which must be supplied in a certain proportion to the physical capital stock.

Therefore we assumed an exogenously given government budget requirement. By assuming a rational government behavior we found that a revenue neutral shift from non–environmental taxes to a pollution tax would boost growth for two reasons: Economic growth is stimulated by a higher pollution tax. The additional revenue can be used to reduce a non–environmental tax which has an additional stimulating growth effect. The latter described growth effect is the second growth dividend of a cleaner environment.

A. Appendix

A.1. Growth Rates Along a Balanced Growth Path

A balanced growth path is characterised as a state where all variables grow at a constant, possibly zero, rate. Therefore, derivatives of growth rates with respect to time are zero along a balanced growth path.

From differentiating equation (2.21) and (2.23) with respect to time and taking into account that $(1 = l + u + v)$, it follows:

$$\dot{l} = \dot{u} = \dot{v} = 0 \tag{A.1}$$

Taking logs and derivatives with respect to time of equation (2.18) yields:

$$(1+\chi)\hat{Z} - \chi\hat{K} = \hat{C} \tag{A.2}$$

Inserting $\frac{C}{K}$ from equation (2.18) into equation (2.20) and (2.22) and replacing $\left(\frac{K}{uH}\right)^{\alpha-1}$ by $\frac{K}{K}$ in both equations yields, respectively:

$$\hat{C} = \alpha A\frac{Y}{K} - \left(\eta_P\chi\frac{C}{K}\right)^{\frac{1}{1+\chi}} - \delta_K - \rho \tag{A.3}$$

$$\hat{K} = A\frac{Y}{K} - \frac{C}{K} - \left(\eta_P\chi\frac{C}{K}\right)^{\frac{1}{1+\chi}} - \delta_K \tag{A.4}$$

Inserting $\frac{C}{K}$ from equation (A.3) in (A.4) and differentiating with respect to time, we see that:

$$\hat{K} = \hat{Y} \tag{A.5}$$

Inserting $\frac{Y}{K}$ from equation (A.3) in (A.4) and differentiating with respect to time, we find that:

$$\hat{C} = \hat{K} \tag{A.6}$$

Taking logs and differentiating both sides of the production function (2.1) and taking condition (A.5) into consideration we get:

$$\hat{H} = \hat{Y} \tag{A.7}$$

Inserting condition (A.6) into (A.2) leads to:

$$\hat{C} = \hat{Z} \tag{A.8}$$

Together, conditions (A.1) and (A.5) – (A.8) yield (3.1) in the text.

A.2. Partial Derivatives of the Reduced Form N

Partial derivatives of N (equation (3.7)), are given by:

$$
\begin{array}{rcll}
\frac{\partial N}{\partial g} & = & \frac{\alpha\left(1-\tau^K\right)\left(\rho-\tau^K M\right)D-J^2}{J^2}, \text{ for } \rho < \tau^K M & < 0 \\
\frac{\partial N}{\partial g} & = & \frac{\alpha\left(1-\tau^K\right)\left(\rho-\tau^K M\right)D-J^2}{J^2}, \text{ for } \rho > \tau^K M & \lesseqgtr 0 \\
\frac{\partial N}{\partial \tau^C} & = & \frac{DF}{(1+\tau^C)J} & < 0 \\
\frac{\partial N}{\partial \tau^H} & = & \frac{DF}{(1-\tau^H)J} & < 0 \\
\frac{\partial N}{\partial \tau^K} & = & -\frac{\alpha\left[(g+\delta_K)(M+\rho)+M\rho+(g+\delta_K)^2\right]D}{J^2} & < 0 \\
\frac{\partial N}{\partial \bar{\tau}^P} & = & \frac{\chi}{1+\chi}\frac{\left(1-\tau^K\right)\alpha\left[\tau^K(g+\delta_K)+\rho\right]M^{-\chi}D}{J^2} & > 0 \\
\frac{\partial N}{\partial \alpha} & = & -\frac{\left[\tau^K(g+\delta_K)+\rho\right]D}{(1-\alpha)J} & < 0 \\
\frac{\partial N}{\partial A} & = & 0 & = 0 \\
\frac{\partial N}{\partial B} & = & 1 & > 0 \\
\frac{\partial N}{\partial \eta_l} & = & \frac{DF}{\eta_l J} & < 0 \\
\frac{\partial N}{\partial \eta_P} & = & 0 & = 0 \\
\frac{\partial N}{\partial \rho} & = & -1+\frac{[(J-\rho)F-\rho J]D}{\rho J^2} & < 0 \\
\frac{\partial N}{\partial \delta_H} & = & -1 & < 0 \\
\frac{\partial N}{\partial \delta_K} & = & \frac{\alpha\left(1-\tau^K\right)\left(\rho-\tau^K M\right)D}{J^2} & \lesseqgtr 0
\end{array}
\tag{A.9}
$$

where following definitions are used:

$$
\begin{array}{rcll}
D & \equiv & \frac{1+\tau^C}{1-\tau^H}\frac{\eta_l\rho}{1-\alpha} & > 0 \\
F & \equiv & (\alpha-1)\left(1-\tau^K\right)M+\left[\alpha\left(1-\tau^K\right)-1\right](g+\delta_K)-\rho & < 0 \\
J & \equiv & g+\delta_K+\rho+\left(1-\tau^K\right)M & > 0 \\
M & \equiv & \left(\chi\bar{\tau}^P\right)^{1/(1+\chi)} & > 0
\end{array}
$$

$\frac{\partial N}{\partial g}$ can not be signed clearly. In the following it is assumed to be negative. For $\frac{\partial N}{\partial g} > 0$ partial derivatives $\frac{\partial g}{\partial *}$, showed in (A.10), would have the opposite sign. This contradicts with results of [5] Devereux & Love (1994) and [13] Milesi–Ferretti &Roubini (1995) and does not make sense. For example, it can not be the case that a increased efficiency studying parameter B reduces growth.

Using the implicit function rule and the results of A.9, we can derive the following partial derivatives of g.

$$
\begin{array}{rcll}
\frac{\partial N}{\partial g} & = & \frac{\alpha\left(1-\tau^K\right)\left(\rho-\tau^K M\right)D-J^2}{J^2} & \overset{!}{<} 0 \\
\frac{\partial g}{\partial \tau^C} & = & -\frac{DFJ}{(1+\tau^C)[\alpha(1-\tau^K)(\rho-\tau^K M)D-J^2]} & < 0 \\
\frac{\partial g}{\partial \tau^H} & = & -\frac{DFJ}{(1-\tau^H)[\alpha(1-\tau^K)(\rho-\tau^K M)D-J^2]} & < 0 \\
\frac{\partial g}{\partial \tau^K} & = & \frac{\alpha\left[(g+\delta_K)(M+\rho)+M\rho+(g+\delta_K)^2\right]D}{\alpha(1-\tau^K)(\rho-\tau^K M)D-J^2} & < 0 \\
\frac{\partial g}{\partial \bar{\tau}^P} & = & -\frac{\frac{\chi}{1+\chi}\left(1-\tau^K\right)\alpha\left[\tau^K(g+\delta_K)+\rho\right]M^{-\chi}D}{\alpha(1-\tau^K)(\rho-\tau^K M)D-J^2} & > 0 \\
\frac{\partial g}{\partial \alpha} & = & \frac{\left[\tau^K(g+\delta_K)+\rho\right]DJ}{(1-\alpha)[\alpha(1-\tau^K)(\rho-\tau^K M)D-J^2]} & < 0 \\
\frac{\partial g}{\partial A} & = & 0 & = 0 \\
\frac{\partial g}{\partial B} & = & -\frac{J^2}{\alpha(1-\tau^K)(\rho-\tau^K M)D-J^2} & > 0 \\
\frac{\partial g}{\partial \eta_l} & = & -\frac{DFJ}{\eta_l[\alpha(1-\tau^K)(\rho-\tau^K M)D-J^2]} & < 0 \\
\frac{\partial g}{\partial \eta_P} & = & 0 & = 0 \\
\frac{\partial g}{\partial \rho} & = & -\frac{[(J-\rho)F-\rho J]D-\rho J^2}{\rho[\alpha(1-\tau^K)(\rho-\tau^K M)D-J^2]} & < 0 \\
\frac{\partial g}{\partial \delta_H} & = & \frac{J^2}{\alpha(1-\tau^K)(\rho-\tau^K M)D-J^2} & < 0 \\
\frac{\partial g}{\partial \delta_K} & = & -\frac{\alpha\left(1-\tau^K\right)\left(\rho-\tau^K M\right)D}{\alpha(1-\tau^K)(\rho-\tau^K M)D-J^2} & \lesseqgtr 0
\end{array}
\tag{A.10}
$$

A.3. Partial Derivatives of the Reduced Form O

Similar to the derivation of N we can derive a implicit reduced form of ratio $\frac{K}{H}$ by using first order conditions (2.13) and (3.3) – (3.6):

$$
\begin{aligned}
O \equiv 0 = & -\left(\frac{B}{\rho}\frac{K}{H}\right)^{\alpha-1} + \frac{\left(1+\tau^C\right)}{\left(1-\tau^H\right)}\frac{\eta_l}{(1-\alpha)A} \\
& \frac{\rho\left\{\left[1-\left(1-\tau^K\right)\alpha\right]A\left(\frac{B}{\rho}\frac{K}{H}\right)^{\alpha-1}-\tau^K\left(\chi\bar{\tau}^P\right)^{1/(1+\chi)}+\rho\right\}}{B-\left(1-\tau^K\right)\left[\alpha A\left(\frac{B}{\rho}\frac{K}{H}\right)^{\alpha-1}-\left(\chi\bar{\tau}^P\right)^{1/(1+\chi)}\right]+\delta_K-\delta_H}
\end{aligned}
\tag{A.11}
$$

The partial derivatives of ∂O with respect to $\frac{K}{H}$ and all tax rates are given by:

$$\begin{aligned}
\frac{\partial O}{\partial \frac{K}{H}} &= \begin{matrix}(1-\alpha)\left(\frac{B}{\rho}\frac{K}{H}\right)^{\alpha-1}\left(\frac{K}{H}\right)^{\alpha-2} \\ +\frac{\rho Q(1-\alpha)A\left(\frac{B}{\rho}\right)^{\alpha-1}\left(\frac{K}{H}\right)^{\alpha-2}\left[\alpha R-\left[1-\left(1-\tau^K\right)\alpha\right]S\right]}{S^2}\end{matrix} && \overset{!}{<} 0 \\
\frac{\partial O}{\partial \tau^C} &= \frac{\rho Q}{1+\tau^C}\frac{R}{S} && > 0 \\
\frac{\partial O}{\partial \tau^H} &= \frac{\rho Q}{1+\tau^H}\frac{R}{S} && > 0 \qquad \text{(A.12)} \\
\frac{\partial O}{\partial \tau^K} &= \frac{\rho Q\left[\alpha A\left(\frac{B}{\rho}\frac{K}{H}\right)^{\alpha-1}-M\right]\left(B-\delta_H-\rho-\left[A\left(\frac{B}{\rho}\frac{K}{H}\right)^{\alpha-1}-M-\delta_K\right]\right)}{S^2} && < 0 \\
\frac{\partial O}{\partial \bar{\tau}^P} &= \frac{\rho Q}{S^2}\frac{\partial M}{\partial \bar{\tau}^P}\left[-\tau^K S-\left(1-\tau^K\right)R\right] && < 0
\end{aligned}$$

Where following definitions are used:

$$\begin{aligned}
M &\equiv \left(\chi\bar{\tau}^P\right)^{1/(1+\chi)} && > 0 \\
Q &\equiv \frac{1+\tau^C}{1-\tau^H}\frac{\eta_l \rho}{(1-\alpha)A} && > 0 \\
R &\equiv \overbrace{\left[1-\left(1-\tau^K\right)\alpha\right]A\left(\frac{B}{\rho}\frac{K}{H}\right)^{\alpha-1}-\tau^K M+\rho}^{\frac{C}{K}} && > 0 \\
S &\equiv \overbrace{B-\left(1-\tau^K\right)\left[\alpha A\left(\frac{B}{\rho}\frac{K}{H}\right)^{\alpha-1}-M\right]+\delta_K-\delta_H}^{l} && > 0
\end{aligned}$$

$\frac{\partial O}{\partial \frac{K}{H}}$ can not be signed clearly, but in the following it is assumed to be negative. $\frac{\partial O}{\partial \frac{K}{H}} > 0$ would be counter intuitive and in contradiction with the results of (A.10) in connection with the first order conditions (2.13) and (3.3)– (3.6). By using the implicit function rule we can derive the intuitive results summarised in (A.13).

$$\frac{\partial \frac{K}{H}}{\partial \tau^C}, \frac{\partial \frac{K}{H}}{\partial \tau^H}, \frac{\partial \frac{K}{H}}{\partial \tau^K} > 0 \text{ and } \frac{\partial \frac{K}{H}}{\partial \bar{\tau}^P} < 0 \qquad \text{(A.13)}$$

A.4. A Revenue Neutral Tax Reform

Replacing ratios $\frac{C}{K}$ $\frac{K}{uH}$ by use of first order conditions (2.13) and (3.3) – (3.6) and substituting r and w by equations (2.10) and (2.11), equation (3.10) is a function of parameters, tax rates and g.

$$\bar{G} = \frac{\left\{\left[1-\alpha\left(1-\tau_K\right)\right]\tau^C+(1-\alpha)\tau^H+\alpha\tau^K\right\}}{\alpha\left(1-\tau_K\right)}\left(g+\delta_K\right)$$

$$+\frac{\left[\tau^{C}+(1-\alpha)\,\tau^{H}+\alpha\tau^{K}\right]}{\alpha\,(1-\tau_{K})}\rho+M\left[\frac{1-\alpha}{\alpha}\left(\tau^{C}+\tau^{H}\right)+\chi^{-1}\right] \tag{A.14}$$

Partial derivatives of $\partial\bar{G}$ with respect to tax rates are given by:

$$\begin{aligned}
\frac{\partial\bar{G}}{\partial\tau^{C}} &= \frac{[1-\alpha(1-\tau_{K})](g+\delta_{K})+\rho+(1-\alpha)\left(1-\tau^{K}\right)M}{\alpha(1-\tau_{K})}+\frac{T}{\alpha(1-\tau_{K})}\frac{\partial g}{\partial\tau^{C}} && \gtreqless 0\\
\frac{\partial\bar{G}}{\partial\tau^{H}} &= \frac{(1-\alpha)\left(g+\rho+\delta_{K}+\left(1-\tau^{K}\right)M\right)}{\alpha(1-\tau_{K})}+\frac{T}{\alpha(1-\tau_{K})}\frac{\partial g}{\partial\tau^{H}} && \gtreqless 0\\
\frac{\partial\bar{G}}{\partial\tau^{K}} &= \frac{\left\{\left(\alpha\tau^{C}+\alpha\right)(1-\tau_{K})+T+\rho\alpha+\rho\left[\tau^{C}+(1-\alpha)\tau^{H}\right]\right\}(g+\delta_{K})}{\alpha(1-\tau_{K})^{2}}+\frac{T}{\alpha(1-\tau_{K})}\frac{\partial g}{\partial\tau^{K}} && \gtreqless 0\\
\frac{\partial\bar{G}}{\partial\bar{\tau}^{P}} &= \frac{T}{\alpha(1-\tau_{K})}\frac{\partial g}{\partial\bar{\tau}^{P}}+\frac{\frac{1-\alpha}{\alpha}\left(\tau^{C}+\tau^{H}\right)+\chi^{-1}}{1+\chi}M^{-\chi} && > 0
\end{aligned} \tag{A.15}$$

where T is defined as:

$$T \equiv [1-\alpha\,(1-\tau_{K})]\,\tau^{C}+(1-\alpha)\,\tau^{H}+\alpha\tau^{K} \quad > 0$$

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