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Abstract

The implications of an ecological tax reform are not yet well investigated when firms do not behave competitively and the provision level of public services is not exogenously fixed. To fill this gap, we present a model encompassing a monopolistic firm and endogenous provision of public services: At some initial state the firm faces only a capital tax, but a proposed tax reform calls for the imposition of a second tax – an emission tax. We derive the optimal (second-best) tax formulae of the initial and the reformed tax system, providing some insight into those variables that determine governmental behavior: Under the initial tax system, the tax rate on capital decreases as the government puts more weight to ecological problems, whereas the reformed capital tax is independent of the environmental damage.

Since we deal with a drastic rather than with a marginal tax reform, a comparison of the initial and the reformed tax rates is difficult. Yet, numerical calculations suggest that the government does not only establish a positive emission tax but also increases the tax rate on capital, implying that both tax rates, public revenue, and the environmental quality are initially too low. Moreover, although profit and consumer surplus fall, the ecological tax reform implies significant, and possibly huge, welfare gains, which are accompanied by substantial improvements of the environmental quality. Hence, this paper rather rejects than supports the occurrence of a 'double dividend'; yet, it shows that the existence of real costs of an ecological tax reform may not be abused as an argument to hinder its enforcement.

Keywords: ecological tax reform, pollutant emissions, monopoly taxation, second-best analysis, optimal taxation

(JEL: D42, H21, H23, H25, H32)

1 Introduction

Within the last years much political attention has been paid to the establishment of an ecological tax system in order to correct for environmental diseconomies. Since it is not the only task of the government to redress externalities but also to provide public services, the tax system is required to raise public funds as well. The advocates of an ecological tax reform argue that the introduction of 'green taxes' represents an excellent policy tool to cut other distortionary taxes and to raise public revenue in a more efficient way.[1] In this sense, the government does not only enhance the environmental quality but also households' 'non-environmental utility' through reducing the overall economic costs of financing public expenditure.

Recently, several authors have considered the impact of an ecological tax reform on some selected variables of the non-environmental subutility.[2] Namely, they investigate the trade-offs between environmental quality, on the one hand, and public consumption, employment, and profits, on the other hand. The analysis indicates whether and which socioeconomic groups may endure gross costs[3] from a tax reform.

Clearly, while the establishment of an ecological tax system requires an adjustment of the whole tax system, this policy measure embodies uncertainties: a redistribution process is set up that is feared by many people. If some interest groups suspect that their clienteles endure extra taxes through the establishment of green taxes while the expected benefits are vague, they will offer resistance against the proposed tax reform. If these interest groups are sufficiently powerful, they are possibly able to block the transition towards an ecological tax system and thereby to obstruct a significant overall welfare gain. For example, trade unions and employers' associations may fear that firms endure higher (or extra)

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[1] See for example NORDHAUS (1993), p. 316 f.

[2] See for example VAN DER PLOEG AND BOVENBERG (1993A), JOHANSSON (1994), BOVENBERG AND DE MOOIJ (1994A,B), BOVENBERG AND VAN DER PLOEG (1994), GOULDER (1995), and DE MOOIJ AND BOVENBERG (1995).

[3] *Gross costs* denotes the non-environmental welfare that has to be sacrificed to realize a specific environmental policy.

taxes[4] which may reduce profits and jeopardize jobs.

Therefore, the idea that a tax reform does not only improve environmental quality but also boosts non-environmental utility is appealing. If it turns out to be true that the environmental quality can be improved at zero gross costs – and in this sense a double-dividend is attained –, the private sector would refrain from opposing an ecological tax reform. Hence, if a double dividend can be reached, politicians can be confident that despite of a couple of uncertainties all socioeconomic groups will approve the establishment of green taxes.

Unfortunately, the increasing literature dealing with this topic – subsumed under the title *double dividend literature* – rather denies than affirms the existence of a double dividend.[5] Whether a double dividend prevails depends crucially on the specific structure of the model. Since results do not seem to be robust, one must be alert that the literature, cited above, exhibits a couple of limiting assumptions: the analysis typically focuses on perfect competition and frequently assumes constant returns to scale technologies; moreover, most authors do not consider endogenous provision of public services but suppose a given public budget requirement.[6] Thus, the existing double dividend literature focuses on consumers' behavior (e. g., endogenous labor supply) but simplifies or idealizes the behavior of the government and of the industry.

Recognizing this, the question arises, how are results affected if we deal with *imperfect competition* and *endogenous provision of public goods*? And, moreover, provided that the hypothesis of a double dividend has to be rejected, are the gross costs of an ecological tax reform large compared to the benefits or are they rather insignificant? If they turned out to be small, many of the uncertainties accompanying an ecological tax reform could be discarded, for there is much

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[4] Indeed, in most economies, the relative scarcity of public funds (huge public deficits) prompts the finance minister to look for new fiscal sources.

[5] If the labor supply curve is upward-sloping, an 'employment' dividend cannot be reaped; other dividends may possibly, but need not, occur. (See e. g. BOVENBERG AND VAN DER PLOEG (1994) and LIGTHART AND VAN DER PLOEG (1994).) DE MOOIJ AND BOVENBERG (1995) show that there is some potential for an overall double-dividend if the initial tax system is inefficient.

[6] The papers of BOVENBERG AND VAN DER PLOEG (1994) and LIGTHART AND VAN DER PLOEG (1994) who allow for endogenous provision of public services represent an exception.

scope for compensating those who will otherwise suffer.[7]

For this purpose, we present a partial model that allows us to compare the initial tax rates – those which do not fully reflect ecological diseconomies – with their reformed counterparts and to investigate the induced equilibrium allocations. To contrast sharply with the existing literature, we consider the 'most non-competitive' case: a monopolistic firm. This firm uses two factors – capital and environmental inputs – to produce a consumer good. Households receive the firm's profit as dividend income and benefit from consuming the firm's output. In addition, they suffer from industrial pollutant emissions but approve the provision of public services, measured in terms of public revenue. At the initial state of the world, the government levies taxes on capital but does not tax pollutant emissions. The reason that the production factor 'environment' remains untaxed is a reflection of the fact that the government (society) is not fully aware of the ecological problems. The advocates of a green tax reform, however, recognize the total ecological damage stemming from pollutant emission and demand the introduction of an emission tax.[8] Under this tax regime, the government uses two, instead of one, tax rates to maximize social welfare.[9] In any case the tax system serves the threefold purpose of regulating the output market, raising public funds, and (partially) affecting the environmental quality. Correspondingly, the initial capital tax is determined by three components: a subsidy term by which the government seeks to enhance output, a fiscal term that reflects public financial needs, and an environmental term that reflects the social awareness of environmental problems at the initial state of the world.[10] Under the ecological tax reform, the

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[7] In a model where the level of public spending is exogenously fixed, Bovenberg and de Mooij (1994b) also recognize that *"even though households may suffer a decline in real wage [non-environmental] income due to a less efficient tax system, they may nevertheless gain in terms of overall utility if a rise in environmental income more than offsets the adverse effect on wage income."*

[8] This can also be interpreted as a shift of social preferences towards a 'greener' welfare function.

[9] Since the government adjusts both tax rates, and does not only vary the emission tax marginally, our approach differs from that of a marginal tax reform frequently used in the literature. (See for example Bovenberg and de Mooij (1994b).)

[10] In the polar case where the government (or the society) completely ignores the ecological problems, the third part drops out.

tax rate on capital is no more (directly) dependent on marginal environmental damage, for the emission tax now serves, among others, the purpose of improving the environmental quality.

After characterizing the optimal (second-best) tax rates under both regimes, we compare both tax systems to reveal the economic and ecological implications of the proposed 'green' tax reform. Since a comparison of the tax formulae under both regimes does not yield clear-cut results, we calibrate a more specific model to compute the economic effects of the proposed ecological tax reform. Parametric variation of two parameters, the social value of public funds and a productivity coefficient of the firm's production function, provide us further insight: Within some wide range of parameter values, the tax rates on capital and on emissions are determined too low initially, given that an emission tax is available. Accordingly, the proposed tax reform requires a higher price of environmental inputs and of capital, implying a larger tax burden for the industry. Clearly, a more severe taxation of industrial inputs unambiguously hampers economic activity – the firm's output and its profit decrease; but it promotes the environmental quality and yields a higher tax revenue. The composed effect of the tax reform on overall welfare turns out to be unambiguously positive and may even be huge. Hence, although industry suffers through lower profits and consumers have to endure lower output (and higher prices), the proposed ecological tax reform implies significant welfare improvements.

This paper is structured as follows. Section 2 presents the basic framework of our model. As a benchmark, Section 3 briefly depicts the first-best environmental policy. In Section 4 we characterize the government's optimal policy when there is only one tax instrument, the capital tax rate, available. When, under the ecological tax reform, a new tax instrument is established, the government has to redesign its tax vector. The reformed tax rates are characterized in Section 5. In Section 6 we compare the taxation rules of both regimes, the initial and the ecological tax regime. In Section 7 we analyze the consequences of a 'green' tax reform for a more specific version of our model. And Section 8 summarizes the paper.

2 The Model

2.1 The Firm

Consider a firm which is the sole supplier of a consumer good.[11] This monopolistic firm produces its output by the use of capital, K, and environmental inputs (emissions), E; its technology can be characterized by a production function $F(K, E)$ which is concave in all variables. Let ρ_k and ρ_e denote the before-tax prices of capital and emissions, and τ_k and τ_e the per unit taxes on capital and emissions, respectively. Then, the cum-tax factor prices are given by $p_k := \rho_k + \tau_k$ for capital and $p_e := \rho_e + \tau_e$ for emissions. The monopoly faces a downward sloping inverse demand curve, $P(Q)$, which is 'not too convex' in the sense that

$$P''(Q) < -\frac{2P'(Q)}{Q} \quad \forall Q \in \mathbb{R}_+. \tag{1}$$

Condition (1) ensures that the firm's revenue $\tilde{R}(Q) := P(Q)Q$ is a (strictly) concave function of Q which, together with the concavity of F, implies that revenue $R(K, E) := \tilde{R}(F(K, E))$ is also (strictly) concave in K and E. Therefore, profit, defined by

$$\pi(K, E; p_k, p_e) := P(Q)Q - p_k K - p_e E \tag{2}$$

with $Q = F(K, E)$, is (strictly) concave in K and E.

Profit maximizing behavior of the monopolistic firm is characterized by[12]

$$R_k = (P + P'Q)F_k = \rho_k + \tau_k, \tag{3}$$

$$R_e = (P + P'Q)F_e = \rho_e + \tau_e. \tag{4}$$

Equations (3) and (4), in conjunction with $Q = F(K, E)$, implicitly define the (unconditional) factor demands, $K(p_k, p_e)$ and $E(p_k, p_e)$. Substituting these demand functions into (2) gives the (reduced) profit function depending on factor

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[11] Instead of a single firm, we can think of a couple of *cooperative firms* who act compliantly and collusively on the output market in order to achieve monopolistic market power (merged industrial branch).

[12] Subindices of functions denote partial derivatives as long as not stated otherwise.

prices, exclusively:[13]

$$\Pi(p_k, p_e) \;=\; P\left(F(K(\cdot), E(\cdot))\right) F(K(\cdot), E(\cdot)) - p_k K(\cdot) - p_e E(\cdot). \qquad (5)$$

For the purpose of the subsequent analysis, we need to know the (partial) derivatives of the factor demands w. r. t. factor prices. Differentiation of (3) and (4) yields

$$\begin{bmatrix} dK \\ dE \end{bmatrix} = \frac{1}{det(H(R))} \begin{bmatrix} R_{ee} & -R_{ke} \\ -R_{ke} & R_{kk} \end{bmatrix} \begin{bmatrix} d\tau_k \\ d\tau_e \end{bmatrix}, \qquad (6)$$

where $det(H(R))$ denotes the determinant of the Hessian matrix of $R(K, E)$. By strict concavity of R, we know that $H(R)$ is negative definite and hence

$$R_{kk} < 0, \quad R_{ee} < 0, \quad det(H(R)) = R_{kk} R_{ee} - R_{ke}^2 > 0. \qquad (7)$$

To ensure unique signs of the cross-derivative R_{ke} we make the following assumption: Evaluated at (3) and (4), F_{ke} is 'not too large', in the sense that

$$F_{ke} \;<\; -\frac{2P'(Q) + P''(Q)Q}{P(Q) + P'(Q)Q} F_k F_e. \qquad (8)$$

Note that, evaluated at the firm's optimal policy, the term $P + P'Q$ equals the marginal cost of Q implying that the right hand side of (8) is positive.

Then, it can be easily shown that (1) and (8) suffice to ensure that R_{ke} is negative. Solving (6) for the desired derivatives yields

$$K_{p_k} \;=\; \frac{R_{ee}}{det(H(R))} \;<\; 0, \qquad K_{p_e} \;=\; -\frac{R_{ke}}{det(H(R))} \;>\; 0, \qquad (9)$$

$$E_{p_e} \;=\; \frac{R_{kk}}{det(H(R))} \;<\; 0, \qquad E_{p_k} \;=\; -\frac{R_{ke}}{det(H(R))} \;>\; 0. \qquad (10)$$

Since R_{ke} is negative, the cross derivatives K_{p_e} and E_{p_k} are positive, i. e., capital and emissions are gross-substitutes in production.

2.2 Consumers

Consumers derive utility from the consumption of the private good produced by the monopolistic firm but suffer from pollutant emissions. The social damage

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[13] A dot as an argument of a function stands for the omitted arguments.

caused by industrial pollutant emissions, $D(E)$, is assumed to be monotonously increasing and a strictly convex function of E. In addition to the private good, residents benefit from the provision of public services measured by their related expenditures, T. Assuming separability, residents' welfare consists of net-consumer surplus, plus the social benefit of the public revenue (public services) minus the social damage stemming from industrial pollutant emissions, plus dividend income. Suppose that residents hold all stocks of the firm and therefore receive its full profit as dividend income. Then, we can write consumers' welfare as[14]

$$\mathcal{W} = \int_0^Q P(q)dq - P(Q)Q + \lambda T - \alpha D(E) + \pi(\cdot), \qquad (11)$$

where the firm's profit is given by (2). The parameter $\alpha \in [0,1]$ represents the social weight associated with the ecological damage resulting from industrial pollutant emissions,[15] and λ denotes the social value of public funds (the social marginal values of money in the hands of the government).

2.3 The Government

The government seeks to maximize consumers' utility by determining its policy tools appropriately. We consider two policy regimes. At the initial tax regime no environmental taxes are levied but the use of capital is subject to taxation. This traditional tax system, where the government is restricted to use τ_k exclusively, may reflect either the ignorance of ecological problems or the intention to promote the industry (or at least not to impede it through the establishment of new tax rates). Then the society, or a part of it, becomes aware of these problems and proposes an ecological tax reform comprising the introduction of an emission tax and an adjustment of the capital tax. Hence, in the second regime two, rather than only one, tax rates available for the government.

Correspondingly, public revenue stems, in general, from taxation of the mo-

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[14] The concavity of $\mathcal{W}$ in K and E is ensured by concavity of F and $-D$ in K and E and by the concavity of $\int_0^Q P(q)dq - P(Q)Q$ and $\tilde{R}(Q)$ in Q.

[15] The weight α allows us to consider shifts in preferences, namely a shift towards a 'greener' welfare function, or alternatively to consider a policy putting more attention to ecological problems.

nopolistic firm[16] plus any revenue raised from other sources, $\bar{T}$, which is treated as exogenous here.[17] Then, total public revenue equals $T + \bar{T}$, where

$$T := \tau_k K + \tau_e E. \tag{12}$$

While we focus on taxation of a single firm, we treat $T/\bar{T}$ as relatively small. Therefore, the social value of public funds λ is not affected by τ_k and τ_e and can be viewed as a given constant.[18] Since we deal with distortionary taxation, λ differs from the marginal utility of private income, in general. More precisely, if an increase in public revenue increases the excess burden of the tax system, the shadow cost of public funds exceeds consumers' marginal utility of income: $\lambda > 1$. Only if public goods are complementary to taxed goods the excess burden may decrease with higher public spending (see AUERBACH (1985), p. 112).

3 Environmental Policy in a First-Best World

Before characterizing the optimal tax rates under both policy regimes, we first consider the Pareto efficient allocation, which serves as a benchmark in the subsequent analysis. Within a command and control economy the regulator could establish the first-best allocation by choosing the real variables K and E directly and by undertaking any income transfer sufficient to equate the marginal cost of public funds and the private marginal utility of income. Maximizing welfare, (11), with respect to (w. r. t.) capital, emissions, and the transfer payment yields the following optimality conditions:[19]

$$\begin{aligned} PF_k &= \rho_k, && (13)\\ PF_e &= \rho_e + D', && (14)\\ \lambda &= 1. && (15) \end{aligned}$$

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[16] While the government is able to tax all inputs of the firm, an additional tax on output is redundant. (See also footnote 20.)

[17] Since $\bar{T}$ is exogenous, it is already left out in the welfare function (11).

[18] λ is the Lagrangian multiplier of the *overall* public budget constraint and thus can be interpreted as the exogenously given shadow price (or shadow cost) of public services.

[19] If the government is not able to fix $\bar{T}$ at any desired level, eq. (15) can only hold by chance.

Equation (13) states that capital should be used up to that point where its marginal product equals its factor price (net of taxes). Similarly, the environmental factor should be used to that extent where its marginal product equals its social cost, which consists of its market price (net of taxes) plus the marginal damage caused by the use of environmental inputs (eq. (14)). In addition, resources are used to provide public services efficiently: the marginal rate of substitution between the private and the public good equals its marginal rate of transformation which is equal to unity (eq. (15)).

Next, the question arises how can the first-best outcome be sustained in a decentralized market economy? If the appropriate fiscal instruments, namely a capital tax, an emission tax, and poll taxes, are available, the efficient solution can be supported by adjusting τ_k and τ_e according to the following rules:

$$\begin{bmatrix} \tau_k \\ \tau_e \end{bmatrix} = \begin{bmatrix} P'QF_k \\ P'QF_e + D' \end{bmatrix}, \tag{16}$$

and by levying head taxes sufficient to provide public services efficiently.

While public services can be provided efficiently through imposing the appropriate head taxes, the government does not face any fiscal incentive to raise additional public funds through distortionary taxation. It rather exclusively seeks to correct the firm's non-competitive behavior by subsidizing the use of capital, $\tau_k < 0$, and thereby encouraging production.[20] The sign of the emission tax, however, remains ambiguous. Whether the emission tax is positive or negative depends on two features: on the steepness of the inverse demand curve and of the social damage function. Yet, in any case, the emission tax falls short of the social marginal damage, i. e., it lies below its Pigouvian level. This reflects the fact that, evaluated at $\tau_k = \tau_e = 0$, output is too low while emissions are only too low for sufficiently flat damage curves, but too high for steep damage curves.[21]

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[20] Alternatively, the government can establish the first-best outcome by subsidizing output and taxing emissions without imposing any tax (or subsidy) on capital. In this, case the tax rate on output would be equal to $P'Q < 0$; the tax rate on emissions, equal to $D' > 0$. However, since we want to focus on factor substitution, we consider factor, not output, taxation.

[21] A similar formula for the emission tax was found by BARNETT (1980). Yet, due to the lack of a second complementary tax rate, the optimal emission tax given therein (eq. (9)) is second-best.

4 The Initial Tax Regime

In practice, the government has to rely on distortionary taxation. Since poll taxes and lump-sum transfers are not available, the government is required to use non-neutral taxes in order to raise the required level of public funds.

Empirically, environmental taxes have been, and still are, very uncommon. The ignorance of the opportunity to establish environmental taxes results partly from a lacking knowledge or comprehension of environmental problems and partly from protection or promotion of the industry. Correspondingly, while governments still hesitate to employ explicit emission taxes, they sometimes seek to (mildly) improve the prevailing environmental quality indirectly through other tax rates. To model this governmental behavior, assume that either the regulator is initially only aware of some portion $\alpha \in [0,1]$ of the environmental problems caused by industrial pollutant emissions; or she is aware of the full damage but due to political pressure of some interest groups, e. g., employers' associations and trade unions, she ignores the portion $1-\alpha$ in order not to impede economic activities. Thus, to calculate the capital tax rate at the initial state of the world where no taxes are levied on pollutant emissions directly, differentiate the welfare function (11) w. r. t. τ_k, evaluated at $\tau_e = 0$. Using (5) and (12), this procedure yields

$$\frac{\partial W}{\partial \tau_k} \;=\; \lambda(K_{p_k}\tau_k + K) - P'Q(F_k K_{p_k} + F_e E_{p_k}) - K - \alpha D' E_{p_k} \;=\; 0. \qquad (17)$$

Solving (17) for τ_k gives us

Proposition 4.1 *The optimal initial capital tax rate, where $\tau_e^\circ = 0$, is given by*

$$\tau_k^\circ \;=\; \frac{1}{\lambda}\left(\frac{P'Q}{K_{p_k}}(F_k K_{p_k} + F_e E_{p_k}) - (\lambda - 1)\frac{K}{K_{p_k}} + \alpha D' \frac{E_{p_k}}{K_{p_k}}\right). \qquad (18)$$

The optimal initial tax rate on capital consists of three parts. The first one stems from non-competitive behavior of the firm. Since the tax rate affects factor demand, the output of the firm and the market clearing output price change. (Recall that the signs of the derivatives of factor demand are given by (9) and (10).) If an increase in τ_k induces factor substitution that leads to a decrease of production, this policy measure reduces consumer surplus. Hence, if $|F_k K_{p_k}| > F_e E_{p_k}$, the first term is negative. The second term weighs the increase of public revenue against the decrease of the firm's profit, where the latter is equivalent to consumers' loss of capital income. If the marginal social value of public funds exceeds the marginal utility of private income, $\lambda > 1$, the relative scarcity of public revenue prompts the government, ceteris paribus, to increase the tax rate; and the higher λ, the more the government taxes capital ($\partial \tau_k^\circ / \partial \lambda > 0$). The third term reflects the perceived environmental damage resulting from pollutant emission. While an increased economic activity requires more environmental inputs, environmental quality declines as industrial output rises. In the initial tax regime, the government disregards (or is not aware of) the portion $1 - \alpha$ of the marginal environmental damage; and the more the government ignores the detrimental impact of the firm's activity on environmental quality, i. e., the lower is α, the higher(!) is the tax rate.

Corollary 4.1 *The initial tax rate on capital, τ_k° is a decreasing function of the weight given to environmental damage: $\partial \tau_k^\circ / \partial \alpha < 0$).*

Contrary to what one might believe, if the regulator is not allowed (or hesitates) to apply emission taxes, the (constrained) optimal capital tax is the lower, and therefore the firm's profit is the higher, the more the regulator takes into account the environmental damage associated with the firm's pollutant emissions. Similarly, τ_k° is the lower the higher is the marginal damage resulting from pollutant emissions. The intuition behind this result is the following. For any fixed price of environmental inputs, increasing the tax on capital induces the firm to use less capital and to emit more pollutants. Hence, a higher tax on capital implies an indirect subsidy on pollutant emissions. However, the more the government becomes aware of the ecological problems (a higher α), the less the government finds it desirable to subsidize pollutant emissions. In sum, although the government is constrained to apply a single tax rate, it seeks to pursue a threefold purpose: to regulate the output market, to raise public funds, and to affect the environmental quality.[22]

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[22] It has well been recognized that the government seeks to pursue multiple targets by a single tax rate under imperfect competition. While in the classical RAMSEY-BOITEUX pricing problem the optimal (second-best) tax rate accounts for the scarcity of public funds and for

5 The Ecological Tax Reform

Now, suppose that the society (or at least a part of it) becomes aware of the total ecological damage resulting from industrial pollutant emissions ($\alpha = 1$) and proposes an ecological tax reform calling for the introduction of an emission tax. Since the establishment of a new tax causes the initial tax system to be determined suboptimally in general, the capital tax rate must also be adjusted. Therefore, the reformed tax rates are calculated by maximizing the welfare function w. r. t. τ_k and τ_e simultaneously. The first order conditions (f. o. c. s) characterizing the solution of this optimization problem are given by

$$\begin{aligned} \frac{\partial W}{\partial \tau_k} &= \lambda(E_{p_k}\tau_e + K_{p_k}\tau_k + K) - P'Q(F_k K_{p_k} + F_e E_{p_k}) - K - D'E_{p_k} = 0, && (19) \\ \frac{\partial W}{\partial \tau_e} &= \lambda(E_{p_e}\tau_e + K_{p_e}\tau_k + E) - P'Q(F_k K_{p_e} + F_e E_{p_e}) - E - D'E_{p_e} = 0, && (20) \end{aligned}$$

where we have made use of (3) and (4) (envelope theorem).

To get further insight into the structure of the optimally reformed tax rates, solve equations (19) and (20) for the vector (τ_k, τ_e). This procedure yields

Proposition 5.1 *The optimal reformed tax rates are given by*

$$\begin{bmatrix} \tau_k \\ \tau_e \end{bmatrix} = \begin{bmatrix} \frac{1}{\lambda}P'QF_k + \frac{\lambda - 1}{\lambda}\frac{EE_{p_k} - KE_{p_e}}{K_{p_k}E_{p_e} - K_{p_e}E_{p_k}} \\ \frac{1}{\lambda}P'QF_e + \frac{\lambda - 1}{\lambda}\frac{KK_{p_e} - K_{p_k}E}{K_{p_k}E_{p_e} - K_{p_e}E_{p_k}} + \frac{1}{\lambda}D' \end{bmatrix}. \qquad (21)$$

The (second-best) tax rates are determined by two respectively three terms. Within each formula the first term stems from the monopolistic behavior of the firm, reflecting the marginal impact of the tax rate on consumer surplus. These terms represent the government's endeavor to correct for the distortion of the output market by enhancing the firm's output through encouraging the use of capital and emissions. (Note that both terms are negative and, therefore, ignoring the other terms, represent a subsidy of both inputs.) However, contrary to the initial

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non-competitive behavior of the firm(s), it accounts for monopolistic behavior and the marginal social damage stemming from pollutant emission in the regulation problems discussed by BARNETT (1980), BAUMOL AND OATES (1988) (ch. 6), and others.

tax rate (18), each tax rate accounts only for the marginal product of the corresponding factor. While the tax formula of τ_k° includes a $P'QF_e$-term, the reformed tax rate on capital does not; neither does τ_e include a $P'QF_k$-term.

The second terms result from distortionary taxation of industrial inputs and correspond to the extent of inefficient provision of public services. The factor $(\lambda - 1)/\lambda$ stems from the divergency between the private and social value of income and can be interpreted as the marginal excess burden of distortionary taxation. Because we know from (7), (9), and (10) that $K_{p_k}E_{p_e} - K_{p_e}E_{p_k}$ is equal to the inverse of the determinant of the Hessian matrix of R, the denominators of the second terms of (21) are unambiguously positive. Hence, as long as public funds are 'relatively scarce' in the sense that $\lambda > 1$, the second parts of the right hand side of (21) are non-negative.

The third term determining τ_e results from the marginal environmental damage of industrial pollutant emissions. Contrary to the capital tax, the emission tax depends directly[23] on the marginal environmental damage – as the initial capital tax τ_k° does. Moreover, while we have seen that τ_k° is the lower the higher is the marginal damage resulting from pollutant emissions, the reformed emission tax depends positively on marginal damage. Thus, while the reformed capital tax rate is determined by only two distortions, resulting from non-competitive behavior of the firm and from the use of an overall second-best tax system, the emission tax also incorporates environmental diseconomies.

If the government is free to choose any fiscal instrument, i. e., it is not urged to use a distortionary tax system, the marginal cost of public funds equals unity, public goods are provided efficiently, and, therefore, the marginal excess burden is equal to zero. In this case, the first-best solution could be established by adjusting head taxes/lump sum transfers and the tax rates appropriately.[24]

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[23] Clearly both tax rates are determined simultaneously by the equation system (21) and are therefore interdependent. If we speak of independence, we mean that there is no first-order impact.

[24] This is a generalization of EBERT's (1992) result (cf. eq. (8c)) in the sense that we consider the taxation of two independent production factors whereas EBERT (1992) assumes that emissions are perfectly related to output; and, therefore, his model is confined to output taxation.

Corollary 5.1 *If the marginal social cost of public funds is equal to unity,* $\lambda = 1$, *the optimal reformed tax rates are first-best.*

Proof: by comparison of (21) and (16).

So far we have derived and discussed the tax rates under both taxation regimes. To come back to our basic question – which consequences does the ecological tax reform imply? – we have to compare both tax systems.

6 A Comparison of both Tax Regimes

Whether the ecological tax reform leads to higher tax rates and a higher tax burden for the industry, to an increase of public revenue, and/or to an improvement of the environmental quality can only be answered by a comparison of the initial tax system and its reformed counterpart. However, comparing tax formulae is a delicate task, for they hold at different points.[25] Keeping this in mind, we contrast the initial tax rates, given by $\tau_e^\circ = 0$ and (18), and the reformed tax rates, given by (21), under the conventional 'ceteris paribus assumption'. Since it is inconvenient to compare both tax systems by using equations (18) and (21) directly, we utilize the corresponding first order conditions, (17), (19), and (20).

Let us begin with the capital tax rate. Inspecting (17) and (19), we see that the latter differs from the first by a term that is proportional to

$$-\left[(1-\alpha)\frac{D'}{\lambda} - \tau_e\right]. \qquad (22)$$

τ_k exceeds, ceteris paribus, τ_k° if (22) is positive but falls short of the initial capital tax if this term is negative. Clearly, for all negative emission tax rates the capital tax declines compared to the initial tax rate; but for $\tau_e > 0$, the direction of adjustment is ambiguous. Three polar cases may show this. If we evaluate terms at the initial emission tax, $\tau_e = 0$, τ_k falls short of τ_k°. However, using the Pigouvian tax, $\tau_e = D'$, the government raises the capital tax above its initial level. In the case where α equals unity, (22) is positive if and only if τ_e is also positive.

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[25] The point is that we consider a *drastic* rather than a *marginal* tax reform.

Similar ambiguity arises in case of the emission tax. Although in this case, there is no evaluation problem, for the initial emission tax rate is equal to zero, the question, whether $\tau_e - \tau_e^\circ (= \tau_e)$ is positive or not, remains open. Naturally, we may expect the emission tax to be positive, but this does not necessarily occur, as indicated earlier. The outcome hinges on the steepness of the social damage curve, on the inverse demand curve and on the curvatures of the production function. Note that as long as the directions of the tax changes remain unclear, we cannot even rule out that the 'ecological' tax reform makes industrial pollutant emissions go up and the environmental quality go down.

Clearly, while the directions of the adjustments of the tax rates remain unclear, we cannot hope to get unique signs for the impact of the tax reform on the firm's profit and public revenue. Totally differentiating both, (5) and (12), yielding

$$\begin{aligned} d\Pi &= -\left(K d\tau_k + E d\tau_e\right), & (23)\\ dT &= \left(E_{p_k}\tau_e + K_{p_k}\tau_k\right) d\tau_k + \left(E_{p_e}\tau_e + K_{p_e}\tau_k\right) d\tau_e - d\Pi, & (24) \end{aligned}$$

shows that $d\Pi$ and dT can be of either sign.

Hence, although we have derived the tax formulae for the initial as well as for the reformed tax regime, a comparison of both does not provide us a clear-cut result. We are not able to decide whether the capital tax and/or the emission tax is increased or decreased. (And similar is true for the firm's profit and public revenue.) To gain further insight, we introduce specific functional forms of the social damage, the production, and the inverse demand function, in the ensuing analysis.

7 A More Specific Model

Let the social damage resulting from industrial pollutant emissions be a quadratic function of E,

$$D(E) = \frac{d_0}{2}E^2 \quad \Longrightarrow \quad D'(E) = d_0 E, \qquad (25)$$

where $d_0 > 0$.

Suppose that the production technology of the monopolistic firm can be characterized by a Cobb-Douglas production function,

$$F(K,E) \;=\; a_0 K^{a_1} E^{a_2}, \qquad a_0, a_1, a_2 > 0, \tag{26}$$

where the parameters of F satisfy

$$a_1 \;\geq\; a_2 \qquad \text{and} \qquad a_1 + a_2 \;=\; 0.5.$$

(26) implies

$$\begin{aligned} F_k(K,E) &= \frac{a_1}{K}F(K,E), & F_{kk}(K,E) &= \frac{a_1(a_1-1)}{K^2}F(K,E), \\ F_e(K,E) &= \frac{a_2}{E}F(K,E), & F_{ee}(K,E) &= \frac{a_2(a_2-1)}{E^2}F(K,E), \\ & & F_{ke}(K,E) &= \frac{a_1 a_2}{KE}F(K,E). \end{aligned}$$

Let the firm face an affine-linear inverse demand curve,

$$P(Q) \;=\; 1 - cQ \qquad \forall Q \in [0,1], \quad c > 0. \tag{27}$$

Note that since the production function exhibits decreasing returns to scale, the cost function is convex; which, in conjunction with (27), guarantees an interior solution of the profit-maximization problem of the firm, for the specified inverse demand curve is 'not too convex' in the sense of (1):

$$P'' \leq -2P'/Q \quad \Leftrightarrow \quad 0 \leq 2c/Q.$$

In the following, let c be equal to one.

According to (3) and (4), the firm's profit-maximizing production decision is determined by its f. o. c. s

$$\begin{aligned} \frac{a_1}{K}Q(1-2Q) &= p_k, \qquad (28) \\ \frac{a_2}{E}Q(1-2Q) &= p_e, \qquad (29) \end{aligned}$$

and (26), implying $0 < Q < 1/2$. Solving this equation system for K, E, and Q yields the firm's factor demand,

$$\begin{aligned} K &= \xi\psi^2, \qquad (30) \\ E &= \psi^2, \qquad (31) \end{aligned}$$

and its supply function,

$$Q = a_0\xi^{a_1}\psi, \tag{32}$$

where $\xi := (a_1p_e)/(a_2p_k)$ and $\psi := (a_0a_2\xi^{a_1})/(p_e + 2a_0^2a_2\xi^{2a_1})$.

To determine the signs of the derivatives of factor demand w. r. t. factor prices, we can either differentiate (30) and (31) w. r. t. p_k and p_e or apply (9) and (10). To pursue the latter, we need the derivatives of the revenue function, $R(K, E)$:

$$\begin{aligned}
R_k &= \frac{a_1}{K}Q(1-2Q), & (33)\\
R_e &= \frac{a_2}{E}Q(1-2Q), & (34)\\
R_{kk} &= \frac{a_1}{K^2}Q(-1+a_1+2Q-4a_1Q), & (35)\\
R_{ee} &= \frac{a_2}{E^2}Q(-1+a_2+2Q-4a_2Q), & (36)\\
R_{ke} &= \frac{a_1}{K}\frac{a_2}{E}Q(1-4Q), & (37)\\
det(H(R)) &= \frac{a_1}{K^2}\frac{a_2}{E^2}Q^2(2Q-1)(a_1+a_2-1+2[1-2(a_1+a_2)]Q), & (38)
\end{aligned}$$

with $Q = F(K, E)$. Using $a_1 + a_2 = 0.5$, (35), (36), and (38) reduce to

$$\begin{aligned}
R_{kk} &= \frac{a_1}{K^2}Q(-1+a_1+2Qa_2), & (39)\\
R_{ee} &= \frac{a_2}{E^2}Q(-1+a_2+2Qa_1), & (40)\\
det(H(R)) &= \frac{a_1}{K^2}\frac{a_2}{E^2}\frac{Q^2}{2}(1-2Q). & (41)
\end{aligned}$$

Note that the signs of K_{p_e} and E_{p_k} are ambiguous: while $1/4 < Q(< 1/2)$ the cross-derivative of the revenue w. r. t. K and E is negative; it is positive for all $0 < Q < 1/4$. The crucial parameter here is a_0. If

$$a_0 > \sqrt{\frac{p_e}{2a_2}}\,\xi^{-a_1} =: \tilde{a}_0, \tag{42}$$

R_{ke} is negative and thus the cross derivatives K_{p_e} and E_{p_k} are positive; otherwise, they are negative. Hence, whether Q falls short or exceeds 1/4 and whether the cross-derivatives of the factor demands are positive or negative crucially depends on the productivity parameter a_0.

Now, to calculate the factor demands and their derivatives, specify the parameters of the production function, the pre-tax factor prices, and the social damage curve. Let $\rho_k = 1$ and $\rho_e = 0.1$; let $a_1 = 0.3$, $a_2 = 0.2$; and let $d_0 = 10$. In this case, the critical value for a_0, given by (42), reduces to

$$a_0 > \tilde{a}_0 = 5^{0.5}3^{-0.3}2^{-0.2}p_k^{0.3}p_e^{0.2} \approx 1.4(1+\tau_k)^{0.3}(0.1+\tau_e)^{0.2}.$$

Note that $\tilde{a}_0$ is a function of τ_k and τ_e.

The optimal tax rates of both regimes, the initial and the ecological tax regime, are adjusted in accordance with (18) respectively (21). Since these tax rates depend on the social value of public funds, λ, on the productivity parameter, a_0, and on the weight initially attached to the social damage, α, any tuple (λ, a_0, α) induces a pair of allocations: the allocations under the initial and under the reformed tax rates. Thus, varying λ, a_0, and α parametrically gives us a set of market equilibria and the induced welfare effects, that could easily be computed by using the above formulae.

In the ensuing subsections, we analyze our computational results, summarized in Tables 1 to 8 of Appendix B. These calculations allow us to compare the allocations under both taxation regimes in a very explicit way. To contrast both regimes as appealingly as possible, Figures 1 to 4 of Appendix A graphically present the tax induced changes of the interesting variables. But before turning to the effects of the ecological tax reform, we should get a notion of the unregulated economy, where all tax rates are fixed at zero. For this purpose, Figure 0 of Appendix A and Table 0 of Appendix B depict the firm's variables and the corresponding social welfare level for the laissez faire economy.

With regard to the two taxation regimes, Tables 1, 2, 3, and 4 show the government's optimal initial capital tax rate, implicitly given by p_k°, and the induced allocation; while Tables 5, 6, 7, and 8 refer to the situation after the ecological tax reform has taken place. Throughout these tables the social value of public funds is increased. Starting from $\lambda = 1$, where the social value of public funds equals the private value of income, λ increases up to two. Within each table a_0 is varied parametrically. (Similar is true for Figures 1 to 4 of Appendix A.)

7.1 The Initial Tax Rates

The thin lines of Figures 1 to 4 of Appendix A and Tables 1 to 4 of Appendix B exhibit our results for the initial tax regime. The latter are structured as follows. Given the social price of public funds, λ, and the initial social weight attached to the ecological damage, α, the productivity parameter a_0 (1st column) is increased within each table, ranging from 0.90 to (at least) 2.60.[26] The optimal capital tax of the initial tax regime is implicitly given in the second column ($\tau_k^\circ = p_k^\circ - 1$). Columns three, four, and five show the behavior of the firm (factor demand and output). The first derivatives of factor demand, whose signs have turned out to be crucial in the foregoing analysis, are given in the next three columns. Each table continues by a second part containing the firm's revenue, its cost, and its profit. The last two columns are attached to the public sector, depicting public revenue and the resulting welfare level.

Starting from $a_0 = 0.90$, the capital tax rate first decreases (the subsidy increases) up to an a_0-value that is close to 1.20, and it increases beyond this value.[27] When a_0 increases, less capital is used (except for the first two a_0-values in Tables 3 and 4). Similar is true for pollutant emissions. Though E_{p_k} is positive (7th column), the first order effect of p_k on E is not sufficiently strong to increase the use of environmental inputs. A more severe taxation of capital makes the firm demand less capital and emit less pollutants. However, the emission-capital ratio increases as a_0 goes up. Hence, *technical progress*, measured in terms of a higher a_0-value, *leads to more pollutant intensive production*, albeit total pollutant emissions decrease and the prevailing environmental quality improves. Note that, although the firm uses less of both factors, output increases (slightly), since the productivity gain more than outweighs the input reduction.[28]

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[26] Here we only present those results of the initial regime that are calculated for the polar case of $\alpha = 1$. Carrying out the same calculations for $\alpha < 1$ does not alter the results qualitatively. The main effect of a lower α-value is a higher initial price of capital.

[27] The fact that capital is not taxed but subsidized depends on the pre-tax prices of capital and emissions as well as on the steepness of the social damage function. Since appropriately changing these exogenous parameters turns the subsidy into a positive tax, the fact that $p_k^\circ < 1$ should not be overemphasized.

[28] Note also that the firm's output exceeds 1/4 (but falls short of 1/2), confirming our presumption that a_0 satisfies condition (42).

While a_0 increases, capital and emissions become less variable w. r. t. factor price changes. ($K_{p_k}, K_{p_e}, E_{p_k}$, and E_{p_e} decrease in absolute values, except for very low a_0-values when λ is sufficiently high.) This reflects the fact that since capital and emissions are reduced as the productivity rises, the cost of giving up one additional unit of any of both factors increases implying less elastic factor demand. In particular, note that the cross-derivatives are positive (column 7). This confirms our previous assumption that, evaluated at the firm's optimal production plan, the cross-derivative of the production function is not too large in the sense of (8).

Since there is, except for very low a_0-values, little variability in Q, the firm's revenue, ranging from 0.2383 to 0.2497 for $\lambda = 1$ and from 0.2120 to 0.2495 for $\lambda = 2$, remains relatively constant. On the contrary, a significant change in the firm's cost can be observed. While a_0 goes up, production cost falls to some 20% of its $a_0 = 0.9$-value. Accordingly, profit increases and even approaches to revenue as production becomes more effective, though the use of capital becomes more expensive.

Since there is a significant erosion of the tax basis as the capital tax increases, one might think that public tax revenue falls as the government tightens the tax screw. But the induced reduction in capital demand does not outweigh the effect of a higher tax rate on capital. Thus, along the path of technical progress, the government faces an increasing branch of the 'Laffer curve'. Naturally, similar is true for society's welfare. But while welfare increases rapidly for lower productivity parameters, its growth is (slightly) slowed down for higher values of a_0.

It is worthwhile to emphasize that the structure of the paths of the economic variables through Tables 1, 2, 3, and 4 is constant. (See also the thin graphs of Figures 1 to 4.) This means that our qualitative results (the patterns of the graphs) are robust w. r. t. the social value of public funds. Moreover, while throughout Tables 1 to 4, λ doubles from 1 to 2, the firm's revenue remains almost unchanged; similarly, profit and welfare are only slightly decreased (at least if a_0 is not close to 0.9). This gives us the possibly surprising result that *the outcome is relatively more affected by the parameter a_0 than by the social price of public funds.*

7.2 The Ecological Tax Reform

The bold lines of Figures 5 to 8 of Appendix A and Tables 5 to 8 of Appendix B depict our computational results, when the government considers to implement the proposed ecological tax reform. Again, throughout these tables and figures the social value of public funds increases from one to two, while within each of them a_0 is varied parametrically, ranging from 0.9 to (at least) 2.2.

Starting from $a_0 = 0.9$, the price of capital decreases continuously if the firm becomes more productive. When the social price of public funds goes up, the decline of p_k is reduced (the p_k-graph becomes flatter); if public funds are sufficiently scarce, $\lambda = 2$, this process stops and the government taxes capital at a constant rate of 33.33%, independent of a_0. Similarly, the government reduces the emission tax while a_0 rises; and the higher is λ the more the government hesitates to lower the emission tax (the p_e-graph becomes flatter). If λ approaches two, p_e is kept almost constant (still slightly decreasing except for very low a_0-values).

If the firm becomes highly productive, i. e., a_0 becomes sufficiently large, the government does not only subsidize capital but also pollutant emissions in order to promote economic activity. At this point, where the government begins to subsidize pollutant emissions, say a_0^*, both factor prices equal their initial values. (The p_k- and the p_e-graph cut the p_k°- and the p_e°-graph, respectively.)[29] Hence, if a_0 exceeds a_0^*, the firm obviously benefits from the ecological tax reform, for both tax rates are lowered.

If the firm becomes even more productive such that a_0 exceeds some other critical value, say $\hat{a}_0 (> a_0^\circ)$, the subsidy may even exceed the pre-tax factor price resulting in negative cum-tax prices.[30] However, since these cases seem to be of less empirical relevance (cost becomes negative and profit exceeds revenue), little attention is put on the right tail of the a_0-range where both inputs are heavily subsidized in the remainder of our analysis.

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[29] The a_0-value where p_k and p_e coincide with their initial values, a_0^*, is given by 1.74 for $\lambda = 1.0$, by 1.87 for $\lambda = 1.1$, and by 2.56 for $\lambda = 1.5$; for $\lambda = 2.0$, the intersection of the p_k- and the p_e-graph with the p_k°- and the p_e°-graph lies out of the considered a_0-range.

[30] The a_0-value where p_k and p_e become simultaneously negative, $\hat{a}_0$, is given by 1.871 for $\lambda = 1.0$ and by 2.01 for $\lambda = 1.1$; for any higher λ-value, the intersection of the p_k- and the p_e-graph with the abscissa is out of the considered a_0-range.

Now, let us inspect factor demand and its derivatives as well as the firm's supply. Starting from $a_0 = 0.9$, the firm uses more capital and emits more pollutants if its productivity goes up. However, if a_0 approaches some critical value, say $\bar{a}_0$, capital and emissions reach their peaks, and both reduced beyond $\bar{a}_0$. (The higher the social value of public funds the lower is $\bar{a}_0$.) Note that the variability of factor demand (w. r. t. a_0) is relatively low compared to the variability of output. This reflects the fact that the firm makes use of the productivity gains through increasing its output while keeping its factor demand almost constant. Correspondingly, there is little variability of the emission-capital ratio (slightly decreasing for low and slightly increasing for high a_0-values). Thus, technical progress, measured in terms of a higher a_0-value, *does not* induce significant changes of the input mix.

Also contrary to what we found for the initial tax regime, the derivatives of factor demand w. r. t. factor prices *increase* in absolute values if a_0 goes up (at least if factor prices are not too close to zero).[31] As we have expected from our previous analysis, while a_0 does not exceed $\tilde{a}_0 \approx 1.10$, defined by (42), the cross-derivatives K_{p_e} and E_{p_k} are negative; but else, positive. Note that in the first case, we also have $Q < 1/4$; whereas in the second case, output exceeds $1/4$. This implies that our result of the initial regime where both cross-derivatives have been positive is also true under the second regime for almost all a_0-values. Hence, our hypothesis that evaluated at the firm's optimal production plan, the cross-derivatives of factor demand are positive is supported by the numerical results under both regimes.

The effects of higher values of a_0 and λ on the firm's profit are unambiguous. Holding λ constant, the firm's profit increases as a_0 goes up, whereas its cost increases slightly for low but decrease substantially for higher a_0-values: For lower values of the productivity parameter, the reduction of both tax rates is insufficient to outweigh the cost increase resulting from higher capital and emission demand. Holding, on the contrary, a_0 constant, the firm's output, revenue, and its profit decrease, whereas its cost increases as λ goes up. Thus, *the scarcer public funds*

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[31] This is consistent with our finding from the initial tax regime that the variability of K and E is the higher the lower are the factor prices. Since higher a_0-values make the government to lower its tax rates (increase its subsidies), $K_{p_k}, K_{p_e}, E_{p_k}$, and E_{p_e} increase in absolute values. (If, however, a_0 exceeds $\tilde{a}_0$, the derivatives of factor demand do not behave well, in the sense that K_{p_k} and E_{p_e} become positive.)

the more the government exploits the industry through tightening the tax screw. Correspondingly, public revenue increases if the shadow cost of public funds goes up. The more public services are underprovided (measured by a higher λ) the more the government uses distortionary tax rates to raise public funds. However, a higher λ-value does neither imply a higher nor a lower welfare level; whereas, holding λ constant, higher a_0-values unambiguously imply a higher welfare. While a higher price of public funds keeps welfare almost unchanged, a variation of the firm's productivity alters welfare significantly. Similar is true for industrial profit: The profit reduction is rather small as λ increases, compared to the profit decline when a_0 falls.

Note that public revenue falls if the firm's productivity increases, unless λ is very high and a_0 is sufficiently low. *When the firm becomes more productive, the government gives the firm a tax relief*, resulting in a lower public revenue but higher welfare. Only if public funds are particularly scarce, the government may use industrial productivity gains to collect more revenue.

Similar to what we found under the initial tax regime, our qualitative findings are robust w. r. t. the social value of public funds, i. e., the patterns of the considered economic variables are more or less invariant. Our computational results show that, also for the ecological tax regime, a_0 is a rather critical parameter for the optimal tax rates and the resulting allocation. A change of the production parameter a_0 may affect results even more than a change of the social value of public funds.

7.3 Comparing both Tax Regimes

Now, we turn to the basic question: which consequences does the proposed ecological tax reform imply? To answer this, we have to compare for any given values of a_0 and λ the variables of the initial and of the reformed tax regime. Let us go through the different variables successively, thereby neglecting the, empirically less relevant, highest a_0-values where the reformed factor prices become negative ($a_0 > \hat{a}_0$).

First of all, compare the tax rates of the initial tax regime with those of the ecological tax reform. The transition towards the reformed tax system implies higher factor prices for all a_0-values not exceeding a_0^*. Hence, for any $a_0 < a_0^*$ the initial after-tax factor prices p_k° and $p_e^\circ = 0.1$ fall short of their reformed counterparts. Moreover, the critical value a_0^* increases as the shadow cost of public funds goes up. If λ is sufficiently high, the tax reform implies higher factor prices for the whole considered interval of a_0. Yet, we cannot rule out the polar case where the productivity parameter a_0 exceeds a_0^*, and the government finds it advantageous to subsidize rather than to tax pollutant emissions and to tax capital less than under the initial regime.[32] (The horizontal lines in Tables 5, 6, and 7 separate the areas for which the reformed factor prices exceed their initial counterparts from those where the opposite is true.)

Since through the tax reform p_k and p_e are increased for $a_0 < a_0^*$ (and decreased else), capital demand, pollutant emissions, and thus output fall if $a_0 < a_0^*$ (increase else). Thus, the transition towards an ecological tax system augments the environmental quality but leads to lower output levels. Correspondingly, the firm's revenue decreases, its cost increases, and its profit falls, whereas public tax revenue ascends and overall welfare is improved. Hence, neglecting the extreme cases where the tax rates are reduced ($a_0 > a_0^*$), *industry suffers from the ecological tax reform while welfare is improved.* Especially for the lower range of a_0-values, the transition towards an ecological tax system implies significant potential welfare gains accompanied by substantial improvements of the environmental quality and higher public revenue. (The arguments are reversed for $a_0 > a_0^*$.)

To sum up, for a wide range of parameter values there is a strong tendency of the government not only to establish a positive tax on pollutant emissions but also to increase the tax rate on capital. Or in other words, the initial tax rates are too low, given that two tax rates are available. Clearly, if the industry faces too low factor prices, industrial pollutant emissions are too high. Increasing the tax rates of both(!) factors discourages production and lowers profit. But although economic activity is hampered through higher tax rates, resulting in a narrowing of the tax base, public revenue increases.[33] While the social price of public funds

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[32] Clearly, by definition of $\hat{a}_0$ and a_0^* we have $a_0^* < \hat{a}_0$.

[33] In the terms of BOVENBERG AND VAN DER PLOEG (1994), LIGTHART AND VAN DER PLOEG (1994), and others, this paper rejects the hypothesis of a 'blue' double dividend (profits) but

exceeds the marginal utility of private income, this income transfer implies a welfare improvement per se. Moreover, since pollutant emissions are reduced significantly, the prevailing environmental quality is considerably improved. Hence, although there may be significant costs associated with the transition towards an ecological tax system, partly paid by the industry through lower profits and partly by consumers through higher output prices, *welfare improvements are guaranteed and may even be huge.*

8 Conclusions

We have considered the welfare effects induced by the transition from some initial tax system towards an ecologically reformed tax system. At the initial state, the government exclusively taxes the use of capital. The proposed tax reform requires levying taxes on pollutant emissions as well and reconsidering the level of the capital tax rate. To investigate the implications of this 'green' tax reform, we first calculate the optimal (second-best) tax rates of both tax regimes.

In the initial tax regime, the government is not (fully) aware of the ecological damage resulting from industrial pollutant emissions. Consequently, an emission tax is not established and public funds are raised through the imposition of a tax rate on capital, exclusively. In this case, the capital tax consists of three parts, reflecting the fact that the government seeks to pursue a threefold purpose: to regulate the monopolistic firm, to raise public funds, and to improve the environmental quality (if the government perceives at least some portion of the social damage stemming from pollutant emissions). Contrary to what one might expect, the tax rate on capital *decreases* as the government becomes aware of the ecological problems, provided that the government relies only on capital taxation. The intuition behind this is that through lowering the capital tax the government seeks to induce a factor substitution effect: if the use of capital becomes more attractive, the firm substitutes environmental inputs by capital.

Under the ecological tax system an environmental tax is introduced and the capital tax is adjusted appropriately. Now, the optimal tax rate on capital is

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supports the existence of a 'red' double dividend.

composed only of two terms: one representing the government's endeavor to affect the firm's output decisions and one to raise public funds. The optimal emission tax, however, incorporates a third term, reflecting the social damage resulting from industrial pollutant emissions.

Although we have been able to derive the tax formulae of both fiscal regimes, a comparison of them does not provide us clear-cut results concerning our basic question: which economic and ecological consequences does the proposed tax reform imply? For example, we cannot infer in which direction tax rates, industrial profit, public revenue, and environmental quality move. This ambiguity arises because we deal with a drastic rather than with a marginal tax reform. Therefore, to gain further insight, we consider a more specific version of our model: Assuming a quadratic damage function, a Cobb-Douglas production function, and an affine-linear inverse demand curve the model is investigated comprehensively.

Among others, the tax rates depend on the social value of public funds and on the productivity parameter of the firm. Parametrical variation of these parameters provides us some insight into the patterns of the optimal tax rates and the resulting allocations. It turns out that, under both tax regimes, the outcome is more affected by the productivity of the firm than by the social price of public funds. Similarly, under both fiscal regimes, our qualitative findings – the patterns of the crucial economic variables – are robust w. r. t. the social value of public funds.

A comparison of both tax regimes reveals the consequences of an ecological tax reform: Given the firm's productivity is not too high, *the ecological tax reform implies an increase of both tax rates; a decrease of capital demand, pollutant emissions, and total output; moreover, the firm's cost increases, while its revenue and profit fall; but public tax revenue rises.* In an extreme case, where the productivity parameter exceeds some critical value, the government does not increase but reduce the tax rates, and all effects are reversed. In any case, the realization of an ecological tax reform implies significant, and possibly huge, welfare gains, which are commonly accompanied by substantial improvements of the environmental quality; yet we have to expect profit and consumer surplus to fall.

Appendix A

Without any regulatory policy

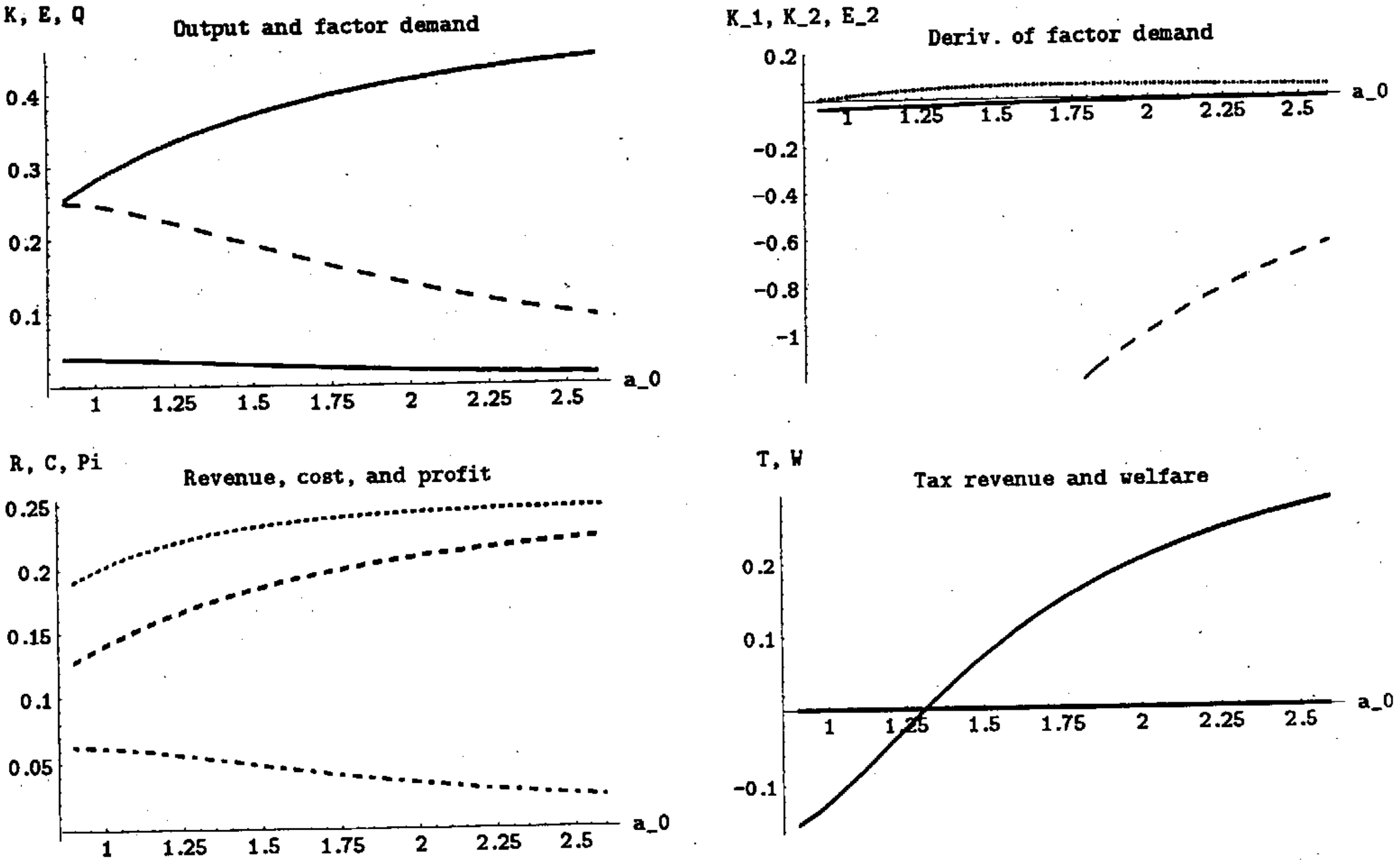


Figure 0

Comparing Both Regimes for $\lambda = 1.0$

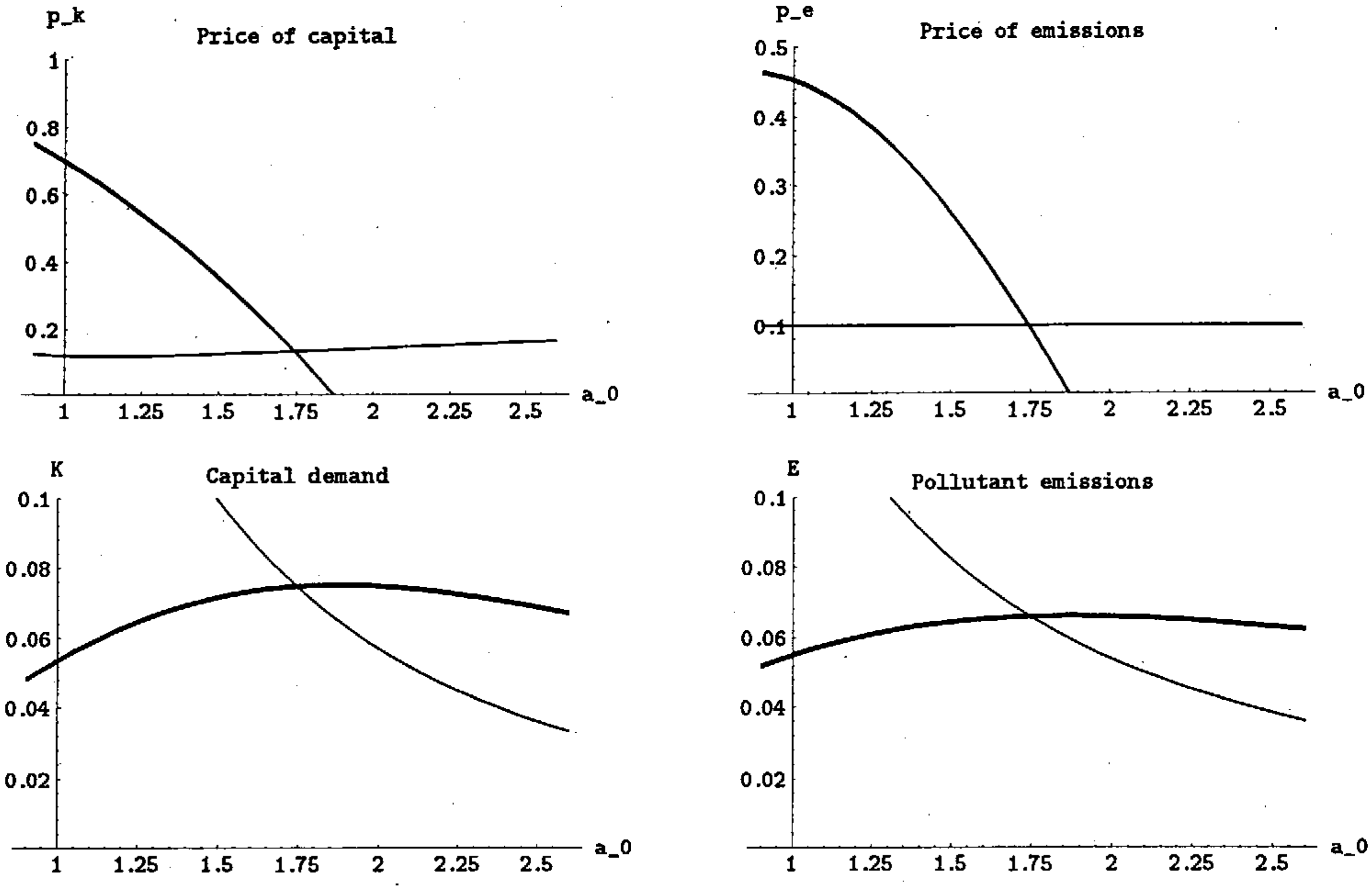


Figure 1a

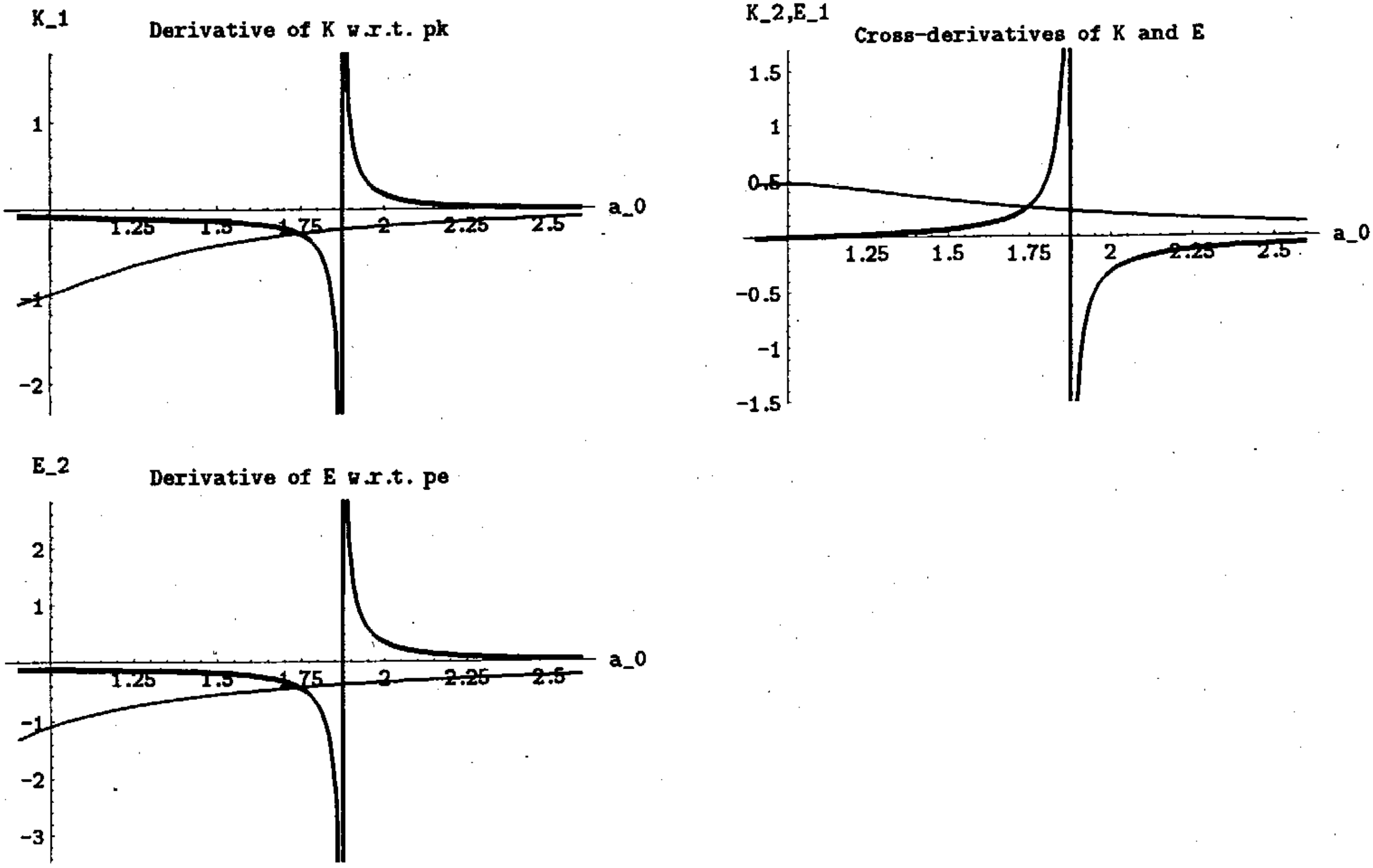

K_1
Derivative of K w.r.t. pk
1
-1
-2
1.25
1.5
1.75
2
2.25
2.5
a_0
K_2,E_1
Cross-derivatives of K and E
1.5
1
0.5
-0.5
-1
-1.5
1.25
1.5
1.75
2
2.25
2.5
a_0
E_2
Derivative of E w.r.t. pe
2
1
-1
-2
-3
1.25
1.5
1.75
2
2.25
2.5
a_0

Figure 1b

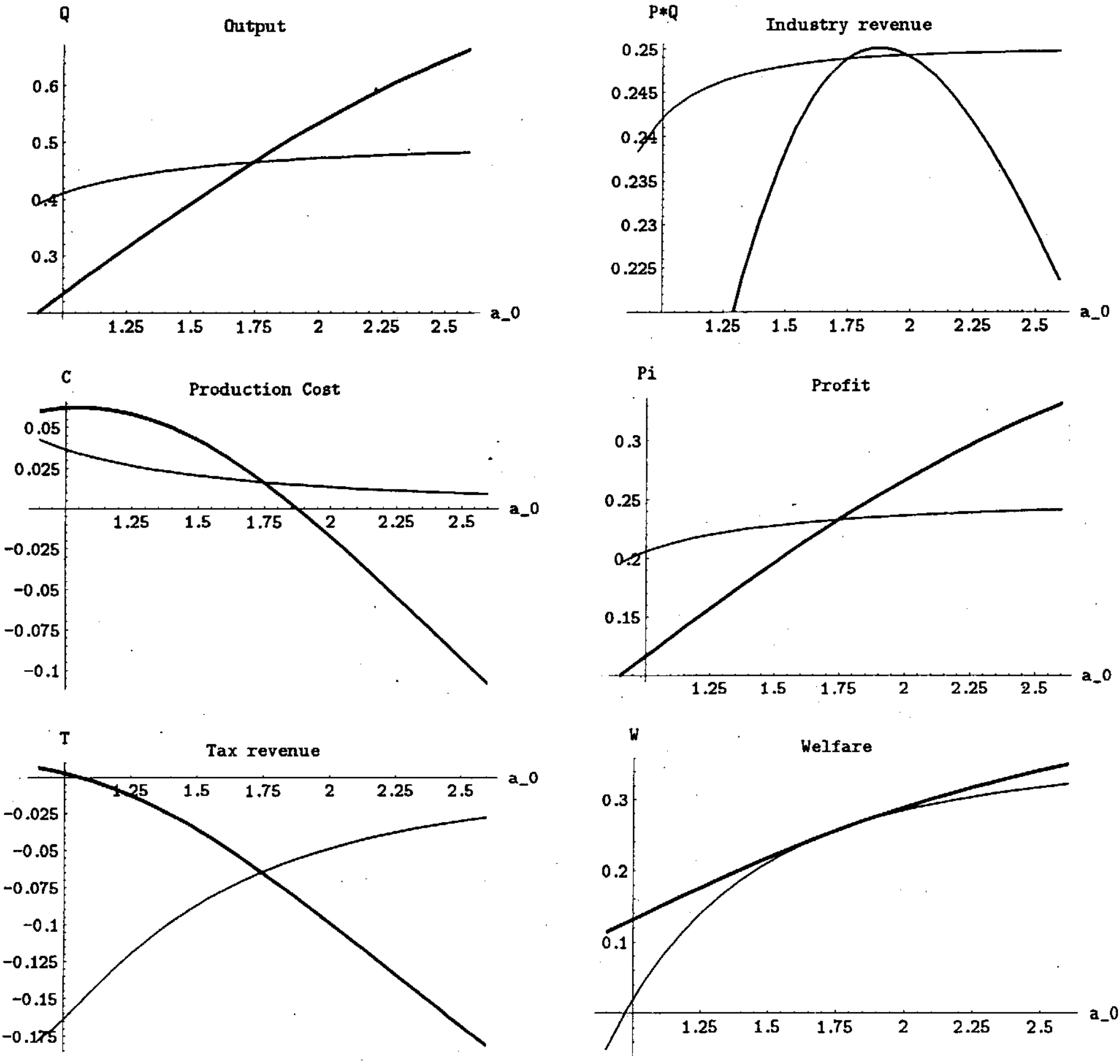
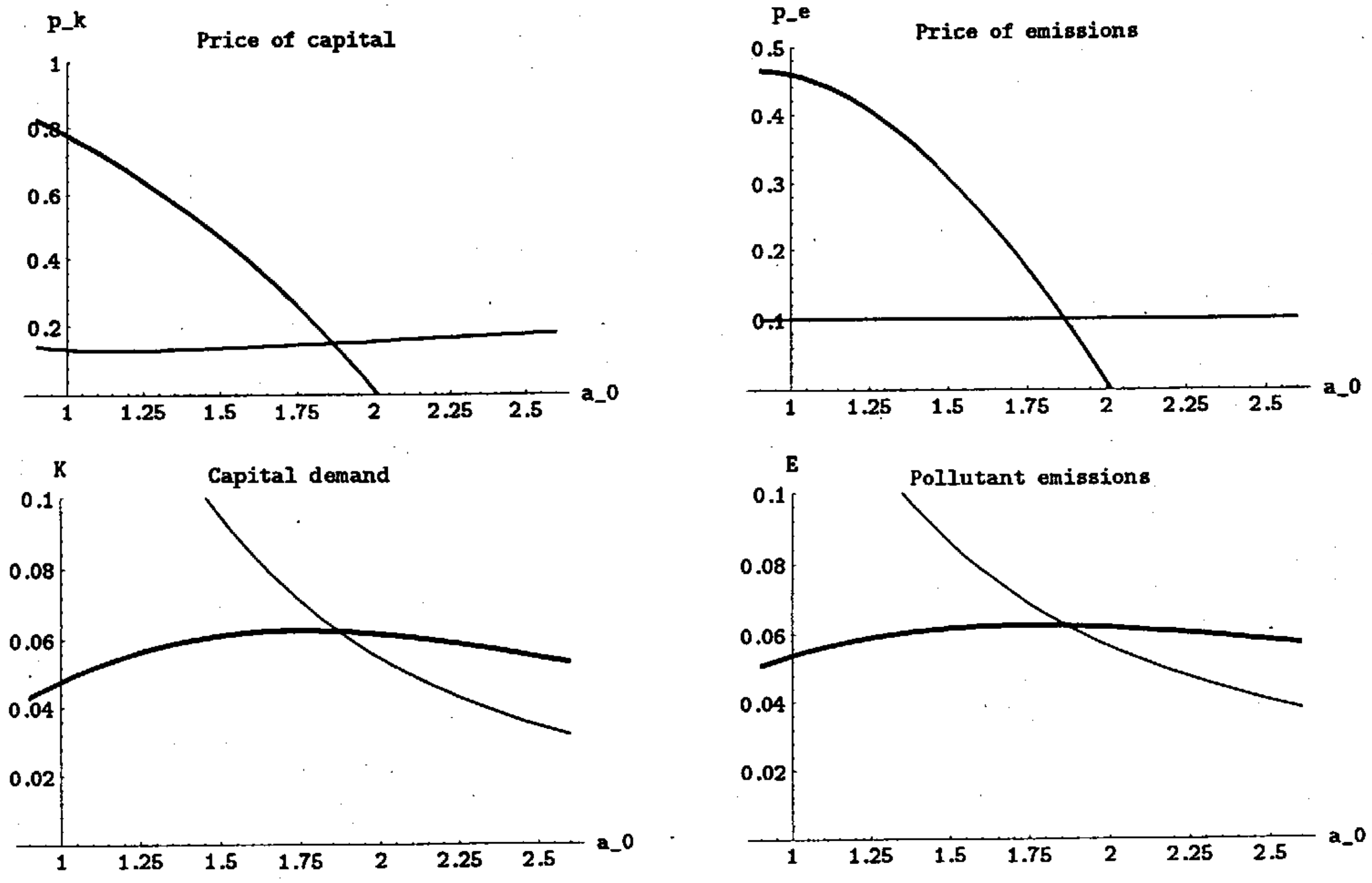

Q
Output
0.6
0.5
0.4
0.3
1.25
1.5
1.75
2
2.25
2.5
a_0
P*Q
Industry revenue
0.25
0.245
0.24
0.235
0.23
0.225
1.25
1.5
1.75
2
2.25
2.5
a_0
C
Production Cost
0.05
0.025
-0.025
-0.05
-0.075
-0.1
1.25
1.5
1.75
2
2.25
2.5
a_0
Pi
Profit
0.3
0.25
0.2
0.15
1.25
1.5
1.75
2
2.25
2.5
a_0
T
Tax revenue
-0.025
-0.05
-0.075
-0.1
-0.125
-0.15
-0.175
1.25
1.5
1.75
2
2.25
2.5
a_0
W
Welfare
0.3
0.2
0.1
1.25
1.5
1.75
2
2.25
2.5
a_0

Figure 1c

Comparing Both Regimes for $\lambda = 1.1$



Figures 2a

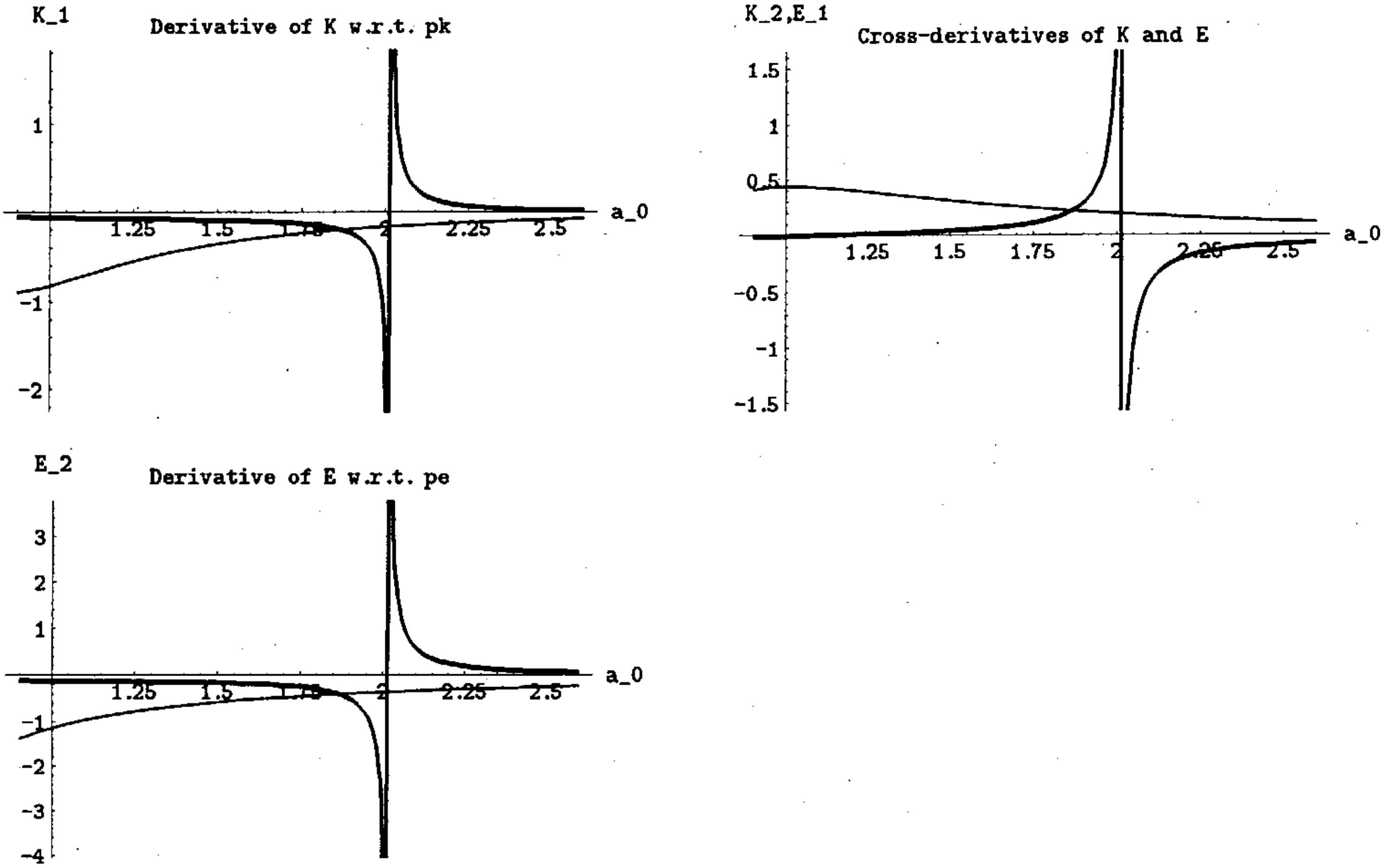

K_1
Derivative of K w.r.t. pk
1
-1
-2
1.25
1.5
1.75
2
2.25
2.5
a_0
K_2,E_1
Cross-derivatives of K and E
1.5
1
0.5
-0.5
-1
-1.5
1.25
1.5
1.75
2
2.25
2.5
a_0
E_2
Derivative of E w.r.t. pe
3
2
1
-1
-2
-3
-4
1.25
1.5
1.75
2
2.25
2.5
a_0

Figure 2b

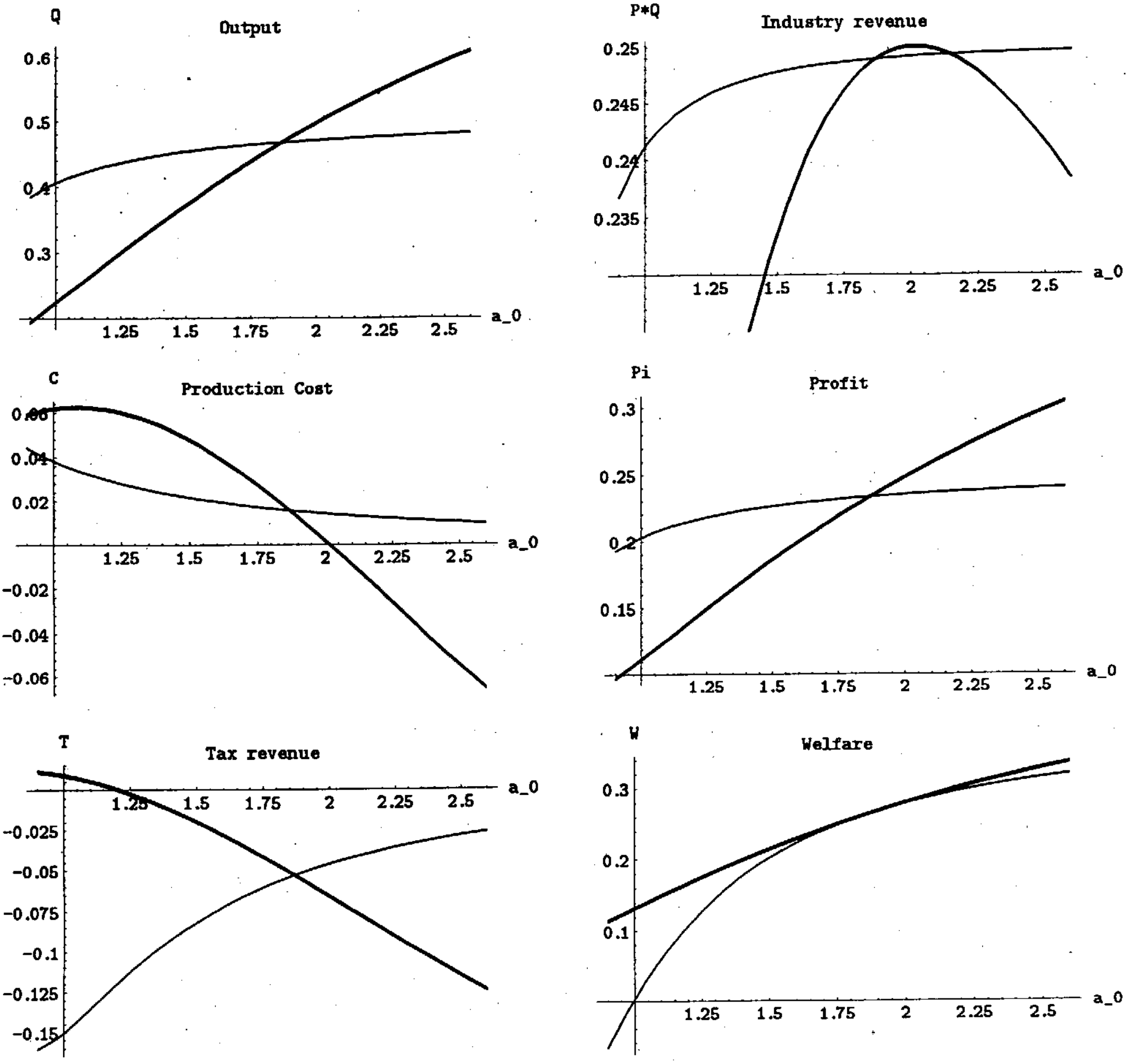

Q
Output
0.6
0.5
0.4
0.3
1.25
1.5
1.75
2
2.25
2.5
a_0
P*Q
Industry revenue
0.25
0.245
0.24
0.235
1.25
1.5
1.75
2
2.25
2.5
a_0
C
Production Cost
0.06
0.04
0.02
-0.02
-0.04
-0.06
1.25
1.5
1.75
2
2.25
2.5
a_0
Pi
Profit
0.3
0.25
0.2
0.15
1.25
1.5
1.75
2
2.25
2.5
a_0
T
Tax revenue
-0.025
-0.05
-0.075
-0.1
-0.125
-0.15
1.25
1.5
1.75
2
2.25
2.5
a_0
W
Welfare
0.3
0.2
0.1
1.25
1.5
1.75
2
2.25
2.5
a_0

Figure 2c

Comparing Both Regimes for $\lambda = 1.5$

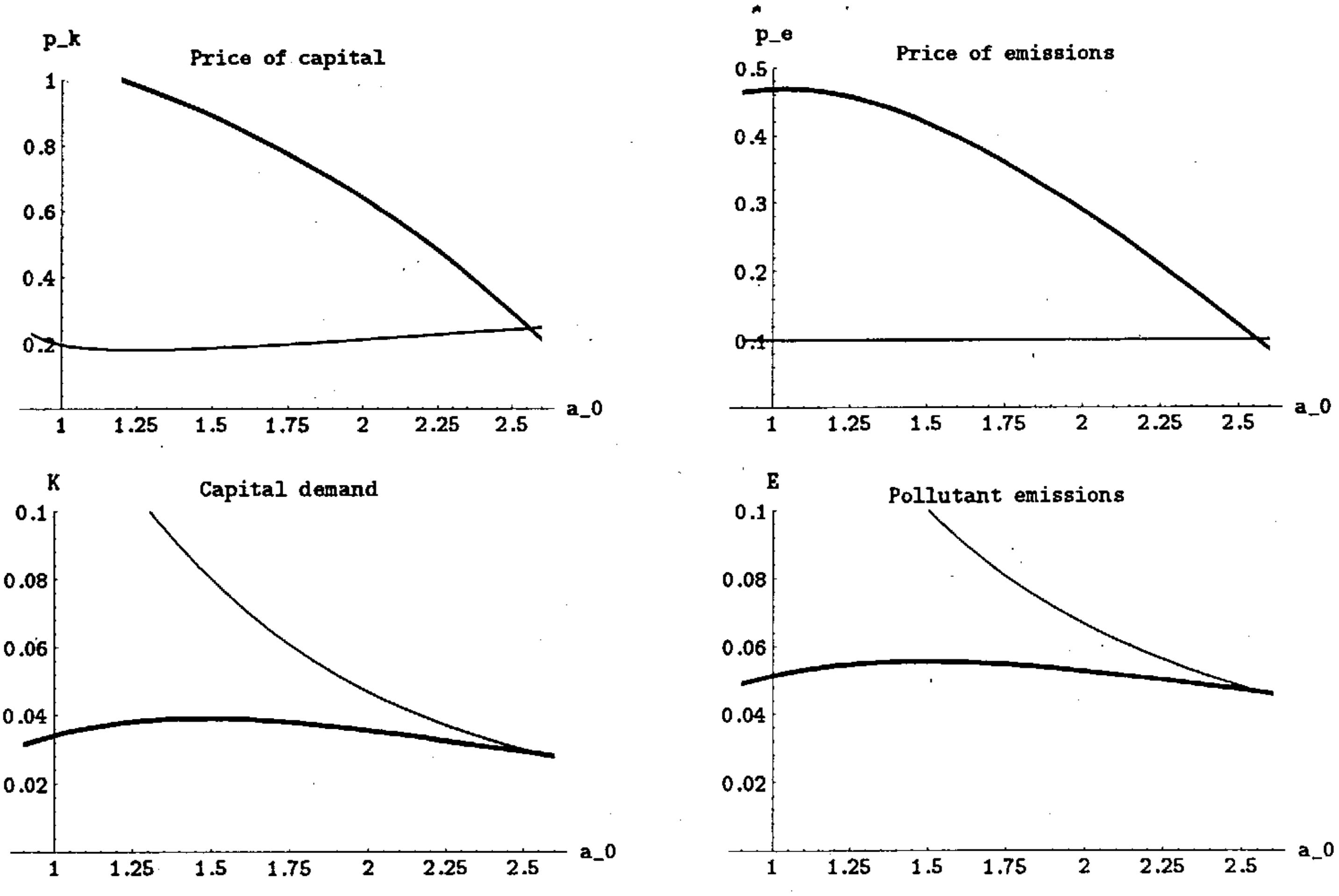


Figure 3a

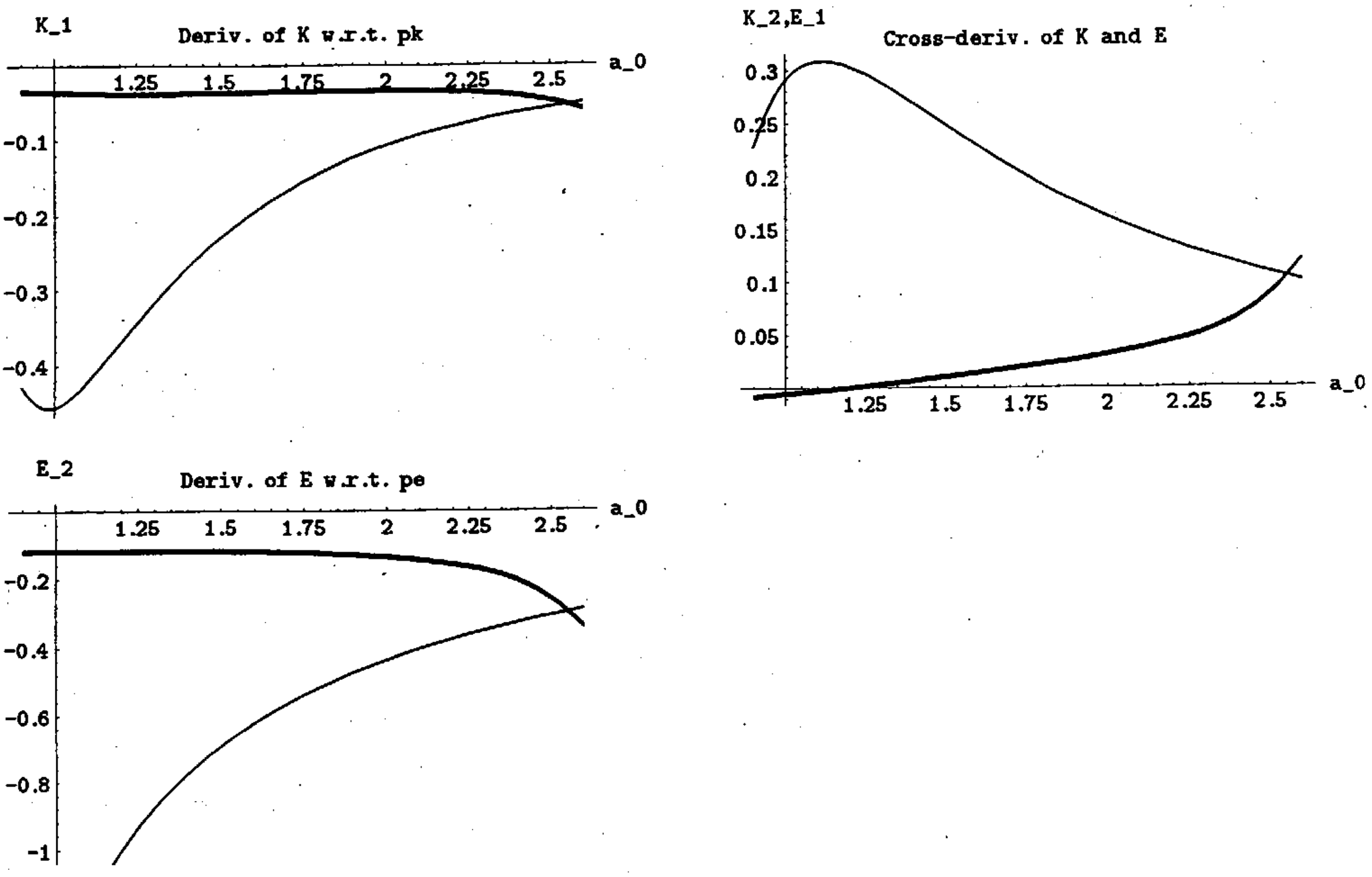

K_1
Deriv. of K w.r.t. pk
a_0
1.25
1.5
1.75
2
2.25
2.5
-0.1
-0.2
-0.3
-0.4
K_2,E_1
Cross-deriv. of K and E
0.3
0.25
0.2
0.15
0.1
0.05
a_0
1.25
1.5
1.75
2
2.25
2.5
E_2
Deriv. of E w.r.t. pe
a_0
1.25
1.5
1.75
2
2.25
2.5
-0.2
-0.4
-0.6
-0.8
-1

Figure 3b

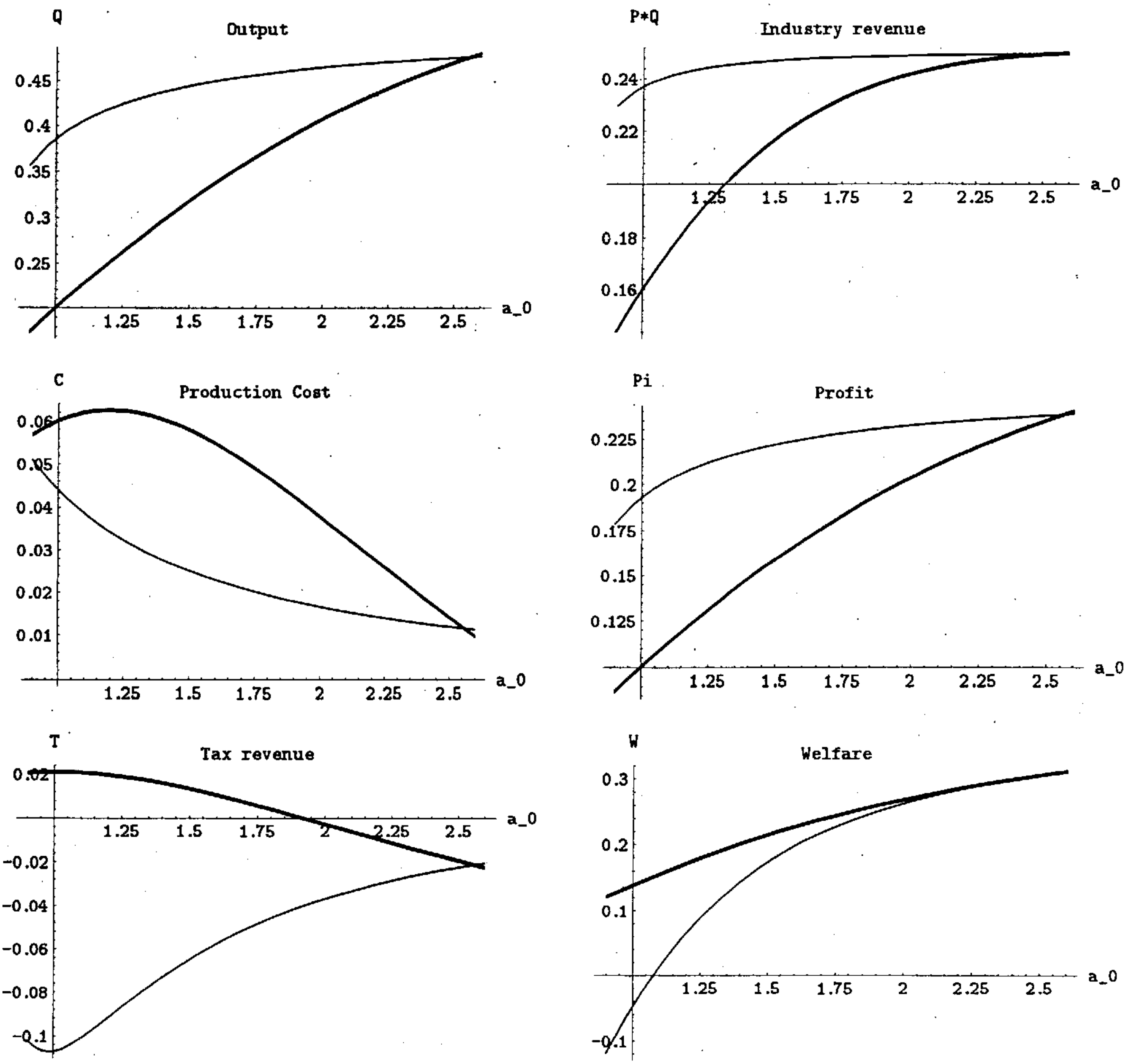

Q
Output
0.45
0.4
0.35
0.3
0.25
1.25
1.5
1.75
2
2.25
2.5
a_0
P*Q
Industry revenue
0.24
0.22
0.18
0.16
1.25
1.5
1.75
2
2.25
2.5
a_0
C
Production Cost
0.06
0.05
0.04
0.03
0.02
0.01
1.25
1.5
1.75
2
2.25
2.5
a_0
Pi
Profit
0.225
0.2
0.175
0.15
0.125
1.25
1.5
1.75
2
2.25
2.5
a_0
T
Tax revenue
0.02
-0.02
-0.04
-0.06
-0.08
-0.1
1.25
1.5
1.75
2
2.25
2.5
a_0
W
Welfare
0.3
0.2
0.1
-0.1
1.25
1.5
1.75
2
2.25
2.5
a_0

Figure 3c

Comparing Both Regimes for $\lambda = 2.0$

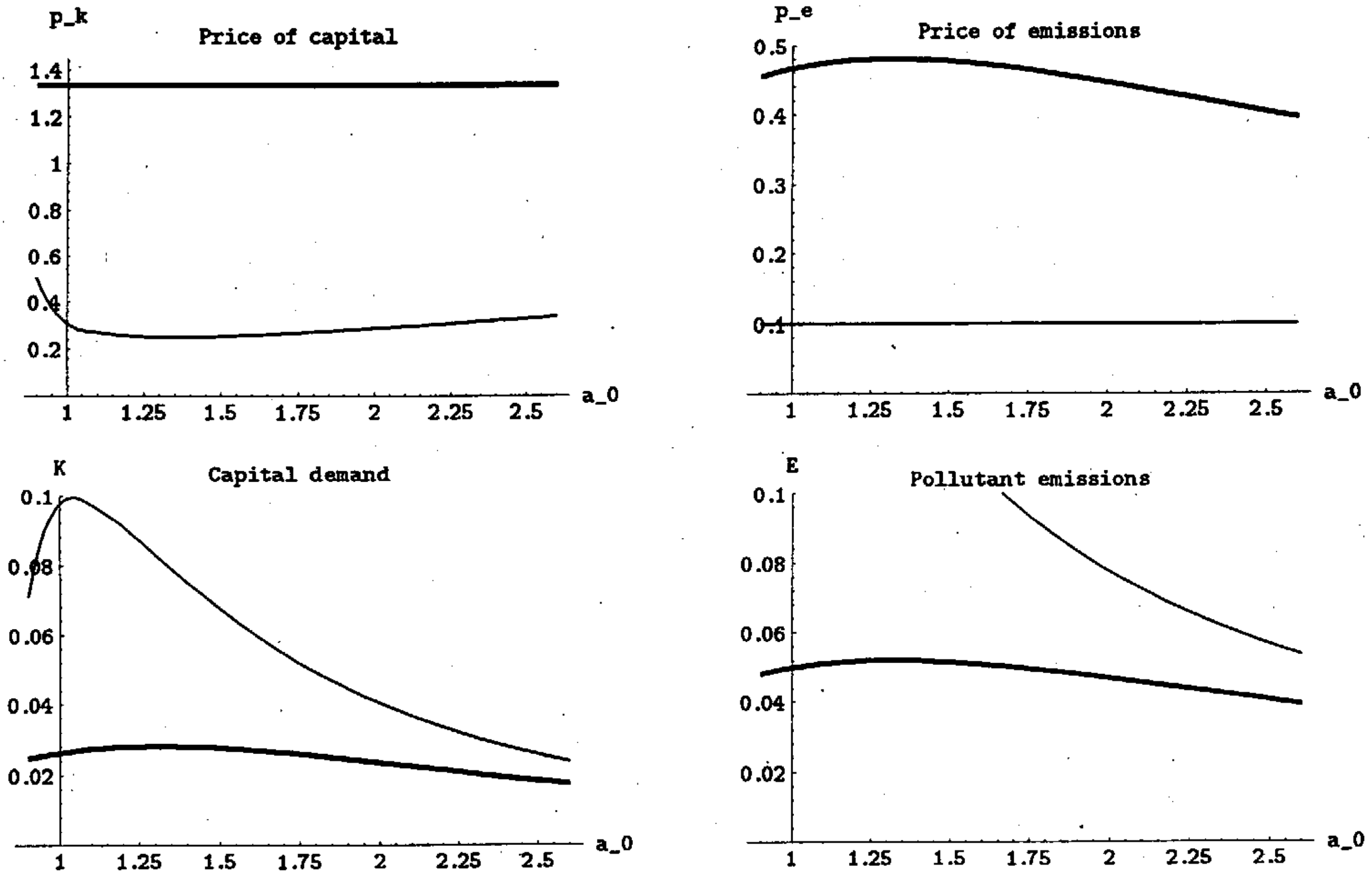
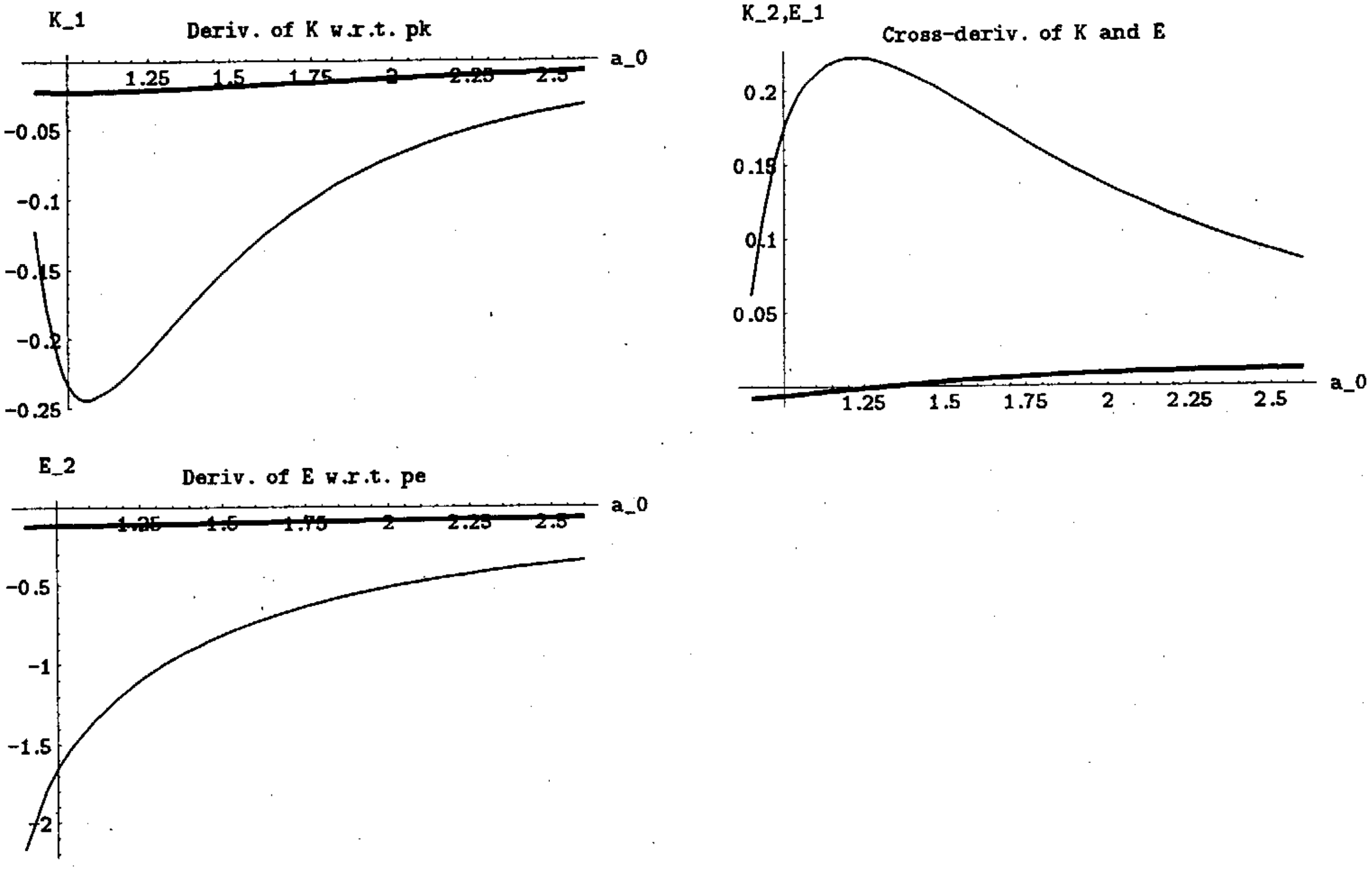


Figure 4a



K_1
Deriv. of K w.r.t. pk
a_0
1.25
1.5
1.75
2
2.25
2.5
-0.05
-0.1
-0.15
-0.2
-0.25
K_2,E_1
Cross-deriv. of K and E
0.2
0.15
0.1
0.05
a_0
1.25
1.5
1.75
2
2.25
2.5
E_2
Deriv. of E w.r.t. pe
a_0
1.25
1.5
1.75
2
2.25
2.5
-0.5
-1
-1.5
-2

Figure 4b

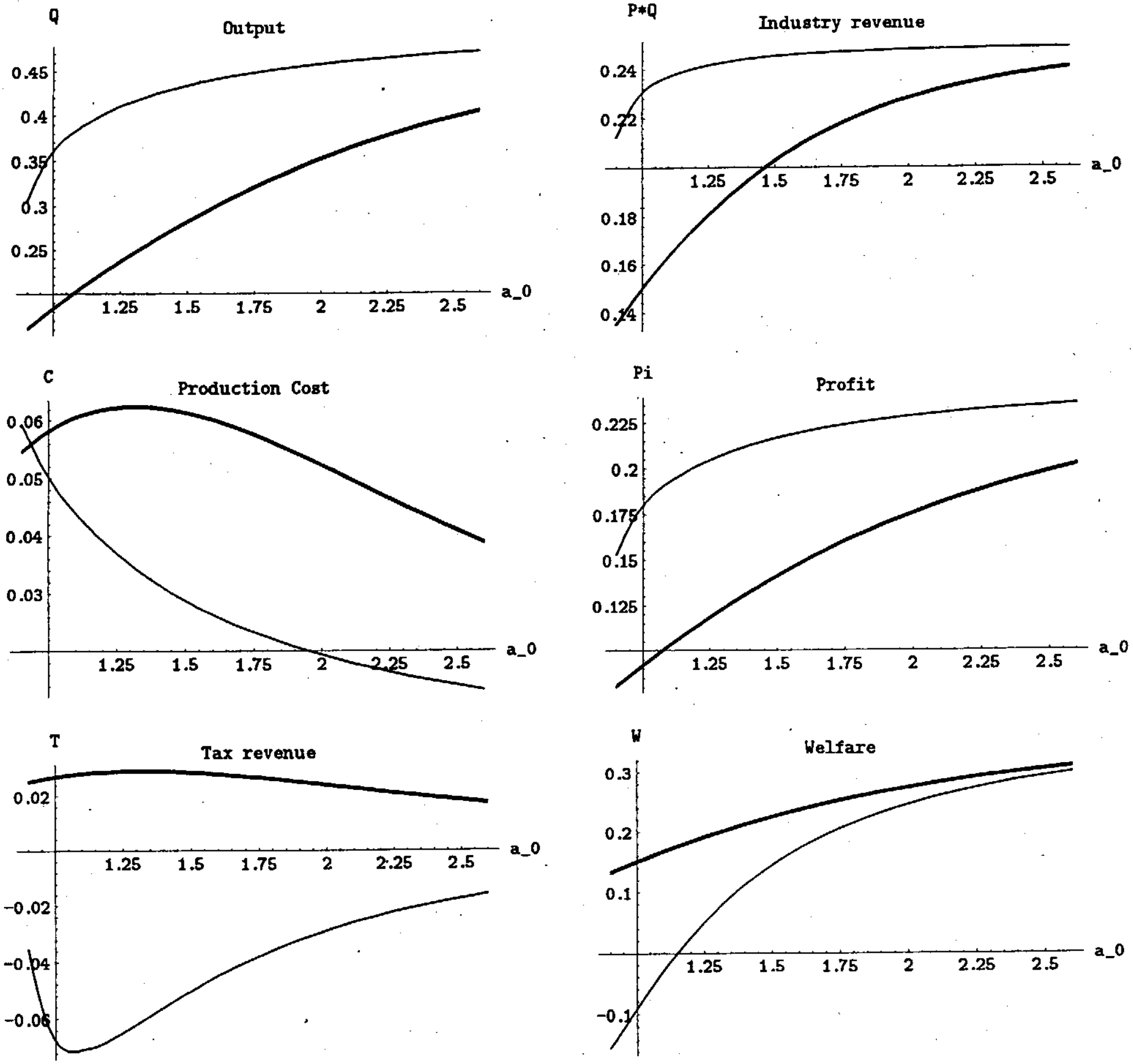

Q
Output
0.45
0.4
0.35
0.3
0.25
1.25
1.5
1.75
2
2.25
2.5
a_0
P*Q
Industry revenue
0.24
0.22
0.18
0.16
0.14
1.25
1.5
1.75
2
2.25
2.5
a_0
C
Production Cost
0.06
0.05
0.04
0.03
1.25
1.5
1.75
2
2.25
2.5
a_0
Pi
Profit
0.225
0.2
0.175
0.15
0.125
1.25
1.5
1.75
2
2.25
2.5
a_0
T
Tax revenue
0.02
-0.02
-0.04
-0.06
1.25
1.5
1.75
2
2.25
2.5
a_0
W
Welfare
0.3
0.2
0.1
-0.1
1.25
1.5
1.75
2
2.25
2.5
a_0

Figure 4c

Appendix B

Table 0: **Without any regulatory policy**

a_0	K	E	Q	K_{p_k}	K_{p_e}, E_{p_k}	E_{p_e}
0.90	0.0375	0.2499	0.2547	-0.0371	0.0028	-2.4805
1.00	0.0369	0.2462	0.2808	-0.0342	0.0182	-2.3404
1.10	0.0358	0.2383	0.3040	-0.0311	0.0309	-2.1777
1.20	0.0342	0.2279	0.3243	-0.0281	0.0406	-2.0085
1.40	0.0306	0.2037	0.3576	-0.0227	0.0526	-1.6860
1.60	0.0269	0.1790	0.3832	-0.0183	0.0572	-1.4088
1.80	0.0235	0.1564	0.4030	-0.0149	0.0574	-1.1814
2.00	0.0205	0.1366	0.4184	-0.0122	0.0552	-0.9979
2.20	0.0179	0.1196	0.4306	-0.0102	0.0518	-0.8502
2.40	0.0158	0.1051	0.4403	-0.0086	0.0480	-0.7308
2.60	0.0139	0.0928	0.4483	-0.0073	0.0441	-0.6335

Table 0: **Without any regulatory policy; continued**

a_0	$P(Q)Q$	$C(Q)$	$\Pi(Q)$	$\mathcal{W}$
0.90	0.1898	0.0625	0.1273	-0.1525
1.00	0.2020	0.0615	0.1404	-0.1232
1.10	0.2116	0.0596	0.1520	-0.0859
1.20	0.2191	0.0570	0.1621	-0.0451
1.40	0.2297	0.0509	0.1788	0.0353
1.60	0.2364	0.0448	0.1916	0.1047
1.80	0.2406	0.0391	0.2015	0.1603
2.00	0.2433	0.0341	0.2092	0.2034
2.20	0.2452	0.0299	0.2153	0.2365
2.40	0.2464	0.0263	0.2202	0.2619
2.60	0.2473	0.0232	0.2241	0.2816

Table 1: **Initial tax rates** ($\lambda = 1.0$)

a_0	p_k°	K	E	Q	K_{p_k}	K_{p_e}, E_{p_k}	E_{p_e}
0.90	0.1247	0.2040	0.1696	0.3918	-1.0793	0.4627	-1.3114
1.00	0.1179	0.1861	0.1462	0.4111	-0.9683	0.4795	-1.0854
1.10	0.1160	0.1653	0.1278	0.4248	-0.8270	0.4621	-0.9207
1.20	0.1165	0.1455	0.1130	0.4351	-0.6940	0.4308	-0.7950
1.40	0.1208	0.1125	0.0906	0.4496	-0.4852	0.3594	-0.6164
1.60	0.1270	0.0881	0.0746	0.4594	-0.3450	0.2952	-0.4962
1.80	0.1341	0.0702	0.0628	0.4664	-0.2518	0.2431	-0.4103
2.00	0.1413	0.0569	0.0536	0.4716	-0.1886	0.2018	-0.3463
2.20	0.1486	0.0469	0.0465	0.4756	-0.1448	0.1693	-0.2969
2.40	0.1556	0.0392	0.0407	0.4788	-0.1136	0.1435	-0.2579
2.60	0.1625	0.0332	0.0360	0.4813	-0.0909	0.1229	-0.2264

Table 1: **Initial tax rates** ($\lambda = 1.0$)**; continued**

a_0	$P(Q)Q$	$C(Q)$	$\Pi(Q)$	T	$\mathcal{W}$
0.90	0.2383	0.0424	0.1959	-0.1786	-0.0498
1.00	0.2421	0.0366	0.2055	-0.1641	0.0190
1.10	0.2443	0.0320	0.2124	-0.1461	0.0748
1.20	0.2458	0.0282	0.2175	-0.1285	0.1199
1.40	0.2475	0.0226	0.2248	-0.0989	0.1860
1.60	0.2484	0.0187	0.2297	-0.0769	0.2305
1.80	0.2489	0.0157	0.2332	-0.0608	0.2614
2.00	0.2492	0.0134	0.2358	-0.0489	0.2837
2.20	0.2494	0.0116	0.2378	-0.0399	0.3001
2.40	0.2495	0.0102	0.2394	-0.0331	0.3126
2.60	0.2497	0.0090	0.2407	-0.0278	0.3222

Table 2: **Initial tax rates** ($\lambda = 1.1$)

a_0	p_k°	K	E	Q	K_{p_k}	K_{p_e}, E_{p_k}	E_{p_e}
0.90	0.1419	0.1871	0.1770	0.3850	-0.8914	0.4044	-1.3879
1.00	0.1321	0.1734	0.1527	0.4060	-0.8214	0.4328	-1.1459
1.10	0.1290	0.1553	0.1335	0.4206	-0.7112	0.4241	-0.9709
1.20	0.1289	0.1374	0.1181	0.4316	-0.6017	0.3993	-0.8379
1.40	0.1330	0.1070	0.0948	0.4470	-0.4242	0.3371	-0.6494
1.60	0.1396	0.0840	0.0782	0.4572	-0.3026	0.2787	-0.5228
1.80	0.1472	0.0671	0.0659	0.4646	-0.2211	0.2304	-0.4326
2.00	0.1553	0.0545	0.0564	0.4700	-0.1656	0.1917	-0.3653
2.20	0.1633	0.0449	0.0489	0.4742	-0.1270	0.1611	-0.3136
2.40	0.1713	0.0375	0.0429	0.4776	-0.0995	0.1367	-0.2726
2.60	0.1790	0.0318	0.0379	0.4803	-0.0795	0.1171	-0.2396

Table 2: **Initial tax rates** ($\lambda = 1.1$); **continued**

a_0	$P(Q)Q$	$C(Q)$	$\Pi(Q)$	T	$\mathcal{W}$
0.90	0.2369	0.0443	0.1925	-0.1606	-0.0667
1.00	0.2412	0.0382	0.2030	-0.1505	0.0032
1.10	0.2437	0.0334	0.2103	-0.1353	0.0608
1.20	0.2453	0.0295	0.2158	-0.1197	0.1075
1.40	0.2472	0.0237	0.2235	-0.0927	0.1764
1.60	0.2482	0.0196	0.2286	-0.0723	0.2230
1.80	0.2487	0.0165	0.2323	-0.0572	0.2555
2.00	0.2491	0.0141	0.2350	-0.0460	0.2790
2.20	0.2493	0.0122	0.2371	-0.0376	0.2963
2.40	0.2495	0.0107	0.2388	-0.0311	0.3094
2.60	0.2496	0.0095	0.2401	-0.0261	0.3195

Table 3: **Initial tax rates** ($\lambda = 1.5$)

a_0	p_k°	K	E	Q	K_{p_k}	K_{p_e}, E_{p_k}	E_{p_e}
0.90	0.2307	0.1326	0.2040	0.3573	-0.4270	0.2276	-1.6899
1.00	0.1975	0.1336	0.1759	0.3861	-0.4552	0.2909	-1.3756
1.10	0.1859	0.1243	0.1541	0.4049	-0.4202	0.3080	-1.1590
1.20	0.1820	0.1125	0.1365	0.4184	-0.3683	0.3032	-0.9975
1.40	0.1840	0.0898	0.1101	0.4370	-0.2692	0.2687	-0.7716
1.60	0.1914	0.0715	0.0912	0.4492	-0.1950	0.2279	-0.6216
1.80	0.2013	0.0575	0.0772	0.4579	-0.1432	0.1913	-0.5152
2.00	0.2123	0.0469	0.0664	0.4643	-0.1073	0.1608	-0.4362
2.25	0.2267	0.0370	0.0560	0.4703	-0.0770	0.1305	-0.3624
2.50	0.2412	0.0298	0.0480	0.4747	-0.0570	0.1072	-0.3071
2.75	0.2555	0.0244	0.0416	0.4782	-0.0433	0.0893	-0.2643
3.00	0.2694	0.0203	0.0365	0.4810	-0.0336	0.0752	-0.2303

Table 3: **Initial tax rates** ($\lambda = 1.5$)**; continued**

a_0	$P(Q)Q$	$C(Q)$	$\Pi(Q)$	T	W
0.90	0.2296	0.0510	0.1786	-0.1020	-0.1187
1.00	0.2370	0.0440	0.1931	-0.1072	-0.0478
1.10	0.2409	0.0385	0.2024	-0.1012	0.0139
1.20	0.2433	0.0341	0.2092	-0.0920	0.0655
1.40	0.2460	0.0275	0.2185	-0.0732	0.1434
1.60	0.2474	0.0228	0.2246	-0.0578	0.1972
1.80	0.2482	0.0193	0.2289	-0.0459	0.2350
2.00	0.2487	0.0166	0.2321	-0.0369	0.2625
2.25	0.2491	0.0140	0.2351	-0.0286	0.2871
2.50	0.2494	0.0120	0.2374	-0.0226	0.3046
2.75	0.2495	0.0104	0.2391	-0.0182	0.3175
3.00	0.2496	0.0091	0.2405	-0.0149	0.3272

Table 4: **Initial tax rates** ($\lambda = 2.0$)

a_0	p_k°	K	E	Q	K_{p_k}	K_{p_e}, E_{p_k}	E_{p_e}
0.90	0.5036	0.0708	0.2378	0.3052	-0.1220	0.0625	-2.1682
1.00	0.3089	0.0975	0.2009	0.3608	-0.2317	0.1730	-1.6524
1.10	0.2722	0.0970	0.1760	0.3860	-0.2400	0.2110	-1.3775
1.20	0.2583	0.0908	0.1563	0.4031	-0.2223	0.2223	-1.1803
1.40	0.2534	0.0749	0.1266	0.4256	-0.1711	0.2106	-0.9102
1.60	0.2605	0.0607	0.1054	0.4401	-0.1266	0.1846	-0.7333
1.80	0.2727	0.0493	0.0896	0.4503	-0.0938	0.1579	-0.6087
2.00	0.2873	0.0404	0.0774	0.4577	-0.0705	0.1342	-0.5165
2.25	0.3075	0.0320	0.0656	0.4670	-0.0505	0.1100	-0.4308
2.50	0.3286	0.0258	0.0566	0.4699	-0.0371	0.0908	-0.3666
2.75	0.3501	0.0212	0.0494	0.4739	-0.0280	0.0758	-0.3169
3.00	0.3715	0.0176	0.0436	0.4772	-0.0215	0.0640	-0.2775

Table 4: **Initial tax rates** ($\lambda = 2.0$)**; continued**

a_0	$P(Q)Q$	$C(Q)$	$\Pi(Q)$	T	$\mathcal{W}$
0.90	0.2120	0.0595	0.1526	-0.0352	-0.1539
1.00	0.2306	0.0502	0.1804	-0.0674	-0.0910
1.10	0.2370	0.0440	0.1930	-0.0706	-0.0287
1.20	0.2406	0.0391	0.2015	-0.0673	0.0259
1.40	0.2445	0.0317	0.2128	-0.0560	0.1114
1.60	0.2464	0.0263	0.2201	-0.0449	0.1717
1.80	0.2475	0.0224	0.2251	-0.0358	0.2147
2.00	0.2482	0.0193	0.2289	-0.0288	0.2461
2.25	0.2488	0.0164	0.2323	-0.0222	0.2745
2.50	0.2491	0.0141	0.2350	-0.0173	0.2947
2.75	0.2493	0.0123	0.2370	-0.0138	0.3096
3.00	0.2495	0.0109	0.2386	-0.0111	0.3208

Table 5: **Tax reform** ($\lambda = 1.0$)

a_0	p_k	p_e	K	E	Q	K_{p_k}	K_{p_e}, E_{p_k}	E_{p_e}
0.90	0.7496	0.4634	0.0481	0.0518	0.2003	-0.0718	-0.0082	-0.1207
1.00	0.6969	0.4527	0.0536	0.0550	0.2326	-0.0801	-0.0033	-0.1248
1.10	0.6391	0.4322	0.0585	0.0576	0.2652	-0.0881	0.0033	-0.1301
1.20	0.5760	0.4024	0.0627	0.0599	0.2977	-0.0964	0.0119	-0.1374
1.40	0.4334	0.3170	0.0693	0.0631	0.3617	-0.1170	0.0390	-0.1636
1.60	0.2675	0.2007	0.0732	0.0650	0.4228	-0.1602	0.1009	-0.2344
1.80	0.0768	0.0582	0.0749	0.0658	0.4800	-0.4367	0.4732	-0.7142
2.00	-0.1403	-0.1063	0.0747	0.0657	0.5328	0.1710	-0.3179	0.3387
2.20	-0.3855	-0.2890	0.0730	0.0650	0.5808	0.0391	-0.1338	0.1058

Table 5: **Tax reform** ($\lambda = 1.0$)**; continued**

a_0	$P(Q)Q$	$C(Q)$	$\Pi(Q)$	T	$\mathcal{W}$
0.90	0.1602	0.0600	0.1001	0.0068	0.1136
1.00	0.1785	0.0622	0.1163	0.0032	0.1314
1.10	0.1949	0.0623	0.1326	-0.0020	0.1492
1.20	0.2091	0.0602	0.1489	-0.0085	0.1668
1.40	0.2309	0.0500	0.1808	-0.0255	0.2008
1.60	0.2440	0.0326	0.2114	-0.0471	0.2326
1.80	0.2496	0.0096	0.2400	-0.0719	0.2617
2.00	0.2489	-0.0175	0.2664	-0.0987	0.2880
2.20	0.2435	-0.0469	0.2904	-0.1265	0.3115

Table 6: **Tax reform** ($\lambda = 1.1$)

a_0	p_k	p_e	K	E	Q	K_{p_k}	K_{p_e}, E_{p_k}	E_{p_e}
0.90	0.8249	0.4649	0.0431	0.0510	0.1933	-0.0594	-0.0084	-0.1197
1.00	0.7776	0.4588	0.0477	0.0539	0.2238	-0.0652	-0.0044	-0.1224
1.10	0.7256	0.4439	0.0517	0.0563	0.2544	-0.0705	0.0008	-0.1259
1.20	0.6687	0.4210	0.0550	0.0582	0.2847	-0.0754	0.0072	-0.1307
1.40	0.5397	0.3529	0.0598	0.0609	0.3436	-0.0859	0.0253	-0.1468
1.60	0.3890	0.2590	0.0622	0.0622	0.3990	-0.1026	0.0572	-0.1830
1.80	0.2151	0.1437	0.0626	0.0625	0.4502	-0.1512	0.1395	-0.2956
2.00	0.0165	0.0109	0.0615	0.0619	0.4966	-1.5215	2.2198	-3.4275
2.20	-0.2083	-0.1358	0.0593	0.0607	0.5383	0.0877	-0.2015	0.2408

Table 6: **Tax reform** ($\lambda = 1.1$)**; continued**

a_0	$P(Q)Q$	$C(Q)$	$\Pi(Q)$	T	$\mathcal{W}$
0.90	0.1559	0.0593	0.0967	0.0111	0.1145
1.00	0.1737	0.0618	0.1119	0.0087	0.1320
1.10	0.1897	0.0625	0.1272	0.0052	0.1494
1.20	0.2036	0.0613	0.1423	0.0005	0.1664
1.40	0.2255	0.0537	0.1718	-0.0121	0.1989
1.60	0.2398	0.0403	0.1995	-0.0281	0.2288
1.80	0.2475	0.0224	0.2251	-0.0464	0.2558
2.00	0.2500	0.0017	0.2483	-0.0660	0.2799
2.20	0.2485	-0.0206	0.2691	-0.0860	0.3010

Table 7: **Tax reform ($\lambda = 1.5$)**

a_0	p_k	p_e	K	E	Q	K_{p_k}	K_{p_e}, E_{p_k}	E_{p_e}
0.90	1.0839	0.4629	0.0314	0.0491	0.1744	-0.0343	-0.0082	-0.1188
1.00	1.0586	0.4679	0.0340	0.0513	0.2002	-0.0360	-0.0058	-0.1184
1.10	1.0306	0.4672	0.0360	0.0530	0.2256	-0.0370	-0.0030	-0.1179
1.20	0.9998	0.4612	0.0375	0.0542	0.2501	-0.0375	0.0000	-0.1175
1.40	0.9293	0.4359	0.0390	0.0554	0.2965	-0.0372	0.0066	-0.1176
1.60	0.8462	0.3962	0.0388	0.0552	0.3382	-0.0361	0.0138	-0.1197
1.80	0.7495	0.3457	0.0375	0.0542	0.3752	-0.0350	0.0217	-0.1254
2.00	0.6383	0.2873	0.0355	0.0525	0.4074	-0.0346	0.0311	-0.1367
2.25	0.4779	0.2068	0.0324	0.0499	0.4416	-0.0366	0.0480	-0.1674
2.50	0.2921	0.1208	0.0292	0.0470	0.4698	-0.0472	0.0849	-0.2524
2.75	0.0798	0.0314	0.0260	0.0441	0.4930	-0.1360	0.3221	-0.8572
3.00	-0.1602	-0.0600	0.0231	0.0412	0.5121	0.0536	-0.1617	0.3986

Table 7: **Tax reform ($\lambda = 1.5$); continued**

a_0	$P(Q)Q$	$C(Q)$	$\Pi(Q)$	T	W
0.90	0.1440	0.0568	0.0872	0.0204	0.1211
1.00	0.1601	0.0600	0.1001	0.0209	0.1383
1.10	0.1747	0.0619	0.1128	0.0206	0.1550
1.20	0.1876	0.0625	0.1251	0.0196	0.1710
1.40	0.2086	0.0603	0.1482	0.0158	0.2006
1.60	0.2238	0.0547	0.1691	0.0104	0.2266
1.80	0.2344	0.0468	0.1876	0.0039	0.2492
2.00	0.2414	0.0377	0.2037	-0.0030	0.2684
2.25	0.2466	0.0258	0.2208	-0.0116	0.2884
2.50	0.2491	0.0142	0.2349	-0.0197	0.3047
2.75	0.2500	0.0035	0.2465	-0.0270	0.3178
3.00	0.2500	0.0062	0.2560	-0.0334	0.3285

Table 8: **Tax reform** ($\lambda = 2.0$)

a_0	p_k	p_e	K	E	Q	K_{p_k}	K_{p_e}, E_{p_k}	E_{p_e}
0.90	1.3333	0.4542	0.0246	0.0481	0.1614	-0.0224	-0.0077	-0.1210
1.00	1.3333	0.4661	0.0262	0.0499	0.1841	-0.0227	-0.0059	-0.1184
1.10	1.3333	0.4740	0.0273	0.0511	0.2059	-0.0226	-0.0041	-0.1154
1.20	1.3333	0.4786	0.0279	0.0518	0.2268	-0.0221	-0.0022	-0.1122
1.40	1.3333	0.4796	0.0280	0.0519	0.2651	-0.0203	0.0014	-0.1057
1.60	1.3333	0.4726	0.0271	0.0509	0.2986	-0.0179	0.0045	-0.0993
1.80	1.3333	0.4605	0.0254	0.0491	0.3274	-0.0155	0.0068	-0.0934
2.00	1.3333	0.4455	0.0235	0.0468	0.3518	-0.0133	0.0086	-0.0880
2.25	1.3333	0.4247	0.0209	0.0437	0.3769	-0.0109	0.0100	-0.0820
2.50	1.3333	0.4035	0.0184	0.0405	0.3971	-0.0089	0.0107	-0.0768
2.75	1.3333	0.3829	0.0161	0.0374	0.4133	-0.0074	0.0110	-0.0722
3.00	1.3333	0.3636	0.0141	0.0345	0.4264	-0.0061	0.0110	-0.0682

Table 8: **Tax reform** ($\lambda = 2.0$)**; continued**

a_0	$P(Q)Q$	$C(Q)$	$\Pi(Q)$	T	W
0.90	0.1354	0.0547	0.0807	0.0252	0.1327
1.00	0.1502	0.0582	0.0920	0.0270	0.1505
1.10	0.1635	0.0606	0.1030	0.0282	0.1675
1.20	0.1754	0.0620	0.1134	0.0289	0.1835
1.40	0.1948	0.0623	0.1326	0.0291	0.2123
1.60	0.2095	0.0601	0.1493	0.0280	0.2369
1.80	0.2202	0.0565	0.1637	0.0262	0.2576
2.00	0.2280	0.0521	0.1759	0.0240	0.2748
2.25	0.2348	0.0464	0.1884	0.0212	0.2922
2.50	0.2394	0.0409	0.1985	0.0184	0.3060
2.75	0.2425	0.0358	0.2066	0.0160	0.3170
3.00	0.2446	0.0314	0.2132	0.0138	0.3257

References

[1] AUERBACH, A. J., 1985, The Theory of Excess Burden and Optimal Taxation, in: A.J. Auerbach and M. Feldstein (eds.), *Handbook of Public Economics*, vol. I, ch. 2, North-Holland.

[2] BARNETT, A. H., 1980, The Pigouvian Tax Rule under Monopoly, *American Economic Review*, 70, 1037 - 1041.

[3] BAUMOL, W. J. AND W.E. OATES, 1988, *The Theory of Environmental Policy*, 2nd ed., Cambridge University Press.

[4] BAYINDIR-UPMANN, T., 1995, Interjurisdictional Tax Competition, Provision of Two Local Public Goods, and Environmental Policy, *Finanzarchiv*, 52, 379 - 400.

[5] BOVENBERG, A. L. AND R. A. DE MOOIJ, 1994A, Environmental Levies and Distortionary Taxation, *The American Economic Review*, 94, 1085 - 1089.

[6] — , 1994B, Environmental Taxes and Labor-Market Distortions, *European Journal of Political Economy*, 10, 655 - 683.

[7] BOVENBERG, A. L. AND F. VAN DER PLOEG, 1993, Green Policies and Public Finance in a Small Open Economy, CentER for Economic Research, Working Paper No. 9335.

[8] — , 1994, Environmental Policy, Public Finance and the Labor-Market in a Second-best World, *Journal of Public Economics*, 55, 349 -90.

[9] CONRAD, K. AND J. WANG, 1993, The Effect of Emission Taxes and Abatement Subsidies on Market Structure, *International Journal of Industrial Organization*, 11, 499 - 518.

[10] EBERT, U., 1992, Pigouvian Tax and Market Structure: The Case of Oligopoly and Different Abatement Technologies, *Finanzarchiv*, 49, 154 - 166.

[11] ENDRES, A., 1983, Do Effluent Charges (Always) Reduce Environmental Damage?, *Oxford Economic Papers*, 35, 254 - 261.

[12] GOULDER, L. H., 1995, Environmental Taxation and the "Double Dividend": a Reader's Guide, *International Tax and Public Finance*, 2, 155 - 182.

[13] JOHANSSON, O., 1994, Optimal Indirect Taxation in a Second-best Perspective with Regard to Externalities, a Public Budget Restriction and Distribution Effects, mimeo.

[14] MOOIJ, R. A. DE AND A. L. BOVENBERG, 1995, Environmental Taxes, International Capital Mobility and Inefficient Tax Systems: Tax Burden vs. Tax Shifting, mimeo.

[15] NORDHAUS, W. D., 1993, Optimal Greenhouse-Gas Reductions and Tax Policy in the "DICE" Model, *American Economic Review (Papers and Proceedings)*, 83, 313 -317.

[16] PLOEG, F. VAN DER AND A. L. BOVENBERG, 1993A, Environmental Policy, Public Goods and the Marginal Cost of Public Funds, *The Economic Journal*, 104, 444 - 454.

[17] — , 1993B, Direct Crowding Out, Optimal Taxation and Pollution Abatement, CentER for Economic Research, Working Paper No. 9365.

[18] REQUATE, T., 1993, Permits or Taxes? How to Regulate Cournot Duopoly with Polluting Firms, in: L. Preisner (ed.), *Institutions and Environmental Protection – Conference Proceedings of the Thrid Annual Meeting of the European Association of Environmental and Resource Economists*, vol. 2, Kraków.

[19] — , 1993, Pollution Control in a Cournot Duopoly via Taxes or Permits, *Journal of Economics*, 58, 255 - 291.

[20] SANDMO, A., 1975, Optimal Taxation in the Presence of Externalities, *Swedish Journal of Economics*, 77, 86 - 98.