CentER for Economic Research

Discussion paper

TILBURG UNIVERSITY

Center
for
Economic Research

No. 9376

POLLUTION CONTROL AND THE DYNAMICS OF THE FIRM: THE EFFECTS OF MARKET BASED INSTRUMENTS ON OPTIMAL FIRM INVESTMENTS

by Peter M. Kort

November 1993

ISSN 0924-7815

Pollution Control and the Dynamics of the Firm: the Effects of Market Based Instruments on Optimal Firm Investments

Peter M. Kort

Econometrics Department and CentER, Tilburg University, 5000 LE Tilburg, The Netherlands
E-Mail: Kort@KUB.NL

This contribution belongs to a category of papers that attempts to determine the effects of environmental regulation on the growth of an individual firm. It extends the existing literature in at least two ways. First, our pollution function explicitly deals with the fact that it is more difficult to reduce pollution by abatement activities when pollution is already low. Second, according to our knowledge it is for the first time that marketable pollution permits are incorporated in a dynamic model of the firm.
In the paper we establish the effects of a pollution tax and marketable permits on the behavior of the firm. For the tax model as well as the marketable permits model we prove that the equilibrium is stable and approached monotonically, and we derive formulas for optimal investment policies. Furthermore, we carry out a phase plane analysis for the pollution tax case, and, finally, a condition is obtained under which long run firm behavior is the same when either a tax or marketable permits are imposed.

1 Introduction

One of the most important problems of firm behavior in practice these days is how to react on environmental regulation. The government has several policy instruments at its disposal to give the firm an incentive to reduce pollution.

In case environmental problems develop smoothly and gradually it is well known that market-based approaches, like taxes and marketable permits, have important efficiency advantages over pollution standards, thus restricting pollution emissions directly (see e.g. Baumol and Oates (1971)). But, as argued by Hahn and Stavins (1991), in practice political and technological constraints can occur that lead to a poor performance of these market-based instruments. Therefore, it is important to recognize that the nature of individual environmental problems can dramatically affect the choice of preferred policy instruments. Thus, for example, for highly localized pollution problems with threshold damage functions (e.g. Dasgupta (1982), Figure 8.3), source-specific standards may be appropriate, whereas for pollution problems characterized by more uniform mixing over larger geographical areas, market-based approaches may be particularly desirable. This leads to the conclusion that the ideal policy package contains a mixture of instruments, with taxes, marketable permits and standards each used in certain circumstances to regulate the sources of environmental damage (Baumol and Oates (1988), p. 190).

Hence, in determining a theoretical framework for establishing the effects of environmental regulation on the firm's investment policy, each of the above mentioned policy instruments should be addressed. Contributions in this area include Helfand (1991, standards), Kort, Van Loon and Luptacik (1991, tax) and Xepapadeas (1992, tax + standards).

The aim of this paper is to establish the optimal dynamic behavior of a firm facing either imposition of a pollution tax or a market for pollution permits. Here the specification of the pollution function is improved compared to models in, e.g., Kort, Van Loon and Luptacik (1991) and Xepapadeas (1992). In these contributions a given abatement expenditure leads to a given pollution reduction, which is thus irrespective of the amount of pollution caused by the production process. This suggests that pollution can be driven to zero or even become negative, and, indeed, in these models a constraint occurs to prevent that pollution becomes negative. In our formulation we adopt the more realistic assumption that marginal costs of abatement increase sharply as the level of pollution shrinks, which implies that driving pollution to zero is very expensive if not impossible. A dynamic model of the firm in which the firm faces a pollution tax is developed in

Section 2. In Section 3 we solve this model by performing a stability analysis, deriving net present value formulas and developing dynamic adjustment paths. In Section 4 we consider a firm that has to buy marketable pollution permits in order to be allowed to pollute the environment, and we compare the results with the tax case. The paper is concluded in Section 5.

2 Pollution tax model

Consider a firm that has the possibility to invest in two different sorts of capital goods. One is productive but also causes pollution as an inevitable byproduct. The other one is non-productive but cleans pollution. The firm's pollution function is given by $E(K_1, K_2)$ which satisfies:

$$E(K_1, K_2) > 0 \text{ for all } K_1 > 0 \text{ and } K_2 \geq 0 \; ; \; E(0, K_2) = 0 \tag{1.1}$$

$$E_{K_1}(K_1, K_2) > 0 \; ; \; E_{K_1K_1}(K_1, K_2) > 0 \tag{1.2}$$

$$E_{K_2}(K_1, K_2) < 0 \text{ for all } K_1 > 0 \; ; \; E_{K_2K_2}(K_1, K_2) > 0 \text{ for all } K_1 > 0 \tag{1.3}$$

$$E_{K_1K_2}(K_1, K_2) = E_{K_2K_1}(K_1, K_2) < 0 \tag{1.4}$$

$$E_{K_1K_1}(K_1, K_2)E_{K_2K_2}(K_1, K_2) > [E_{K_1K_2}(K_1, K_2)]^2 \tag{1.5}$$

in which:

$E(K_1, K_2)$	:	flow of pollution generated by the firm, being a function of K_1 and K_2[1]
$K_1 = K_1(t)$	:	stock of productive capital goods at time t
$K_2 = K_2(t)$	:	stock of abatement capital goods at time t

(1.1) implies that pollution output is positive as long as the productive capital stock is positive. Therefore, pollution is never non-existent when the firm produces.

[1] Stock characteristics of environmental pollution are not considered here. This is because according to Xepapadeas (1992) stock effects are particularly important in a model where the objective is to maximize some welfare indicator and not in a model where private profits are maximized. The pollution flow generated by the firm contributes to the total pollution stock of the whole economy.

(1.2) states that pollution increases in a convex way with increasing productive capital stock, for a given level of abatement capital stock.
(1.3) means that pollution output is smaller the larger the current level of abatement capital stock, for a given positive stock of productive capital. (1.3) also implies that we have diminishing returns to abatement capital stock.
(1.4) states that the increase of pollution, due to an extra unit of productive capital stock, is smaller the larger the level of abatement capital stock. Alternatively, the decrease in pollution output, due to an extra unit of abatement capital stock, is larger the larger the current productive capital stock.
Because $E_{K_2K_1} < 0$ and $E_{K_2K_2} > 0$, our formulation has the realistic property that more abatement investments are required to reduce pollution with some fixed amount as the level of pollution shrinks.
In Xepapadeas (1992) and in Kort, Van Loon and Luptacik (1991) the pollution function is separable in K_1 and K_2. This implies that a given amount of abatement capital stock leads to a given reduction of pollution, irrespective of the current level of pollution, and also that pollution can be zero. In our formulation we got rid of these unrealistic features.
Finally, (1.2), (1.3) and (1.5) imply that function E is strictly convex in (K_1, K_2).

According to Jorgenson and Wilcoxen (1990, p. 330) the most important response of a firm to environmental regulations is investment in costly new equipment for pollution abatement. Therefore, by introducing abatement capital stock as a state variable we assume that the firm can build up abatement capital. Both capital goods evolve according to the standard capital accumulation dynamics:

$$\dot{K}_1 = I_1 - a_1 K_1, \quad K_1(0) > 0 \tag{2}$$

$$\dot{K}_2 = I_2 - a_2 K_2, \quad K_2(0) > 0 \tag{3}$$

in which:

$I_1 = I_1(t)$	:	rate of investment in productive capital goods at time t
$I_2 = I_2(t)$	:	rate of investment in abatement capital goods at time t
a_1	:	depreciation rate of the productive capital goods ($a_1 > 0$ and constant)
a_2	:	depreciation rate of the abatement capital goods ($a_2 > 0$ and constant)

Gross earnings of the firm are given by the instantancous revenue function $S = S(K_1)$. Assume that S is twice continuously differentiable, $S(K_1) > 0$ for $K_1 > 0$, $S'(K_1) > 0$, $S''(K_1) < 0$, $S(0) = 0$. [Function $S(K_1)$ is defined as revenue after maximization with respect to variable inputs, e.g. labor].
Investment is costly. Let, for $i = 1, 2$, $C_i(I_i)$ be the cost of investment with C_i a convex and increasing function, $C_i'(I_i) > 0$, $C_i''(I_i) > 0$, $C(0) = 0$.
The objective of the firm is to maximize the net cash flow stream:

$$\text{maximize: } \int_0^\infty [S(K_1) - C_1(I_1) - C_2(I_2) - \tau E(K_1, K_2)] \exp(-rt) dt \tag{4}$$

in which:

r : discount rate ($r > 0$ and constant)
τ : pollution tax rate ($\tau > 0$ and constant)

As argued by Pindyck (1991) investment expenditures are largely irreversible; that is, they are mostly sunk costs that cannot be recovered. This comes from the fact that usually capital is firm or industry specific, that is, it cannot be used productively by a different firm or in a different industry. To include irreversibility of investment in our model we add the following two non-negativity restrictions:

$$I_1 \geq 0 \tag{5}$$

$$I_2 \geq 0 \tag{6}$$

The decision problem of the firm is to determine an investment path. $\{I_1(t), I_2(t)\}$ over an infinite planning period $[0, \infty)$, such that the objective functional in (4) is maximal, subject to the constraints (2), (3), (5) and (6).

3 Solution

To obtain the optimality conditions for the optimal control problem described at the end of the previous section we use Pontryagin's maximum principle (see e.g. Feichtinger and Hartl (1986)). The current value Hamiltonian and Lagrangian for this problem are:

$$H = S(K_1) - C_1(I_1) - C_2(I_2) - \tau E(K_1, K_2) + \lambda_1(I_1 - a_1 K_1) + \lambda_2(I_2 - a_2 K_2) \quad (7)$$

$$L = H + \eta_1 I_1 + \eta_2 I_2 \quad (8)$$

in which:

$\lambda_i = \lambda_i(t)$: co-state variable belonging to K_i at time t; $i = 1, 2$

$\eta_i = \eta_i(t)$: dynamic Lagrange multiplier belonging to the constraint $I_i \geq 0$ at time t; $i = 1, 2$

The necessary optimality conditions are:

$$-C_1'(I_1) + \lambda_1 + \eta_1 = 0 \quad (9)$$

$$-C_2'(I_2) + \lambda_2 + \eta_2 = 0 \quad (10)$$

$$\dot{\lambda}_1 = (r + a_1)\lambda_1 - S'(K_1) + \tau E_{K_1}(K_1, K_2) \quad (11)$$

$$\dot{\lambda}_2 = (r + a_2)\lambda_2 + \tau E_{K_2}(K_1, K_2) \quad (12)$$

$$\eta_1 \geq 0, \quad \eta_1 I_1 = 0 \quad (13)$$

$$\eta_2 \geq 0, \quad \eta_2 I_2 = 0 \quad (14)$$

If furthermore the transversality conditions

$$\lim_{t \to \infty} \exp(-rt)\lambda_i(t)[\tilde{K}_i(t) - K_i(t)] \geq 0; \quad i = 1, 2 \quad (15)$$

hold for every feasible solution $(\tilde{K}_1, \tilde{K}_2)$, then (9)-(14) are also sufficient for optimality since the maximized Hamiltonian is concave in (K_1, K_2).

3.1 Stability analysis

To get insight into the dynamics of the optimal solution of our model, a stability analysis has to be carried out. By linearizing the non-linear canonical system around the steady state $(K_1^*, K_2^*, \lambda_1^*, \lambda_2^*, I_1^*, I_2^*)$ we obtain the Jacobi matrix evaluated at the equilibrium. An optimal steady state is a solution of:

$$I_1 - a_1 K_1 = 0$$

$$I_a - a_2 K_2 = 0$$

$$(r + a_1)\lambda_1 - S'(K_1) + \tau E_{K_1}(K_1, K_2) = 0$$

$$(r + a_2)\lambda_2 + \tau E_{K_2}(K_1, K_2) = 0$$

$$-C_1'(I_1) + \lambda_1 = 0$$

$$-C_2'(I_2) + \lambda_2 = 0$$

Then the Jacobian of the canonical system evaluated at the equilibrium has the following form:

$$J = \begin{bmatrix} -a_1 & 0 & 1/C_1'' & 0 \\ 0 & -a_2 & 0 & 1/C_2'' \\ -S'' + \tau E_{K_1K_2} & \tau E_{K_1K_2} & r + a_1 & 0 \\ \tau E_{K_2K_1} & \tau E_{K_2K_2} & 0 & r + a_2 \end{bmatrix} \tag{16}$$

The determinant of the Jacobian evaluated at the steady state is given by the expression:

$$\begin{aligned} \det J \;=\; & a_1 a_2 (r + a_1)(r + a_2) + \\ & + \frac{a_1(r + a_1)\tau E_{K_2K_2}}{C_2''} + \frac{a_2(r + a_2)(\tau E_{K_1K_1} - S'')}{C_1''} - \frac{\tau S'' E_{K_2K_2}}{C_1'' C_2''} + \\ & + \frac{\tau^2}{C_1'' C_2''}\left(E_{K_1K_1} E_{K_2K_2} - E_{K_1K_2}^2\right) > 0 \end{aligned} \tag{17}$$

According to Feichtinger and Hartl (1986, Theorem 5.4) we have saddle-point stability with monotonic motions if the following conditions are satisfied:

$$K < 0 \tag{18}$$

$$0 < \det J \leq K^2/4 \tag{19}$$

in which:

$$K = \begin{vmatrix} \frac{\partial \dot{K}_1}{\partial K_1} & \frac{\partial \dot{K}_1}{\partial \lambda_1} \\ \frac{\partial \dot{\lambda}_1}{\partial K_1} & \frac{\partial \dot{\lambda}_1}{\partial \lambda_1} \end{vmatrix} + \begin{vmatrix} \frac{\partial \dot{K}_2}{\partial K_2} & \frac{\partial \dot{K}_2}{\partial \lambda_2} \\ \frac{\partial \dot{\lambda}_2}{\partial K_2} & \frac{\partial \dot{\lambda}_2}{\partial \lambda_2} \end{vmatrix} + 2 \begin{vmatrix} \frac{\partial \dot{K}_1}{\partial K_2} & \frac{\partial \dot{K}_1}{\partial \lambda_2} \\ \frac{\partial \dot{\lambda}_1}{\partial K_2} & \frac{\partial \dot{\lambda}_1}{\partial \lambda_2} \end{vmatrix}$$

Calculating K leads to:

$$K = \left[\frac{-\tau E_{K_2K_2}}{C_2''} - a_2(r + a_2)\right] + \left[\frac{-\tau E_{K_1K_1} + S''}{C_1''} - a_1(r + a_1)\right] < 0 \tag{20}$$

To determine the sign of $K^2/4 - \det J$ we rewrite $\det J$ into (cf. Xepapadeas (1992)):

$$\det J = \left[\frac{-\tau E_{K_2K_2}}{C_2''} - a_2(r + a_2)\right]\left[\frac{-\tau E_{K_1K_1} + S''}{C_1''} - a_1(r + a_1)\right] - \frac{\tau^2 E_{K_1K_2}^2}{C_1''C_2''} \tag{21}$$

Due to (20) and (21) we obtain:

$$\begin{aligned} K^2 - 4\det J &= \left\{\left[\frac{-\tau E_{K_2K_2}}{C_2''} - a_2(r + a_2)\right] + \right. \\ &\left. - \left[\frac{-\tau E_{K_1K_1} + S''}{C_1''} - a_1(r + a_1)\right]\right\}^2 + \frac{4\tau^2 E_{K_1K_2}^2}{C_1''C_2''} > 0 \end{aligned} \tag{22}$$

We conclude that conditions (18) and (19) are satisfied so that the equilibrium is a saddle-point which is approached in a monotonic way.

3.2 Optimal investment policies

The firm's equilibrium values of the productive and abatement capital stock satisfy:

$$S'(K_1^*) = (r + a_1)C_1'(a_1 K_1^*) + \tau E_{K_1}(K_1^*, K_2^*) \tag{23}$$

$$-\tau E_{K_2}(K_1^*, K_2^*) = (r + a_2)C_2'(a_2 K_2^*) \tag{24}$$

For both capital stocks it holds that in equilibrium marginal revenue equals marginal cost. Compared to the standard investment models with convex investment costs (e.g. Takayama (1985), pp. 698-699), here marginal cost of productive investment has increased with τE_{K_1}. This is because owning an additional unit of productive capital stock increases pollution with E_{K_1} so that additional tax must be paid at the expense of τE_{K_1}. We conclude that introducing a tax on pollution results in a lower equilibrium value of productive capital stock, and thus in a lower level of production and pollution. The marginal revenue of abatement capital stock consists of a decrease in taxation expenses due to the fact that the extra unit of abatement capital stock reduces pollution. Comparative static analysis shows that, surprisingly enough, the level of pollution in equilibrium does not necessarily decrease when the pollution tax rate increases. But, from comparative dynamic analysis we can conclude that cumulative discounted pollution certainly decreases with increasing pollution tax rate (cf. Xepapadeas (1992), pp. 264-266).

Let us assume for the moment that the productive investment rate is positive. Then, after solving the differential equation (11), substituting (9) (with $\eta_1 = 0$) into this relation, and using (23) as a fixed point, we derive that at each moment of time the level of productive investment must satisfy

$$\int_t^{\infty} \{S'(K_1(s)) - \tau E_{K_1}(K_1(s), K_2(s))\} \exp(-(a_1 + r)(s - t))ds - C_1'(I_1(t)) = 0 \tag{25}$$

where the left-hand side is the "net present value of marginal investment". For an interpretation consider the acquisition of an extra unit of capital at time t. The firm incurs an extra expense at time t in amount of marginal investment cost C_1'. On the other hand, the marginal unit of productive capital generates - as of time t - a stream of cash flows consisting of revenue from selling products (S') minus pollution tax payments (τE_{K_1}).

This cash flow stream is corrected for depreciation by multiplication by $\exp(-a_1(s-t))$ and is discounted to time t by multiplication by $\exp(-r(s-t))$. Condition (25) states that the net present value of marginal productive investment equals zero. Hence, the optimal level of productive investment satisfies the fundamental economic principle of balancing marginal revenue with marginal expenses.

If the productive investment rate equals zero (25) changes into:

$$-\eta_1 = \int_t^{\infty} \{S'(K_1(s)) - \tau E_{K_1}(K_1(s), K_2(s))\} \exp(-(a_1+r)(s-t))ds - C_1'(0) \quad (26)$$

This expression shows that the firm does not invest when the net present value of marginal investment is negative. This makes sense, because now marginal expenses exceed marginal revenue. (26) shows that it will be optimal to have a zero productive investment rate when the productive capital stock is large and the abatement capital stock is low.

From (10), (12) and (24) we obtain that a positive abatement investment rate always satisfies the following equation:

$$\int_t^{\infty} -\tau E_{K_2}(K_1(s), K_2(s)) \exp(-(a_2+r)(s-t))ds - C_2'(I_2(t)) = 0 \quad (27)$$

(27) implies that the level of abatement investments is such that marginal abatement investment expenses (C_2') balance the discounted decrease in pollution tax payments over the whole planning period, caused by an extra unit of abatement investment carried out at time t. We conclude that the net present value of marginal abatement investment equals zero. Analogous to the case of productive investment it holds that abatement investment will be zero whenever this net present value is negative.

3.3 Phase plane analysis

Linearization of (2), (3), (11) and (12) around the steady state yields the following system

$$\dot{z} = J(z - z^*), \quad (28)$$

where $z = (K_1, K_2, \lambda_1, \lambda_2)^\top \in \mathbf{R}^4$, z^* is the stationary state and J is the Jacobian presented in (16). A general solution is of the form

$$z(t) = \sum_{i=1}^{4} c_i z_i \exp(\xi_i t) + z^*, \tag{29}$$

where $\xi_1, \xi_2, \xi_3, \xi_4$ are the eigenvalues of J and z_1, z_2, z_3, z_4 are the corresponding eigenvectors, as far as all ξ_i have multiplicity 1. For this model the latter is assured by inequality (22) (cf. eqn. (5.36) of Feichtinger and Hartl (1986)).
Because conditions (18) and (19) are satisfied, we know from Theorem 5.4 of Feichtinger and Hartl (1986) that all eigenvalues are real, with $\xi_{1,2} < 0$ and $\xi_{3,4} > 0$. For all solutions in the stable manifold it holds that $c_3 = c_4 = 0$ in (29). Otherwise the solution would explode, because $\xi_{3,4} > 0$.
If we only consider the first two coordinates of the linearized system, and we set the second coordinates of z_1 and z_2 equal to unity (this can be done without any objection since the eigenvectors are unique only up to a scalar multiple), we obtain:

$$\begin{pmatrix} K_1 \\ K_2 \end{pmatrix} = c_1 \exp(\xi_1 t) \begin{pmatrix} z_{11} \\ 1 \end{pmatrix} + c_2 \exp(\xi_2 t) \begin{pmatrix} z_{21} \\ 1 \end{pmatrix} + \begin{pmatrix} K_1^* \\ K_2^* \end{pmatrix} \tag{30}$$

After differentiation of (30) w.r.t. time we get:

$$\begin{pmatrix} \dot{K}_1 \\ \dot{K}_2 \end{pmatrix} = \xi_1 c_1 \exp(\xi_1 t) \begin{pmatrix} z_{11} \\ 1 \end{pmatrix} + \xi_2 c_2 \exp(\xi_2 t) \begin{pmatrix} z_{21} \\ 1 \end{pmatrix} \tag{31}$$

Next, (30) may be solved for $c_1 \exp(\xi_1 t)$, $c_2 \exp(\xi_2 t)$,

$$c_1 \exp(\xi_1 t) = \frac{K_1 - K_1^* - z_{21}(K_2 - K_2^*)}{z_{11} - z_{21}},$$

$$c_2 \exp(\xi_2 t) = \frac{z_{11}(K_2 - K_2^*) - (K_1 - K_1^*)}{z_{11} - z_{21}}, \tag{32}$$

and substituting from (32), we may write (31) as:

$$\begin{pmatrix} \dot{K}_1 \\ \dot{K}_2 \end{pmatrix} = \frac{1}{z_{11} - z_{21}} \begin{pmatrix} \xi_1 z_{11} - \xi_2 z_{21} & z_{11} z_{21}(\xi_2 - \xi_1) \\ \xi_1 - \xi_2 & \xi_2 z_{11} - \xi_1 z_{21} \end{pmatrix} \begin{pmatrix} K_1 - K_1^* \\ K_2 - K_2^* \end{pmatrix} \tag{33}$$

To draw a phase diagram we are interested in the slope of the isoclines $\dot{K}_1 = 0$ and $\dot{K}_2 = 0$:

$$\left.\frac{dK_2}{dK_1}\right|_{\dot{K}_1=0} = \frac{-\partial\dot{K}_1/\partial K_1}{\partial\dot{K}_1/\partial K_2} = \frac{\xi_2 z_{21} - \xi_1 z_{11}}{z_{11} z_{21}(\xi_2 - \xi_1)} \tag{34}$$

$$\left.\frac{dK_2}{dK_1}\right|_{\dot{K}_2=0} = \frac{-\partial\dot{K}_2/\partial K_1}{\partial\dot{K}_2/\partial K_2} = \frac{\xi_2 - \xi_1}{\xi_2 z_{11} - \xi_1 z_{21}} \tag{35}$$

To calculate these slopes we have to restrict our attention to the case where $r = 0$. Furthermore, to simplify the tedious calculations we impose that $a_1 = a_2 = a$. By following the method employed in Turnovsky (1981) we can show that the slopes of the two lines are respectively (the proof is relegated to the Appendix):

$$\left.\frac{dK_2}{dK_1}\right|_{\dot{K}_1=0} = \frac{-C_1''\{a^2 + (\tau E_{K_1K_1} - S'')/C_1'' + \sqrt{\det J}\}}{\tau E_{K_2K_1}} > 0 \tag{36}$$

$$\left.\frac{dK_2}{dK_1}\right|_{\dot{K}_2=0} = \frac{\tau E_{K_2K_1}}{-C_2''\{a^2 + \tau E_{K_2K_2}/C_2'' + \sqrt{\det J}\}} > 0 \tag{37}$$

A straightforward exercise shows that

$$\left.\frac{dK_2}{dK_1}\right|_{\dot{K}_1=0} > \left.\frac{dK_2}{dK_1}\right|_{\dot{K}_2=0}, \tag{38}$$

so that the $\dot{K}_1 = 0$ isocline is steeper than the $\dot{K}_2 = 0$ isocline.

Now, we are ready to draw the phase diagram, which is done in Figure 1. The line $\dot{K}_1 = 0$ traces out the combinations of K_1 and K_2 for which K_1 is stationary. Likewise $\dot{K}_2 = 0$ is the locus of combinations of K_1 and K_2 corresponding to stationary values of K_2. These two lines divide the (K_1, K_2)-space into four quadrants. Above the line $\dot{K}_1 = 0$, $\dot{K}_1 > 0$, while below it $\dot{K}_1 < 0$. Similarly above the line $\dot{K}_2 = 0$, $\dot{K}_2 < 0$, while below it $\dot{K}_2 > 0$. Accordingly, the overall adjustment of the system in the four regions is in the directions indicated by the arrows.

[Insert Figure 1 about here]

For reasons of surveyability we have only drawn those trajectories where abatement capital stock increases all the way and where productive capital stock is not very large in the beginning of the trajectory. We see that then both productive and abatement capital stock increase on the final path that ends at the equilibrium. This policy can be preceeded by a phase where K_1 decreases (productive investment can even be zero (cf. eqn. (26))) when K_1 is large, initially (trajectory (a)). Trajectory (a) could be the final phase of a solution where, at time zero, the firm is at its unregulated equilibrium at the moment that the government imposes a pollution tax (the unregulated steady state satisfies eqn. (23) without the term τE_{K_1}. This makes that K_1 is larger in the unregulated equilibrium compared to the regulated one). Remember that the phase diagram only holds locally around the steady state.

4 Marketable permits model

The implementation of marketable permits involves several steps (cf. Hahn (1989)). First, a target level of environmental quality is established. Next this level of environmental quality is defined in terms of total allowable pollution. Permits are then allocated to firms, with each permit enabling the owner to pollute a specified amount. Firms are allowed to trade these permits among themselves.

In the USA there has been some limited experience with programs of marketable permits for the regulation of air and water quality, while in Europe there is hardly no experience with marketable permits. The major program of imposing marketable permits as a mechanism for providing economic incentives for pollution control in the USA is the Environmental Protection Agency's Emissions Trading Program for the regulation of air quality (see Tietenberg (1985)).

Existing systems of marketable permits in the United States embody a kind of "grandfathering" scheme involving an initial distribution of pollution permits or "rights" among polluters based on historical pollution. According to Cropper and Oates (1992) a drawback of this system is that heavy polluters are rewarded by receiving a lot of permits, which they can then use either to validate their own pollution output or sell to other firms. In this way the "Polluter Pays Principle" is violated.

Compared to a pollution tax system, a major advantage of the marketable permit approach is that it gives the government direct control over the level of pollution. Under the taxes approach, the government must set a tax, and if, for example, the tax turns

out to be low, pollution still exceed permissible levels. The government will find itself in the uncomfortable position of having to adjust and readjust the tax to ensure that the environment is not severely damaged (Cropper and Oates (1992)).
In this section we consider a firm that has to buy permits in order to be allowed to pollute the environment. According to Siebert (1992, p. 142) marketable permits may be defined on a temporary basis or without a time limit. We will assume here that once a permit is bought it remains valid forever (contrary to e.g. the Wisconsin Fox River Water Permits which are only valid for five years (Hahn (1989))).
If it has good growth prospects the firm will increase production and, after assuming for the moment that abatement capital is too costly, this will also increase pollution which implies that the firm needs to buy extra permits. These permits can be sold to other firms at the moment that the firm reduces pollution by either a sufficient increase of abatement capital stock or a reduction of production. If the price of a permit equals p and the firm needs one permit per unit of pollution, then the firm's expenses on the permit market at time t equal

$$p\dot{E} = p\{E_{K_1}\dot{K}_1 + E_{K_2}\dot{K}_2\} = p\{E_{K_1}(I_1 - a_1K_1) + E_{K_2}(I_2 - a_2K_2)\}. \tag{39}$$

Notice that spendings turn into receivings as soon as pollution decreases over time. Whether the price of a permit will go up or down depends on the behavior of all competitors in the market. Leaving abatement activities aside for the moment, if all firms want to produce more they implicitly want to increase pollution. Therefore, the demand for pollution permits goes up and the price of the permits increases. Notice in this respect that the amount of permits on the market is fixed, which in turn leads to a fixed level of pollution generated by the whole sector.
The above description refers to a market for pollution permits that provides great flexibility due to the absence of transactions costs and other obstacles to trading. However, in practice the rules of the marketable permits can be so restrictive that the flexibility they offer is more imaginary than real (see Cropper and Oates (1992), Hahn (1989)). Nevertheless, in this paper we assume that trading barriers are absent on the permit market.
Like in the tax model also here the objective of the firm is to maximize the net cash flow stream:

$$\text{maximize} : \int_0^\infty \{S(K_1) - C_1(I_1) - C_2(I_2) - p\dot{E}(I_1, I_2, K_1, K_2)\} \exp(-rt)dt \tag{40}$$

The optimal control problem is to maximize (40) subject to (2), (3), (5) and (6). Similar calculations like in the model with a pollution tax lead to the following results. The optimal steady state is a solution of:

$$I_1 - a_1 K_1 = 0$$

$$I_2 - a_2 K_2 = 0$$

$$(r + a_1)\lambda_1 - S'(K_1) - a_1 pE_{K_1}(K_1, K_2) = 0$$

$$(r + a_2)\lambda_2 - a_2 pE_{K_2}(K_1, K_2) = 0$$

$$-C_1'(I_1) - pE_{K_1}(K_1, K_2) + \lambda_1 = 0$$

$$-C_2'(I_2) - pE_{K_2}(K_1, K_2) + \lambda_2 = 0$$

The Jacobian evaluated at the equilibrium has the following form:

$$J = \begin{bmatrix} \frac{-pE_{K_1K_1}}{C_1''} - a_1 & \frac{-pE_{K_1K_2}}{C_1''} & \frac{1}{C_1''} & 0 \\ \frac{-pE_{K_1K_2}}{C_2''} & \frac{-pE_{K_2K_2}}{C_2''} - a_2 & 0 & \frac{1}{C_2''} \\ \alpha & \beta & r + a_1 + \frac{pE_{K_1K_1}}{C_1''} & \frac{pE_{K_1K_2}}{C_2''} \\ \beta & \gamma & \frac{pE_{K_1K_2}}{C_1''} & r + a_2 + \frac{pE_{K_2K_2}}{C_2''} \end{bmatrix} \tag{41}$$

in which:

$$\alpha = -S'' - pE_{K_1K_1}\left(\frac{pE_{K_1K_1}}{C_1''} + 2a_1\right) - \frac{p^2 E_{K_1K_2}^2}{C_2''}$$

$$\beta = -pE_{K_1K_2}\left(\frac{pE_{K_1K_1}}{C_1''} + \frac{pE_{K_2K_2}}{C_2''} + a_1 + a_2\right)$$

$$\gamma = \frac{-p^2 E_{K_1K_2}^2}{C_1''} - pE_{K_2K_2}\left(\frac{pE_{K_2K_2}}{C_2''} + 2a_2\right)$$

Using the computer program Mathematica we were able to calculate the determinant:

$$\det J = a_1a_2(r+a_1)(r+a_2) + \frac{a_1(r+a_1)prE_{K_2K_2}}{C_2''} + \frac{a_2(r+a_2)(prE_{K_1K_1} - S'')}{C_1''} - \frac{prS''E_{K_2K_2}}{C_1''C_2''} + \frac{p^2r^2}{C_1''C_2''}(E_{K_1K_1}E_{K_2K_2} - E_{K_1K_2}^2) > 0 \tag{42}$$

The value of the number K (cf. below expression (19)) equals:

$$K = \left[\frac{-prE_{K_2K_2}}{C_2''} - a_2(r+a_2)\right] + \left[\frac{-prE_{K_1K_1} + S''}{C_1''} - a_1(r+a_1)\right] < 0 \tag{43}$$

Comparing (42) and (43) with (17) and (20) we see that $\det J$ and K have the same value in the tax model and the permits model when $\tau = rp$. Therefore, we can easily conclude that also here conditions (18) and (19) are satisfied so that we have saddle point stability with monotonic motions.

The firm's equilibrium value of productive capital stock is given by:

$$S'(K_1^{**}) = (r+a_1)C_1'(a_1K_1^{**}) + rpE_{K_1}(K_1^{**}, K_2^{**}) \tag{44}$$

Hence marginal revenue equals marginal costs, while marginal pollution costs equal rpE_{K_1}. This is because increasing productive capital stock with one unit during one period raises pollution with E_{K_1}. Therefore, at the beginning of the period the firm has to buy additional permits at the expense of pE_{K_1}. These permits can be sold at the end of the period (notice that pollution increases only during one period) so that the firm needs to borrow pE_{K_1} dollars for one period to finance the permits transaction. This increases interest costs with rpE_{K_1}.

Due to equation (44) we obtain that introducing a marketable permits system leads to a lower equilibrium value of productive capital stock, which in turn leads to lower levels of production and pollution. Further, we see that the effects of marketable permits are particularly significant when the interest rate is large.

At each moment of time the productive investment rate, whenever it is positive, must satisfy:

$$\int_t^\infty \{S'(K_1(s)) - p(s)\dot{E}_{K_1}(I_1(s), I_2(s), K_1(s), K_2(s))\} \exp(-(a_1+r)(s-t))ds - C_1'(I_1(t)) - p(t)E_{K_1}(K_1(t), K_2(t)) = 0 \tag{45}$$

Increasing the productive capital stock with one unit results in immediate extra expenses in amount of marginal cost C_1'', plus spendings on extra permits pE_{K_1} needed to account for the additional pollution generated by this extra unit of capital. It also generates - as of time t - a stream of cash flows consisting of revenue from selling products (S') and changes in future expenses on the permit market ($-p\dot{E}_{K_1}$). Hence, according to (45) the firm fixes productive investment such that the discounted cash inflows and outflows, which are due to marginal investment, are balanced. To state this differently: the net present value of marginal investment equals zero.

The firm's equilibrium value of abatement capital stock is given by

$$(r + a_2)C_2'(a_2K_2^{**}) = -rpE_{K_2}(K_1^{**}, K_2^{**}) \tag{46}$$

while, for every time t, positive abatement investments satisfy:

$$-\int_t^\infty p(s)\dot{E}_{K_2}(I_1(s), I_2(s), K_1(s), K_2(s))\exp(-(a_2 + r)(s - t))ds + \\ -C_2'(I_2(t)) - p(t)E_{K_2}(K_1(t), K_2(t)) = 0 \tag{47}$$

(47) implies that marginal abatement investment expenses (C_2') balance the changes in cash flow on the permit market, caused by this marginal abatement investment. The additional cash flows on the permit market consist of an immediate cash inflow ($-pE_{K_2}$, note that $E_{K_2} < 0$) and revenue/ expenses over the remaining planning period.

After comparing (23) and (24) with (44) and (46) we can conclude that a pollution tax and marketable permits lead to the same equilibrium if it holds that:

$$rp = \tau \tag{48}$$

To understand this equation consider the situation where pollution is increased with one unit during one period. Then, in the pollution tax case the firm incurs an extra expense of τ dollars during this period, whereas in the marketable permits case the firm has to buy a permit in the beginning of this period that can be sold again after the period is over. This implies that the firm has to borrow an amount of money equal to the permit price p during this period, which leads to interest costs of rp dollars. Hence, pollution costs increase with the same amount under both instruments when (48) holds.

5 Conclusions

This contribution belongs to a category of papers that attempts to determine the effects of environmental regulation on the growth of an individual firm. It extends the analysis of its predecessors (e.g. Kort, Van Loon and Luptacik (1991), Hartl (1992), Xepapadeas (1992)) in at least two ways. First, we incorporated a more realistic (but also more complex) pollution function. With more realistic we mean that we explicitly deal with the fact that for lower levels of pollution more abatement effort is required to reduce pollution with some fixed amount. This is contrary to Kort, Van Loon and Luptacik (1991) and Xepapadeas (1992) where it is, rather unrealistically, assumed that abatement costs are independent of the pollution output generated by the production process.
Second, besides dealing with a pollution tax as a form of environmental regulation, we consider the effects marketable permits have on the firm's investment policy. As far as we know this is the first contribution where marketable permits are incorporated in a dynamic model of the firm.
It turns out that under both environmental instruments the equilibrium, where marginal revenue equals marginal cost, is stable and approached monotonically. Imposing a pollution tax as well as a marketable permits system decreases production and pollution in equilibrium. Effects of marketable permits on dynamic firm behavior are intensified in case of a high interest rate.
During the whole planning period the development of productive as well as abatement capital stock is completely determined by an investment rule that dictates the firm to stop investing when the net present value of marginal investment is negative and, when this is not the case, to fix the investment rate such that the net present value of marginal investment equals zero. Then the immediate expenses due to acquiring an additional unit of capital stock exactly balance the discounted future cash flows, such as revenue from selling products, as far as they result from this unit increase of capital stock.
After comparing the effects on the firm's investment policy of a pollution tax and marketable permits we concluded that long run firm behavior will be the same when the tax rate equals the interest rate multiplied by the price of a permit. This rule is economically interpreted and can be seen as a dynamic extension of the well known static result that there are similar effects whenever the permit price equals the tax rate (see e.g. Baumol and Oates (1988), p. 58).
Finally, we mention two interesting topics for future research. First, it could be interesting to consider a dynamic game of several firms operating on a market for pollution

permits. Such a framework could lead to strategic interactions like a firm that buys more permits than needed for covering its pollution in order to obstruct the growth of its competitors.
A second interesting model extension could be to consider permits of limited validity, as opposite to the model considered here where permits remain valid forever. Then the value of a marketable permit will depreciate over time and the resulting depreciation costs will certainly influence the above described rule under which the effects of a pollution tax and marketable permits are equivalent.

Acknowledgement
The author thanks Jan de Klein for computational assistance and an anonymous referee for his remarks. This research has been made possible by a fellowship of the Royal Netherlands Academy of Arts and Sciences.

References

Baumol, W.J., Oates, W.E., 1971, The use of standards and prices for the protection of the environment, Swedish Journal of Economics, 73, 42-54.

Baumol, W.J., Oates, W.E., 1988, The Theory of Environmental Policy, second edition, Cambridge University Press, Cambridge.

Cropper, M.L., Oates, W.E., 1992, Environmental economics: a survey, Journal of Economic Literature, 30, 675-740.

Dasgupta, P., 1982, The Control of Resources, Basil Blackwell, Oxford.

Feichtinger, G., Hartl, R.F., 1986, Optimal Kontrolle Ökonomischer Prozesse: Anwendungen des Maximumprinzips in den Wirtschaftswissenschaften, de Gruyter, Berlin.

Hahn, R.W., 1989, Economic prescriptions for environmental problems: how the patient followed the doctor's orders, Journal of Economic Perspectives, 3, 95-114.

Hahn, R.W., Stavins, R.N., 1991, Economic incentives for environmental protection: integrating theory and practice, CSIA Discussion Paper 91-15, Kennedy School of Government, Harvard University.

Hartl, R.F., 1992, Optimal acquisition of pollution control equipment under uncertainty, Management Science, 38, 609-622.

Helfand, G.E., 1991, Standards versus standards: the effects of different pollution restrictions, American Economic Review, 81, 622-634.

Jorgenson, D.W., Wilcoxen, P.J., 1990, Environmental regulation and U.S. economic growth, Rand Journal of Economics, 21, 314-340.

Kort, P.M., Loon, P.J.J.M. van, Luptacik, M., 1991, Optimal dynamic environmental policies of a profit maximizing firm, Journal of Economics, 54, 195-225.

Pindyck, R.S., 1991, Irreversibility, uncertainty and investment, Journal of Economic Literature, 29, 1110-1148.

Siebert, H., 1992, Economics of the Environment, third edition, Springer, Berlin.

Takayama, A., 1985, Mathematical Economics, second edition, Cambridge University Press, Cambridge.

Tietenberg, T.H., 1985, Emissions Trading: An Exercise in Reforming Pollution Policy, Resources for the Future, Washington, DC.

Turnovsky, S.J., 1981, The optimal intertemporal choice of inflation and unemployemnt, Journal of Economic Dynamics and Control, 3, 357-384.

Xepapadeas, A.P., 1992, Environmental policy, adjustment costs, and behavior of the firm, Journal of Environmental Economics and Management, 23, 258-275.

Appendix. Derivation of the relations (36) and (37)

In case $r = 0$ the two negative eigenvalues of J are given by (see Feichtinger and Hartl (1986), p. 134):

$$\xi_1 = -\sqrt{-\frac{K}{2} + \frac{1}{2}\sqrt{K^2 - 4\det J}} \tag{A.1}$$

$$\xi_2 = -\sqrt{-\frac{K}{2} - \frac{1}{2}\sqrt{K^2 - 4\det J}} \tag{A.2}$$

The eigenvalue ξ_1 and its corresponding eigenvector z_1 have the following relationship

$$\xi_1 z_1 = J z_1, \tag{A.3}$$

and this equation can be expressed as (remember that here we assume that $r = 0$ and $a_1 = a_2 = a$):

$$\xi_1 \begin{pmatrix} z_{11} \\ 1 \\ z_{13} \\ z_{14} \end{pmatrix} = \begin{bmatrix} -a & 0 & 1/C_1'' & 0 \\ 0 & -a & 0 & 1/C_2'' \\ -S'' + \tau E_{K_1K_1} & \tau E_{K_1K_2} & a & 0 \\ \tau E_{K_2K_1} & \tau E_{K_2K_2} & 0 & a \end{bmatrix} \begin{pmatrix} z_{11} \\ 1 \\ z_{13} \\ z_{14} \end{pmatrix} \tag{A.4}$$

and solving for z_{11}, we obtain

$$z_{11} = \{C_2''(\xi_1^2 - a^2) - \tau E_{K_2K_2}\}/\tau E_{K_2K_1}. \tag{A.5}$$

Similarly, corresponding to the eigenvalue ξ_2 we have

$$z_{21} = \{C_2''(\xi_2^2 - a^2) - \tau E_{K_2K_2}\}/\tau E_{K_2K_1}. \tag{A.6}$$

Using (20), (21) (where in both equations we put $r = 0$ and $a_1 = a_2 = a$), (A.1), (A.2), (A.5) and (A.6) we may now establish the following expressions for terms appearing in (34) and (35):

$$\xi_2 z_{21} - \xi_1 z_{11} = \frac{(\xi_2 - \xi_1)C_2''}{\tau E_{K_2K_1}} \left\{a^2 + (\tau E_{K_1K_1} - S'')/C_1'' + \sqrt{\det J}\right\} \tag{A.7}$$

$$z_{11}z_{21} = -C_2''/C_1'' \tag{A.8}$$

$$\xi_2 z_{11} - \xi_1 z_{21} = \frac{(\xi_1 - \xi_2)C_2''}{\tau E_{K_2K_1}}(a^2 + \sqrt{\det J} + \tau E_{K_2K_2}/C_2'') \tag{A.9}$$

Now, substitution of (A.7)-(A.9) into (34) and (35) leads to (36) and (37).
Q.E.D.

Figure caption

Figure 1. Phase diagram in case of no discounting and equal depreciation rates for both capital stocks.

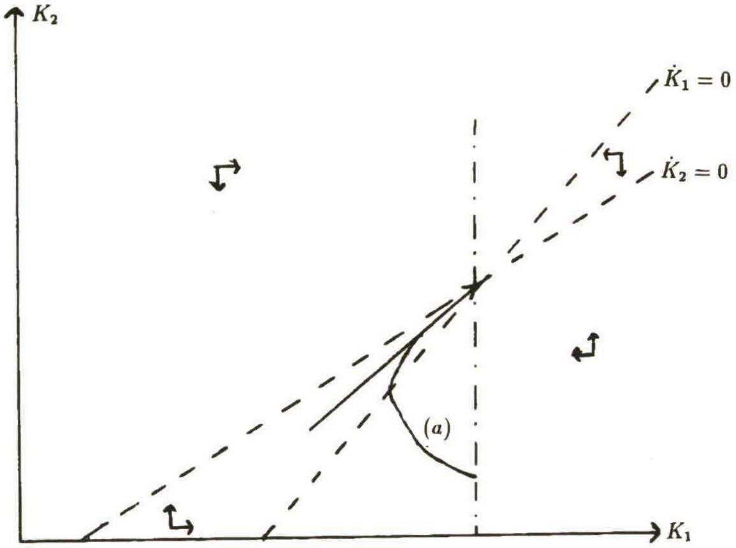

Figure 1

Discussion Paper Series, CentER, Tilburg University, The Netherlands:

(For previous papers please consult previous discussion papers.)

No.	Author(s)	Title
9239	H. Bloemen	A Model of Labour Supply with Job Offer Restrictions
9240	F. Drost and Th. Nijman	Temporal Aggregation of GARCH Processes
9241	R. Gilles, P. Ruys and J. Shou	Coalition Formation in Large Network Economies
9242	P. Kort	The Effects of Marketable Pollution Permits on the Firm's Optimal Investment Policies
9243	A.L. Bovenberg and F. van der Ploeg	Environmental Policy, Public Finance and the Labour Market in a Second-Best World
9244	W.G. Gale and J.K. Scholz	IRAs and Household Saving
9245	A. Bera and P. Ng	Robust Tests for Heteroskedasticity and Autocorrelation Using Score Function
9246	R.T. Baillie, C.F. Chung and M.A. Tieslau	The Long Memory and Variability of Inflation: A Reappraisal of the Friedman Hypothesis
9247	M.A. Tieslau, P. Schmidt and R.T. Baillie	A Generalized Method of Moments Estimator for Long-Memory Processes
9248	K. Wärneryd	Partisanship as Information
9249	H. Huizinga	The Welfare Effects of Individual Retirement Accounts
9250	H.G. Bloemen	Job Search Theory, Labour Supply and Unemployment Duration
9251	S. Eijffinger and E. Schaling	Central Bank Independence: Searching for the Philosophers' Stone
9252	A.L. Bovenberg and R.A. de Mooij	Environmental Taxation and Labor-Market Distortions
9253	A. Lusardi	Permanent Income, Current Income and Consumption: Evidence from Panel Data
9254	R. Beetsma	Imperfect Credibility of the Band and Risk Premia in the European Monetary System
9301	N. Kahana and S. Nitzan	Credibility and Duration of Political Contests and the Extent of Rent Dissipation

No.	Author(s)	Title
9302	W. Güth and S. Nitzan	Are Moral Objections to Free Riding Evolutionarily Stable?
9303	D. Karotkin and S. Nitzan	Some Peculiarities of Group Decision Making in Teams
9304	A. Lusardi	Euler Equations in Micro Data: Merging Data from Two Samples
9305	W. Güth	A Simple Justification of Quantity Competition and the Cournot-Oligopoly Solution
9306	B. Peleg and S. Tijs	The Consistency Principle For Games in Strategic Form
9307	G. Imbens and A. Lancaster	Case Control Studies with Contaminated Controls
9308	T. Ellingsen and K. Wärneryd	Foreign Direct Investment and the Political Economy of Protection
9309	H. Bester	Price Commitment in Search Markets
9310	T. Callan and A. van Soest	Female Labour Supply in Farm Households: Farm and Off-Farm Participation
9311	M. Pradhan and A. van Soest	Formal and Informal Sector Employment in Urban Areas of Bolivia
9312	Th. Nijman and E. Sentana	Marginalization and Contemporaneous Aggregation in Multivariate GARCH Processes
9313	K. Wärneryd	Communication, Complexity, and Evolutionary Stability
9314	O.P.Attanasio and M. Browning	Consumption over the Life Cycle and over the Business Cycle
9315	F. C. Drost and B. J. M. Werker	A Note on Robinson's Test of Independence
9316	H. Hamers, P. Borm and S. Tijs	On Games Corresponding to Sequencing Situations with Ready Times
9317	W. Güth	On Ultimatum Bargaining Experiments - A Personal Review
9318	M.J.G. van Eijs	On the Determination of the Control Parameters of the Optimal Can-order Policy
9319	S. Hurkens	Multi-sided Pre-play Communication by Burning Money
9320	J.J.G. Lemmen and S.C.W. Eijffinger	The Quantity Approach to Financial Integration: The Feldstein-Horioka Criterion Revisited
9321	A.L. Bovenberg and S. Smulders	Environmental Quality and Pollution-saving Technological Change in a Two-sector Endogenous Growth Model

No.	Author(s)	Title
9322	K.-E. Wärneryd	The Will to Save Money: an Essay on Economic Psychology
9323	D. Talman, Y. Yamamoto and Z. Yang	The $(2^{n+m+1} - 2)$-Ray Algorithm: A New Variable Dimension Simplicial Algorithm For Computing Economic Equilibria on $S^n \times R^m_+$
9324	H. Huizinga	The Financing and Taxation of U.S. Direct Investment Abroad
9325	S.C.W. Eijffinger and E. Schaling	Central Bank Independence: Theory and Evidence
9326	T.C. To	Infant Industry Protection with Learning-by-Doing
9327	J.P.J.F. Scheepens	Bankruptcy Litigation and Optimal Debt Contracts
9328	T.C. To	Tariffs, Rent Extraction and Manipulation of Competition
9329	F. de Jong, T. Nijman and A. Röell	A Comparison of the Cost of Trading French Shares on the Paris Bourse and on SEAQ International
9330	H. Huizinga	The Welfare Effects of Individual Retirement Accounts
9331	H. Huizinga	Time Preference and International Tax Competition
9332	V. Feltkamp, A. Koster, A. van den Nouweland, P. Borm and S. Tijs	Linear Production with Transport of Products, Resources and Technology
9333	B. Lauterbach and U. Ben-Zion	Panic Behavior and the Performance of Circuit Breakers: Empirical Evidence
9334	B. Melenberg and A. van Soest	Semi-parametric Estimation of the Sample Selection Model
9335	A.L. Bovenberg and F. van der Ploeg	Green Policies and Public Finance in a Small Open Economy
9336	E. Schaling	On the Economic Independence of the Central Bank and the Persistence of Inflation
9337	G.-J. Otten	Characterizations of a Game Theoretical Cost Allocation Method
9338	M. Gradstein	Provision of Public Goods With Incomplete Information: Decentralization vs. Central Planning
9339	W. Güth and H. Kliemt	Competition or Co-operation
9340	T.C. To	Export Subsidies and Oligopoly with Switching Costs
9341	A. Demirgüç-Kunt and H. Huizinga	Barriers to Portfolio Investments in Emerging Stock Markets

No.	Author(s)	Title
9342	G.J. Almekinders	Theories on the Scope for Foreign Exchange Market Intervention
9343	E.R. van Dam and W.H. Haemers	Eigenvalues and the Diameter of Graphs
9344	H. Carlsson and S. Dasgupta	Noise-Proof Equilibria in Signaling Games
9345	F. van der Ploeg and A.L. Bovenberg	Environmental Policy, Public Goods and the Marginal Cost of Public Funds
9346	J.P.C. Blanc and R.D. van der Mei	The Power-series Algorithm Applied to Polling Systems with a Dormant Server
9347	J.P.C. Blanc	Performance Analysis and Optimization with the Power-series Algorithm
9348	R.M.W.J. Beetsma and F. van der Ploeg	Intramarginal Interventions, Bands and the Pattern of EMS Exchange Rate Distributions
9349	A. Simonovits	Intercohort Heterogeneity and Optimal Social Insurance Systems
9350	R.C. Douven and J.C. Engwerda	Is There Room for Convergence in the E.C.?
9351	F. Vella and M. Verbeek	Estimating and Interpreting Models with Endogenous Treatment Effects: The Relationship Between Competing Estimators of the Union Impact on Wages
9352	C. Meghir and G. Weber	Intertemporal Non-separability or Borrowing Restrictions? A Disaggregate Analysis Using the US CEX Panel
9353	V. Feltkamp	Alternative Axiomatic Characterizations of the Shapley and Banzhaf Values
9354	R.J. de Groof and M.A. van Tuijl	Aspects of Goods Market Integration. A Two-Country-Two -Sector Analysis
9355	Z. Yang	A Simplicial Algorithm for Computing Robust Stationary Points of a Continuous Function on the Unit Simplex
9356	E. van Damme and S. Hurkens	Commitment Robust Equilibria and Endogenous Timing
9357	W. Güth and B. Peleg	On Ring Formation In Auctions
9358	V. Bhaskar	Neutral Stability In Asymmetric Evolutionary Games
9359	F. Vella and M. Verbeek	Estimating and Testing Simultaneous Equation Panel Data Models with Censored Endogenous Variables
9360	W.B. van den Hout and J.P.C. Blanc	The Power-Series Algorithm Extended to the *BMAP/PH/*1 Queue

No.	Author(s)	Title
9361	R. Heuts and J. de Klein	An (s,q) Inventory Model with Stochastic and Interrelated Lead Times
9362	K.-E. Wärneryd	A Closer Look at Economic Psychology
9363	P.J.-J. Herings	On the Connectedness of the Set of Constrained Equilibria
9364	P.J.-J. Herings	A Note on "Macroeconomic Policy in a Two-Party System as a Repeated Game"
9365	F. van der Ploeg and A. L. Bovenberg	Direct Crowding Out, Optimal Taxation and Pollution Abatement
9366	M. Pradhan	Sector Participation in Labour Supply Models: Preferences or Rationing?
9367	H.G. Bloemen and A. Kapteyn	The Estimation of Utility Consistent Labor Supply Models by Means of Simulated Scores
9368	M.R. Baye, D. Kovenock and C.G. de Vries	The Solution to the Tullock Rent-Seeking Game When $R > 2$: Mixed-Strategy Equilibria and Mean Dissipation Rates
9369	T. van de Klundert and S. Smulders	The Welfare Consequences of Different Regimes of Oligopolistic Competition in a Growing Economy with Firm-Specific Knowledge
9370	G. van der Laan and D. Talman	Intersection Theorems on the Simplotope
9371	S. Muto	Alternating-Move Preplays and vN - M Stable Sets in Two Person Strategic Form Games
9372	S. Muto	Voters' Power in Indirect Voting Systems with Political Parties: the Square Root Effect
9373	S. Smulders and R. Gradus	Pollution Abatement and Long-term Growth
9374	C. Fernandez, J. Osiewalski and M.F.J. Steel	Marginal Equivalence in v-Spherical Models
9375	E. van Damme	Evolutionary Game Theory
9376	P.M. Kort	Pollution Control and the Dynamics of the Firm: the Effects of Market Based Instruments on Optimal Firm Investments