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# Environmental policy instruments and ownership of firms

**Juan Carlos Bárcena-Ruiz | María Begoña Garzón**

Departamento de Análisis Económico, Universidad del País Vasco UPV/EHU, Bilbao, Spain

**Correspondence**
María Begoña Garzón, Departamento de Análisis Económico, Facultad de Economía y Empresa, Universidad del País Vasco UPV/EHU, Avenida Lehendakari Aguirre 83, Bilbao 48015, Spain.
Email: mariabegona.garzon@ehu.es

**Abstract**

We assume an economy comprising two countries, with one polluting firm located in each country and transboundary spillovers. Each government may implement an environmental tax or an emission standard to control pollutant emissions. Investors from each country own a percentage of the stock in their local firm and in the firm located abroad. We find that the ownership structure of firms that compete in international markets affects the design of environmental policies by governments. In equilibrium, governments implement emission standards if the stake held by domestic investors in the firm located abroad is small enough. When that stake is intermediate in size and transboundary spillovers are high enough, identical governments choose different environmental policies. Finally, when the stake is large enough both governments implement environmental taxes.

**KEYWORDS**

emission standard, environmental tax, foreign firms, international trade

**JEL CLASSIFICATION**

Q58, L13, F18

## 1 | INTRODUCTION

Since the 1990s increasing concern over the quality of the environment has led governments to implement environmental policies to control pollution. The literature that analyses the choice of the environmental policies implemented by governments has tended to consider that polluting firms are domestic-owned (see, for example, Bárcena-Ruiz, 2006; Bárcena-Ruiz & Campo, 2020; Barrett, 1994; Duval & Hamilton, 2002; Requate, 2006; Ulph, 1996a, 1996b).

It is well known in economic literature that the nationality of firms that compete on international markets affects the structure of markets and the behaviour of regulators. For example, Cato and Matsumura (2017) show that contrasting results can be obtained depending on whether private firms are domestic or foreign owned when a mixed oligopoly is assumed, and that this affects the behaviour of governments. Cai and Karasawa-Ohtashiro (2015) show that international cross-ownership of firms affects the privatisation of a public firm competing with foreign firms.[1] Under a private oligopoly the nationality of firms also influences the behaviour of regulators. In this regard, Bárcena-Ruiz and Casado-Izaga (2020) show that the nationality of firms influences the design of the optimal zoning of urban land by a regulator. Given the importance of the nationality of firms for the behaviour of regulators, we seek to analyse here whether the ownership structure of firms affects the decision by governments as to what environmental policy instruments to use to control pollution.[2] This issue has not been considered by the literature on the environment that assumes international trade under imperfect competition.

The issue analysed in this paper is relevant because, according to the European Commission (2019), firms owned or controlled by foreign investors account for more than 35% of total assets in the EU. The main investors in the EU have traditionally been advanced economies such as the US, Switzerland, Norway, Canada, Australia and Japan. The EU has also developed and implemented some of the strictest emissions standards in the world.[3]

The environmental policy tools most widely used by governments to control pollution are environmental taxes and emission standards. Cairncross (1995) states that countries which have used environmental taxes have found them to be effective. For example, when Sweden introduced a charge of $6000 per ton on nitrous oxide emissions from power stations in 1992, average emissions fell by 35% within 2 years. A Swedish tax on the sulphur content of diesel fuel resulted in a ten-fold rise within 18 months in the proportion of total diesel consumption accounted for by clean diesel. Cairncross (1995 p. 59) also argues that "regulation is by far the most common environmental policy tool". Environmental regulations are especially important in the energy sector, where there are several pollution intensive industries such us petroleum and power generation.[4] In the power generation sector, the Italian multinational Enel is owned by investors from North America (46.4%), the United Kingdom (13.3%) and Germany (6.4%) among others.[5]

The optimality of an environmental tax in a single market was first analysed by Buchanan (1969), assuming a monopoly that generates an externality. He shows that Pigouvian taxation usually leads to suboptimal allocation since it exacerbates the output reduction associated with the monopoly's market

[1]See also Heywood and Ye (2009), Lin and Matsumura (2012), Wang and Chen (2011), and Xu et al. (2017).

[2]The literature on the environment points out that the strict environmental policies of the OECD countries have led polluting firms to shift their production to countries with lax environmental policies, thus causing environmental damage (see, for example, Erdogan, 2014; Markusen, 1997; Markusen et al., 1995; OECD, 2002; Pazienza, 2015; Rauscher, 1995). However, the level of environmental regulation is usually described as having a very small role in location decision-making processes (OECD, 1997). Thus, we do not focus here on the effect of environmental policy tools on FDI but rather consider that firms' ownership is exogenously given: a percentage of the stock in firms is domestic-owned and the rest is foreign-owned.

[3]https://europa.eu/european-union/topics/environment_en.

[4]In the US, investment in pollution abatement increased by 137% from 1979 to 1994 (Ambec & Barla, 2006). Berman and Bui (2001) show that in the early nineties total pollution abatement costs accounted for between 1.51% and 2.5% of US GDP. The same trend can be observed for Canada from 1995 to 2002 (Statistics Canada, 1995, 2002).

[5]https://www.enel.com/investors/investing/shareholders.

power. These distortions can be solved by means of an output subsidy implemented jointly with the environmental tax (Baumol & Oates, 1988). However, that output subsidy is not implemented for political reasons, so a second-best solution is needed. Barnett (1980) and Misiolek (1980) derive a second-best tax rule better suited to a polluting monopoly. That analysis has been extended to consider oligopolistic markets (see, e.g., Duval & Hamilton, 2002; Ebert, 1992; Ohori, 2006; Requate, 2006; Simpson, 1995).

The literature on the environment has also compared the use of emissions standards to environmental taxes under different market structures, focusing mainly on their advantages and disadvantages. Helfand (1999) argues that if firms are identical and there is no uncertainty, taxes and standards generate the same social welfare.[6] However, in competitive markets it is traditionally recognised that environmental taxes have clear efficiency advantages over standards. Baumol and Oates (1988, ch. 4) find that taxes are superior when firms differ. When firms have different abatement costs, and when the abatement level depends only on total emissions, abatement costs are higher with a standard than with a tax. This result holds for any level of pollution abatement (Baumol, 1972; Baumol & Oates, 1988, ch. 11). Another advantage of an environmental tax is that it provides greater incentives for technological change (Jung et al., 1996; Milliman & Prince, 1989). Environmental taxes induce efficient entry of identical firms in the long run, whereas uniform emission standards induce excessive entry (Katsoulacos & Xepapadeas, 1996; Kohn, 1997; Spulber, 1985). Kiyono and Okuno-Fujiwara (2003) show that the social optimum is achieved with both an environmental tax and emission quotas but not with tax-equivalent emission standards. Mäler (1974) finds that the tax approach to controlling pollution externalities under perfect competition is superior to a standards approach. The efficiency advantages traditionally attributed to environmental taxes have been reviewed, and situations have been found in which standards may be more efficient. Helfand (1999) contends that whether taxes are more efficient than standards depends on several factors, for example, how standards are formulated, whether there are information asymmetries and how conditions change over time.[7]

Many other publications have ranked the two environmental policy tools in the presence of market power. Baron (1985) shows that standards are more efficient than environmental taxes by considering a regulated monopoly that has information about its abatement costs that the regulator does not have. Requate (2006) analyses optimal environmental policy tools to control pollution in a Cournot and Bertrand duopoly and in other market structures with market power. Millimet et al. (2009) conduct a survey of theoretical and empirical studies on the economic effects of different environmental policies on market structure. Besanko (1987) shows that an environmental tax is preferred to a standard from a social welfare point of view if the objective is to minimise emissions and pollution damage costs. However, the comparison is inconclusive if the regulator's objective is total surplus less pollution damage. This comparison has also been run considering mixed markets (see, for example, Dong et al., 2019; Kato, 2011). Lahiri and Ono (2007) show that a relative emission standard is welfare-superior to an emission-equivalent tax when the number of firms is fixed, assuming one

[6]When uncertainty is factored into the analysis, either taxes or standards may be more efficient (see Adar & Griffin, 1976; Hoel & Karp, 2001, 2002; Stavins, 1996; Weitzman, 1974).

[7]Rose-Ackerman (1973) suggests that when the effect of emissions is location-specific, a uniform tax is no longer more desirable than a uniform standard. How standards are specified also affects their efficiency (Harford & Karp, 1983; Helfand, 1991, 1993; Rose-Ackerman, 1973). Asymmetric information also affects the efficiency advantages of taxes (see Hoel & Karp, 2001, 2002). The convexity assumption in the social production set traditionally used in the environmental literature also affects the efficiency of environmental taxes (Burrows, 1986, 1996; Hoel, 1998). Holland (2012) shows that if incomplete regulation is assumed and second-best policies are compared, under certain conditions emission taxes are dominated by intensity standards. Buchanan and Tullock (1975) present a positive theory of externality control that explains the observed frequency of direct regulation as opposed to environmental taxes.

country and imperfect competition. Heuson (2010) finds that taxes have a comparative advantage over standards when imperfect competition and uncertain abatement costs are assumed. Bárcena-Ruiz and Sagasta (2021) study what environmental policy is implemented by governments when firms care about social responsibility and find that firms are least concerned about corporate social responsibility under emission standards.

This analysis has been extended to consider international trade. Ulph (1996a) shows that whether an environmental tax is superior to an emission standard from a social welfare point of view depends on whether producing countries are also significant consumers of the polluting product, and on whether all governments or only a subset of them act to reduce emissions. Ulph (1996b) considers two countries with one firm located in each and shows that if governments set environmental taxes and standards non-cooperatively then both output and emissions are greater under environmental taxes.

In this paper, we assume a world market and thus consider that whether an environmental tax is superior to an emission standard depends on two factors: first, the percentage of foreign ownership in domestic firms (a factor that has not been considered to date in the literature on this issue),[8] and secondly the degree to which environmental pollution spills over to trading partners (transboundary spillovers). For this analysis we assume an economy comprising two countries with one firm located in each country, and free trade. The two firms produce a homogeneous good with the same technology, which pollutes the environment. The same technology for abating that pollution is available to both producers. Environmental pollution spills over to trading partners and each government may set an environmental tax or an emission standard to control it. We assume that investors from each country own 1-$\alpha$ percent of the stock of their local firm and $\alpha$ percent of that of the firm located abroad.

In this context we find that which environmental policy tool is chosen by governments depends on the ownership structure of firms. Governments prefer to use emission standards if the stake owned by domestic investors in the firm located abroad (parameter $\alpha$) is low enough. When that stake takes an intermediate value and the degree to which environmental pollution spills over to trading partners is high enough, one government chooses an emission standard and the other sets an environmental tax. This means that identical governments implement different environmental policies. When the stake is high enough, both governments prefer to use environmental taxes. Finally, greater transboundary spillovers lead governments to implement standards for a greater range of values of the stake owned by domestic investors in the firm located abroad.

To understand the above finding it must be noted that as $\alpha$ increases the weight of the profit of the local firm in domestic social welfare falls. This means that each government has incentives to set more stringent environmental policies so as to transfer production and pollution to the other country. By setting a more stringent environmental policy, each government seeks to increase the market share and profits of the firm located abroad, and thus to increase its domestic social welfare. Thus, as $\alpha$ increases the environmental policies of governments become more stringent with both standards and taxes. However, this effect is stronger if governments choose standards than if they choose taxes.

When emissions affect both countries equally, as $\alpha$ increases emissions decrease, but more so with standards than with taxes. This means that environmental damage is lower under standards and that as $\alpha$ increases the weight of environmental damage on social welfare falls. The output of industry, and thus the consumer surplus, is also lower under standards than under taxes, while the producer surplus can be greater or lower depending on the stakes owned by domestic investors in the domestic and foreign firms. Thus, when $\alpha$ is low enough environmental damage has a great weight in social welfare and both governments choose emission standards. When $\alpha$ takes an intermediate value, setting

[8]As far as we know, the only paper which analyses this issue is that of Ohori (2011), although he considers local damage and a single country.

a tax rather than a standard enables each government to increase the market share of its local firm and collect tax revenues while the market share and profits of the firm located abroad decrease. The rise in profits of the local firm and the taxes collected outweigh the fall in profits of the firm located abroad, so the producer surplus (net of total taxes paid by firms) is greater with taxes than with standards. As a result, when $\alpha$ takes an intermediate value, if one government implements a tax the effect of the environmental damage dominates, and the other government reacts by choosing a standard. However, if one government sets up a standard the effect of the consumer and producer surpluses dominate, so the best response of the other government is to set a tax. Finally, when $\alpha$ is high enough both countries implement very stringent environmental policies so environmental damage carries less weight in social welfare. In this last case, both governments set taxes due to the greater consumer and producer surpluses.

A similar result emerges when the environmental damage is local. When $\alpha$ is low enough both governments set standards but when $\alpha$ is high enough they both set environmental taxes. When $\alpha$ takes an intermediate value there are two symmetric equilibria, and the equilibrium in which both governments set standards dominates the one in which they both set taxes. In contrast to the case of global environmental damage, when the environmental damage is local the zone in which each government chooses a different environmental policy tool disappears, because in the latter case emissions only damage the country where the polluting firm is located, so environmental damage has less weight in social welfare.

Considering different values of transboundary externalities gives a result similar to those reported above. Governments prefer to use emission standards if parameter $\alpha$ is low enough. When the degree to which environmental pollution spills over to trading partners is high enough and parameter $\alpha$ takes an intermediate value, one government sets standards and the other taxes; finally, when parameter $\alpha$ is high enough both governments set environmental taxes.

The rest of the paper is organised as follows: Section 2 presents the model. Section 3 shows the main results of the paper. Section 4 analyses the choice of environmental policy instruments by governments and Section 5 reports conclusions.

## 2 | THE MODEL

We consider an economy composed of two countries, denoted by one and two. There is one firm located in each country, and we denote by firm $i$ the firm located in country $i$, so $i = 1, 2$. The two firms produce a homogeneous good whose production process damages the environment. There is free trade, firms sell their product in the world market and there are no transportation costs.

On the consumption side, there is a continuum of consumers of the same type. Consumers may buy the product from either the domestic firm or the foreign one, and firms cannot discriminate between consumers from different countries. The inverse demand function from the world market is $p = A - q_1 - q_2$, where $p$ is the price of the good in the world market and $q_i$ is the amount of the product that firm $i$ sells on the world market, $i = 1, 2$. Given that both firms produce the same product, the consumer surplus derived from worldwide demand is given by $WCS = (q_1 + q_2)^2/2$. Each country is assumed to have half of the consumer population so the consumer surplus in country $i$ is: $CS_i = WCS/2$, $i = 1, 2$ (Bárcena-Ruiz & Garzón, 2014; Duval & Hamilton, 2002).

We assume that the marginal production cost of the firms is given by $c$. Each unit of output produced by each firm causes one unit of pollutant. The output of firm $i$ generates total pollution emissions $e_i$. The same technology for abating this pollutant is available to both firms. The abatement level chosen by firm $i$ is denoted by $a_i$, and its pollution abatement cost function is given by

$CA_i(a_i) = k\left(a_i^2\right)/2,\ i = 1, 2$. If firm $i$ chooses output level $q_i$ and pollution abatement level $a_i$, its total pollutant emissions are $e_i = q_i - a_i$.

To protect the environment the government of each country may choose between two environmental policy instruments: an environmental tax and an emission standard. The former means that government $i$ imposes a tax, $t_i$, per unit of pollutant emitted. Thus, the total taxes payable by firm $i$, which make up the tax revenue collected by the government of country $i$, is $T_i = t_i e_i$. The latter implies that government $i$ imposes a uniform upper bound on pollution that limits the amount of pollutant that firm $i$ may emit, which is denoted by $s_i$. In that case, firm $i$ does not pay environmental taxes. Therefore, the profit of firm $i$ when an environmental tax is set is:

$$\pi_i = \left(A - q_i - q_j - c\right) q_i - t_i e_i - \frac{k}{2} a_i^2,\ i \neq j;\ i, j = 1, 2 \tag{1}$$

When government $i$ sets an emission standard, $s_i$, firm $i$ must to abate all emissions above $s_i$. Thus, its profit is:

$$\pi_i = \left(A - q_i - q_j - c\right) q_i - \frac{k}{2}(q_i - s_i)^2,\ i \neq j;\ i, j = 1, 2 \tag{2}$$

The environmental damage in country $i$ caused by the output of the firms is given by $ED_i = g\left(e_i + d\, e_j\right)^2/2,\ i \neq j; i, j = 1, 2$. The positive parameter $g$ measures the valuation of the environment by the government of country $i$. Parameter $d$, $0 \leq d \leq 1$, measures the degree to which environmental pollution spills over to trading partners (transboundary spillovers). When $d = 0$ the environmental damage is local, so the emissions of each firm only damage the environment of the country where it is located. When $d = 1$ the emissions of each firm cause the same environmental damage in the two countries, so the environmental damage is global.

We assume that investors from country $i$ own 1-$\alpha_i$ percent of the stock of firm $i$ and $\alpha_i$ percent of that of firm $j$, $i \neq j; i, j = 1, 2$. To simplify the analysis we assume that $\alpha_i = \alpha_j = \alpha$, where $\alpha < \overline{\alpha}$.[9] Thus, the producer surplus in country $i$, denoted by $PS_i$, is given by $(1-\alpha)\,\pi_i + \alpha\,\pi_j$ ($i \neq j$; $i, j = 1, 2$), where $\pi_i$ and $\pi_j$ are given by expression (1) or (2) depending on the environmental policy instrument chosen by each government.[10]

The social welfare function considered by the government of country $i$ comprises the consumer surplus ($CS_i$), the producer surplus ($PS_i$), the pollution tax revenue ($T_i$), if any, and the environmental damage, $ED_i$. Specifically it is given by:

$$W_i = CS_i + PS_i + T_i - ED_i,\ i = 1, 2, \tag{3}$$

where $T_i = 0$ if the government of country $i$ sets up an emission standard.

To analyse the choice of environmental policy instrument by each government, we consider a three-stage game. In the first stage both governments simultaneously and independently decide whether to set up an environmental tax or an emission standard. Given those decisions, in the second stage governments simultaneously choose the optimal tax or the optimal standard. In the third stage firms simultaneously and non-cooperatively choose their output and abatement levels. We solve the

[9]We assume that $\alpha < \overline{\alpha} = \left(-123 + 40d - 8d^2 + \sqrt{66169 - 45040d + 10608d^2 - 640d^3 + 64d^4}\right)/160$ to ensure that the emission standards chosen by governments are positive in all cases considered.

[10]Our approach is different from Bárcena-Ruiz and Campo (2017) in that we do not consider cross-ownership between firms.

game by backward induction to obtain a subgame perfect Nash equilibrium. To simplify the exposition of the results, and with no loss of generality, we assume $k = g = 1$.[11]

## 3 | RESULTS

Given that in the first stage each government may set up an environmental tax or an emission standard, there are four subgames to be analysed, which by symmetry may be reduced to three. In the first subgame each government chooses an environmental tax to control pollution. This case is denoted by superscript *tt*. In the second each government chooses an emission standard: this case is denoted by superscript *ss*. In the third and final subgame one government chooses an environmental tax and the other an emission standard: the first country is denoted by superscript *ts* and the second by the superscript *st*. We now analyze the first subgame.

### 3.1 | Environmental taxes

In this subgame the government of each country sets an environmental tax that the firm located in that country must pay. In the third stage of this subgame firm $i$ chooses $q_i$ and $a_i$ to maximise its own profit given by Equation (1). Solving this problem gives the following:

$$q_i = \frac{1}{3}\left(A - c - 2t_i + t_j\right),\ a_i = t_i,\ i \neq j;\ i,\ j = 1, 2 \tag{4}$$

The output of firm $i$ decreases with the environmental tax chosen by government $i\ (\partial q_i/\partial t_i = (-2/3) < 0)$ since the higher $t_i$ is the higher the costs of firm $i$ are. However, the output of firm $i$ increases with the environmental tax chosen by the government of country $j$ $\left(\partial q_i/\partial t_j = (1/3) > 0\right)$ since the higher $t_j$ is the greater the marginal cost of firm $j$ is, so the greater the market share of firm $i$ is. Equation (4) also shows the usual condition, which states that firm $i$ abates pollution to the point where the marginal abatement cost equals the tax. The abatement level of firm $i$, $a_i$, increases with the environmental tax, $t_i$.

In the second stage of this subgame, given Equation (4), government $i$ chooses the environmental tax $t_i$ to maximise social welfare given by Equation (3), $i = 1, 2$. Solving this problem gives the following reaction functions in environmental taxes:

$$t_i = \frac{\left(9 - 52d + 10d^2\right) t_j + (A - c)\left(6 + 8d - 2d^2 + 12\alpha\right)}{75 - 20d + 2d^2 + 30\alpha},\ i \neq j;\ i,\ j = 1, 2. \tag{5}$$

From Equation (5) it emerges that $\partial t_i/\partial t_j > 0$ if and only if $d < (26 - \sqrt{586})/10 \approx 0.1792$. Thus, if one government sets a higher tax the other reacts by doing likewise if transboundary spillovers are low enough (i.e. if $d < 0.1792$), so as to avoid a transfer of production (and pollution) from the other country. Moreover, if one government seeks to gain production (and the associated pollution) by setting a lower tax, the other follows suit in order to avoid a loss in production and in domestic rents. When transboundary spillovers are great enough (i.e. if $d > 0.1792$), if one government raises its tax the other government reacts by lowering its tax to gain market share and rents for its domestic

[11]It can be shown that the main results of the paper hold when parameters $k$ and $g$ are other than 1.

firm. In this case, each government does not react by increasing its tax to transfer production to its rival country, because this would decrease the income of the domestic firm but would only reduce the environmental damage suffered by the country very slightly.

We denote the marginal environmental damage in country $i$ by $MED_i$, where $\mathrm{MED}_i = \partial \mathrm{ED}_i / \partial e_i$. Given the symmetry of the model, subindex $i$ denoting the firm or country is now dropped. From Equation (5) the following result emerges.

**Lemma 1** *When both governments set an environmental tax to control pollution, in equilibrium:*

$$t^{tt} = a^{tt} = \frac{(A-c)\left(3+4d-d^2+6\alpha\right)}{33+16d-4d^2+15\alpha},\ q^{tt} = \frac{(A-c)\left(10+4d-d^2+3\alpha\right)}{33+16d-4d^2+15\alpha}, \mathrm{MED}^{tt} = \frac{(A-c)(1+d)(7-3\alpha)}{33+16d-4d^2+15\alpha},$$

$$PS^{tt} = \pi^{tt} = \frac{(A-c)^2\left(209-24d^3+3d^4+d^2(2-24\alpha)+156\alpha+54\alpha^2+8d(23+12\alpha)\right)}{2\left(33+16d-4d^2+15\alpha\right)^2},$$

$$CS^{tt} = \frac{(A-c)^2\left(10+4d-d^2+3\alpha\right)^2}{\left(33+16d-4d^2+15\alpha\right)^2},\ T^{tt} = \frac{(A-c)^2\left(3+4d-d^2+6\alpha\right)(7-3\alpha)}{\left(33+16d-4d^2+15\alpha\right)^2},\ ED^{tt} = \frac{(A-c)^2(1+d)^2(7-3\alpha)^2}{2\left(33+16d-4d^2+15\alpha\right)^2},$$

$$W^{tt} = \frac{(A-c)^2\left(402-40d^3+5d^4+384\alpha+27\alpha^2+d\left(302+204\alpha-18\alpha^2\right)-3d^2\left(23-4\alpha+3\alpha^2\right)\right)}{2\left(33+16d-4d^2+15\alpha\right)^2}.$$

It can be shown that the environmental tax $t^{tt}$ increases with parameters $d$ and $\alpha$ $\left(\partial t^{tt}/\partial d > 0,\ \partial t^{tt}/\partial \alpha > 0\right)$. When parameter $\alpha$ increases the weight of the profit of the firm located abroad in domestic social welfare increases. Thus, as $\alpha$ increases the government of each country increases its environmental tax to reduce the output of the domestic firm, which increases the output and the profit of the firm located abroad. When parameter $d$ increases, the environmental damage caused in country $i$ by emissions from firm $j$ increases. This leads each government to set a higher environmental tax in order to reduce the environmental damage caused by the emissions of the local firm.

It can be shown that the marginal environmental damage decreases with parameter $\alpha$ $\left(\partial MED^{tt}/\partial \alpha < 0\right)$. When $\alpha$ increases, so does the tax set by the government, so firms generate fewer emissions, which reduces the marginal environmental damage.

Comparing the optimal tax with the marginal environmental damage yields the following:

$$t^{tt} - \mathrm{MED}^{tt} = \frac{(A-c)\left(4+d^2+3d(1-\alpha)-9\alpha\right)}{-33-16d+4d^2-15\alpha},$$

which is nil for $\alpha = \alpha^*$, where $\alpha^* = \frac{4+3d+d^2}{9+3d}$. It can be shown that $\alpha^*$increases with $d$, and that $\alpha^* \in [4/9, 6/9]$. Moreover, $t^{tt} > MED^{tt}$ if $\alpha > \alpha^*$, while $t^{tt} < MED^{tt}$ if $\alpha < \alpha^*$.[12] The comparison, therefore, depends on parameter $\alpha$. If $\alpha = 0$, in which case both firms are domestic-owned, the usual result is obtained, i.e. the tax is lower than the marginal environmental damage. As seen, $\partial t^{tt}/\partial \alpha > 0$ and $\partial MED^{tt}/\partial \alpha < 0$. If $\alpha$ is sufficiently small ($\alpha < \alpha^*$) it is also obtained that the tax is lower than the marginal environmental damage. Because $\alpha$ is small, the change in tax and marginal environmental damage is not sufficient to change the result. If $\alpha$ is large enough ($\alpha > \alpha^*$) it is found that the tax is greater than the marginal environmental damage. When $\alpha$ is large enough, the variation in tax and marginal environmental damage is sufficient to change the result.

Next we analyse the second subgame, in which both governments set emission standards to control pollution.

## 3.2 | Emission standards

When the governments set an emission standard, firms reduce their pollutant emissions by an amount sufficient to exactly meet the standard, since abating emissions is expensive; therefore, $a_i = q_i - s_i$, $i = 1, 2$. In the third stage of this subgame firm $i$ chooses $q_i$ to maximise its own profit, given by Equation (2). Solving this problem gives the following:

$$q_i = \frac{1}{8}\left(2(A-c) + 3s_i - s_j\right), \; i \neq j; \; i, \; j = 1, \; 2. \tag{6}$$

The output of firm $i$ increases with the stringency of the emission standard chosen by the government of country $i$ ($\partial q_i/\partial s_i = (3/8) > 0$): an increase in $s_i$ permits firm $i$ to pollute more so its pollution abatement cost decreases. The output of firm $i$ decreases with the emission standard chosen by government $j$ $\left(\partial q_i/\partial s_j(-1/8) < 0\right)$ because the higher $s_j$ is, the greater the output of firm $j$ is and the lower the output of firm $i$.

In the second stage of this subgame, given Equation (6), government $i$ chooses emission standard $s_i$ to maximise social welfare, given by Equation (3), $i = 1, 2$. Solving this problem, the following reaction functions in emission standards emerge:

$$s_i = \frac{(A-c)(22-24\alpha) - (7+64d)s_j}{99-40\alpha}, \; i \neq j; \; i, \; j = 1, \; 2. \tag{7}$$

From Equation (7) it results that $\partial s_i/\partial s_j < 0$ for all values of parameter $d$, so if one government sets a stringent standard the other reacts by setting a lax standard to gain market share and rents for its domestic firm. Conversely, if one government sets a lax standard the other reacts by setting a stringent standard. If both governments implemented a lax standard this would harm the environment excessively, and if both set a restrictive standard then the consumer and producer surpluses would decrease significantly.

From Equation (7) the following result emerges.

**Lemma 2** *When both governments set an emission standard to control pollution, in equilibrium:*

[12]The result that the tax can be greater than the marginal environmental damage has also been obtained for a Cournot duopoly considering a single country (Simpson, 1995).

$$s^{ss} = \frac{(A-c)(11-12\alpha)}{53+32d-20\alpha},\ a^{ss} = \frac{(A-c)(5+8d+4\alpha)}{53+32d-20\alpha},\ q^{ss} = \frac{8(A-c)(2+d-\alpha)}{53+32d-20\alpha},$$

$$ED^{ss} = \frac{(A-c)^2(1+d)^2(11-12\alpha)^2}{2(53+32d-20\alpha)^2},$$

$$CS^{ss} = \frac{(A-c)^2 64(2+d-\alpha)^2}{(53+32d-20\alpha)^2},$$

$$PS^{ss} = \pi^{ss} = \frac{(A-c)^2\left(647+192d^2-384d(-2+\alpha)-504\alpha+48\alpha^2\right)}{2(53+32d-20\alpha)^2},$$

$$W^{ss} = \frac{(A-c)^2\left(1038-752\alpha+32\alpha^2+d^2\left(199+264\alpha-144\alpha^2\right)-2d\left(-519+56\alpha+144\alpha^2\right)\right)}{2(53+32d-20\alpha)^2}.$$

It can be shown that the emission standard decreases with parameters $d$ and $\alpha$ ($\partial s^{ss}/\partial d < 0, \partial s^{ss}/\partial\alpha < 0$). When $\alpha$ increases the profit of the firm located abroad has a greater weight in domestic social welfare. Thus, the government of country $i$ sets a lower emission standard to decrease the output of firm $i$, which increases the output and profits of the firm located abroad. When $d$ increases, the environmental damage in country $i$ caused by the production process of firm $j$ increases. As a result, each government reduces its emission standard in order to decrease the environmental damage caused by emissions from the local firm.

Next we analyse the third subgame, in which one government chooses an environmental tax to control pollution and the other sets an emission standard.

## 3.3 | Governments implement different environmental policy tools

In this subgame government $i$ is assumed to set an environmental tax while government $j$ chooses an emission standard, $i \neq j;\ i, j = 1, 2$. In the third stage of this subgame firm $i$ chooses $q_i$ and $a_i$ to maximise its profit, $\pi_i$, given by Equation (1); firm $j$ chooses $q_j$ to maximise its profit, $\pi_j$, given by Equation (2). Solving these problems gives the following:

$$q_i = \frac{1}{5}\left(2(A-c)-s_j-3t_i\right),\ a_i = t_i,\ q_j = \frac{1}{5}\left(A-c+2s_j+t_i\right), i \neq j;\ i, j = 1, 2. \tag{8}$$

The output of firm $i$ decreases with the environmental tax chosen by government $i$ ($\partial q_i/\partial t_i = (-3/5) < 0$), which increases the output of firm $j\left(\partial q_j/\partial t_i = (1/5) > 0\right)$, given that both firms produce the same good. The output of firm $j$ increases with the emission standard chosen by government $j\left(\partial q_j/\partial s_j = (2/5) > 0\right)$, because an increase in $s_j$ leads firm $j$ to produce and pollute more and firm $i$ thus to produce less $\left(\partial q_i/\partial s_j = -1/5 < 0\right)$.

In the second stage of the game, given Equation (8), government $i$ chooses the environmental tax $t_i$ and government $j$ sets the emission standard $s_j$ to maximise the social welfares of countries $i$ and $j$ respectively, given by Equation (3). Solving these problems gives the following reaction functions:

$$t_i = \frac{(A-c)(11+15\alpha)-(8-40d)s_j}{99+40\alpha},\ s_j = \frac{2\left(5+40d-8d^2\right)t_i+(A-c)\left(15-20d+4d^2-20\alpha\right)}{75-20d+2d^2-30\alpha}, \tag{9}$$
$$i \neq j;\ i, j = 1, 2.$$

From Equation (9) it emerges that $\partial s_j/\partial t_i > 0$ for all $d$, and $\partial t_i/\partial s_j < 0$ if and only if $d < 0.2$. The result of this subgame, obtained from Equation (9) and shown in Lemma A1, is relegated to the Appendix.[13]

Next we solve the first stage of the game.

## 4 | THE CHOICE OF THE ENVIRONMENTAL POLICY INSTRUMENT

In the first stage of the game each government decides whether to set an environmental tax or an emission standard to control pollution. Denote by $\alpha_1(d)$, $\alpha_2(d)$ and $\alpha_3(d)$ the values of $\alpha$ such that $W^{tt} = W^{st}$, $W^{ts} = W^{ss}$ and $W^{tt} = W^{ss}$, respectively. The critical values of $\alpha_1(d)$, $\alpha_2(d)$ and $\alpha_3(d)$, shown in Figure A1, are characterised in the Appendix. Comparing the social welfare obtained by the countries in the different cases considered gives the following result.

**Lemma 3** *In equilibrium $W^{tt} > W^{st}$ if and only if $\alpha > \alpha_1(d)$, $W^{ts} > W^{ss}$ if and only if $\alpha > \alpha_2(d)$, and $W^{tt} > W^{ss}$ if and only if $\alpha > \alpha_3(d)$.*

*Proof* See Appendix.

It is proved in the Appendix that $\alpha_1(d)$ and $\alpha_2(d)$ are strictly increasing in $d$. Moreover, it can be shown that if $d = 0$ then $W^{tt}$ - $W^{st} = 0$ for $\alpha = 0.0085$, and $W^{ts}$ - $W^{ss} = 0$ for $\alpha = 0.0087$. When $d = 1$ then $W^{tt}$ - $W^{st} = 0$ for $\alpha = 0.3020$, and $W^{ts}$ - $W^{ss} = 0$ for $\alpha = 0.2944$. Therefore, $\alpha_1(d)$ and $\alpha_2(d)$ are cut for values of parameters $d$ and $\alpha$ between 0 and 1. By running simulations it can be shown that $W^{tt}$ - $W^{st} = W^{ts}$ - $W^{ss} = 0$ for $\alpha = 0.1748$ and $d = 0.6705$. Taking into account these results and Lemma 3, four zones can be identified in Figure A1: (i) the values of $\alpha$ and $d$ such that $\overline{\alpha} > \alpha \geq \max\{\alpha_1(d), \alpha_2(d)\}$; (ii) the values of $\alpha$ and $d$ such that $\alpha_1(d) > \alpha > \alpha_2(d)$; (iii) the values of $\alpha$ and $d$ such that $\alpha_2(d) > \alpha > \alpha_1(d)$; and (iv) the values of $\alpha$ and $d$ such that $\min\{\alpha_1(d), \alpha_2(d)\} \geq \alpha \geq 0$.

From Lemma 3 the first stage of the game can be solved. It emerges that the environmental policy instruments set by the governments depend on two factors: the degree to which environmental pollution spills over to trading partners and the percentage of ownership of firms held by domestic investors. To make the explanation of the results obtained in this paper easier to follow, two particular cases are reported before the overall outcome is set out: when there is local damage ($d = 0$) and when emissions affect both countries equally ($d = 1$). These two cases illustrate the different equilibria that arise when the first stage of the game is solved. The overall result is then presented, and an intuition is presented of the outcome for values of the transboundary spillover $d$ other than 0 and 1.

Before the main findings of the paper are reported, various effects that must be taken into account to understand those findings must be explained. Governments implement more rigorous environmental policies with standards than with taxes (taking into account the total emissions of the two countries).[14] This is because under standards firms must reduce emissions to meet the emissions limit, but under taxes they can avoid reducing emissions by paying taxes instead. Reducing emissions

[13] As when the two countries implement taxes, it can be shown that if $\alpha$ is small (large) enough the tax is lower (greater) than the marginal environmental damage.

[14] Given that governments implement more rigorous environmental policies with standards than with taxes, it is found that $2a^{ss} > a^{ts} + a^{st} > 2\,a^{tt}$, which means that the implementation of standards by governments leads to more emissions being abated than the implementation of environmental taxes. As a result, $2\,e^{tt} > e^{ts} + e^{st} > 2e^{ss}$ so total emissions are higher with taxes than with standards.

has a quadratic cost, while under taxes a constant amount is paid per unit emitted. Parameter $\alpha$ (the percentage of shares owned by domestic investors in the firm located abroad) indirectly affects the output of firms through taxes and standards. Specifically, the higher $\alpha$ is, the lower the weight of the profit of the local firm is and the greater the weight of the profit of the firm located abroad is, in domestic social welfare. This affects the environmental policy set by each government and thus the output of the firms. The effect of parameter $\alpha$ on the output of the firms differs depending on whether governments implement taxes or standards. When $\alpha$ increases, the profit of the firm located abroad has a greater weight in domestic social welfare, so governments set stricter environmental policies as $\alpha$ rises. This hurts the local firm since it faces greater environmental costs; it also benefits the firm located abroad and reduces domestic environmental damage. With environmental taxes, firms have the option of paying taxes instead of reducing emissions, so standards become more stringent than taxes as $\alpha$ becomes greater.

## 4.1 | Local damage ($d = 0$)

The first case analysed is that in which pollutant emissions damage only the country where they are generated.

**Proposition 1** *In equilibrium, when environmental damage is local ($d = 0$), if $\alpha \geq 0.0087$ both governments set up environmental taxes and if $\alpha < 0.0087$ both governments implement emission standards.*

This proposition shows that governments set up environmental standards if the percentage of shares owned by domestic investors in the firm located abroad is small enough, and set environmental taxes otherwise. Next, we compare the different components of social welfare obtained under the different possible environmental policy tools.

It can be shown from Lemmas 1, 2 and A1 that $CS^{tt} > CS^{ts} = CS^{st} > CS^{ss}$. As seen, governments set stricter environmental policies when they implement standards than when they set taxes, so the output of industry is greater under taxes (it is straightforward to see that $2\,q^{tt} > q^{ts} + q^{st} > 2q^{ss}$). Given that the consumer surplus increases with the output of industry, the consumer surplus is greatest when both governments set taxes and lowest when both set standards.

For a given policy of the other country, the net producer surplus is greater with taxes than with standards except when the local firm is mainly owned by domestic investors. Specifically, $PS^{tt} + T^{tt} > PS^{st}$ if and only if $\alpha > 0.0296$ and $PS^{ts} + T^{ts} > PS^{ss}$ if and only if $\alpha > 0.0295$. When $\alpha$ is near zero, governments do not take into account the profit of the firm located abroad when choosing their environmental policies. In that case the usual result emerges that a greater output of industry (which implies a greater consumer surplus) also implies a lower net producer surplus; this means that $PS^{st} > PS^{tt} + T^{tt}$ and $PS^{ss} > PS^{ts} + T^{ts}$. As $\alpha$ increases the environmental policy of each government becomes more stringent, and this effect is stronger under standards than under taxes, which reverses the above result for a high enough value of $\alpha$.

It can be seen from Lemmas 1, 2 and A1 that $ED^{tt} > ED^{st}$ if and only if $\alpha > 0.1610$, and $ED^{ts} > ED^{ss}$ if and only if $\alpha > 0.1686$. When $\alpha$ is high enough, governments implement more stringent environmental policies under standards than under taxes, which leads to less environmental damage under standards. As $\alpha$ decreases the environmental policy of each government becomes more lax. This effect is stronger under standards than under taxes, which reverses the above result for a low enough value of $\alpha$ ($ED^{st} > ED^{tt}$ if $\alpha < 0.1610$ and $ED^{ss} > ED^{ts}$ if $\alpha < 0.1686$).

Next we compare the different components of social welfare.[15] When $\alpha < 0.0085$, $\alpha$ is low enough for the greater net producer surplus to carry more weight in social welfare so in equilibrium both governments set emission standards $\left(W^{tt} < W^{st} \text{and} W^{ts} < W^{ss}\right)$. When $0.0085 < \alpha < 0.0087$ there are two symmetric equilibria: in one both firms set taxes and in the other both set standards. However, the second equilibrium Pareto dominates the first since the lower emissions under standards ($e^{ss} < e^{tt}$) lead to greater social welfare.

When $\alpha > 0.0087$, in equilibrium the two governments implement environmental taxes. As shown in Table A1 (see Appendix), the environmental damage and the net producer surplus can be greater or lower with taxes than with standards depending on the value of parameter$\alpha$. However, the consumer surplus is greater with taxes, whichever policy is set by the other government and whatever the value of $\alpha$, which leads each government to implement an environmental tax independently of the decision taken by its rival $\left(W^{tt} > W^{st} \text{ and } W^{ts} > W^{ss}\right)$.

## 4.2 | Pollutant emissions affect both countries equally ($d = 1$)

Next we consider global environmental damage when pollutant emissions affect both countries equally. In this case the following result is obtained.

**Proposition 2** *In equilibrium, when pollutant emissions affect both countries equally ($d$ = 1), if $\alpha \geq 0.3020$ both governments set environmental taxes, if $0.2944 \leq \alpha < 0.3020$ one government sets an emission standard and the other an environmental tax, and if $\alpha < 0.2944$ both governments set emission standards.*

As in Proposition 1, and for the same reasons, it emerges that $CS^{tt} > CS^{ts} = CS^{st} > CS^{ss}$. In addition, $ED^{tt} > ED^{st}$ and $ED^{ts} > ED^{ss}$, so for a given environmental policy by one government, the environmental damage suffered in the other country is greater when the latter country sets a tax than when it sets a standard. This is because governments implement more stringent environmental policies under standards than under taxes, which leads to less environmental damage under standards. Unlike when the environmental damage is local, this result now holds for all values of $\alpha$, since damage is global and pollutant emissions affect both countries equally, so the environmental policy of the governments does not become sufficiently lax when $\alpha$ decreases.

A comparison of the net producer surplus obtained in the different cases considered reveals that $PS^{tt} + T^{tt} > PS^{st}$ if and only if $\alpha > 0.2408$ and $PS^{ts} + T^{ts} > PS^{ss}$ if and only if $\alpha > 0.2383$. The explanation is similar to that given in Proposition 1 for the case of local damage. But given that pollutant emissions affect both countries equally, they both take into account their total emissions so a larger $\alpha$ is needed than when $d = 0$ to obtain the result that the net producer surplus becomes greater with taxes.

Next we compare the different components of social welfare.[16] When $\alpha < 0.2944$, for a given environmental policy of the other government the net producer surplus may be greater or lower with standards than with taxes. The consumer surplus and the environmental damage are greater with taxes. The environmental damage has a strong weight in social welfare, since $d = 1$, so in

[15]A detailed comparison of the components of social welfare can be found in Table A1 (see Appendix).

[16]A detailed comparison of the components of social welfare can be found in Table A2 (see Appendix).

equilibrium both governments implement emission standards since this is a dominant strategy for them $\left(W^{tt} < W^{st} \text{and} W^{ts} < W^{ss}\right)$.

When $0.2944 \le \alpha < 0.3020$, in equilibrium one government sets an emission standard and the other an environmental tax, so they implement different policies. For a given environmental policy of the other government, the net producer surplus is lower under standards than under taxes. In addition, the consumer surplus and the environmental damage are greater under taxes. If one government implements a tax, the effect of environmental damage on social welfare dominates, so the other government reacts by choosing a standard $\left(W^{tt} < W^{st}\right)$. However, if one government sets up a standard the effect of the consumer and net producer surplus dominates, so the best response of the other government is to choose a tax $\left(W^{ts} > W^{ss}\right)$.

Finally, when $\alpha \ge 0.3020$, in equilibrium both governments implement environmental taxes. For a given environmental policy of the other government, the net producer surplus is greater under taxes than under standards. In addition, the consumer surplus and the environmental damage are greater under taxes. The effect of the consumer and producer surpluses on social welfare dominates, so each government chooses an environmental tax regardless of what environmental policy is implemented by the other $\left(W^{tt} > W^{st} \text{ and } W^{ts} > W^{ss}\right)$.

## 4.3 | Different values for transboundary spillover

A comparison of the results obtained with $d = 0$ and with $d = 1$ (see Figure A1) shows that for a low enough $\alpha$ environmental damage is greater under standards than under taxes for $d = 0$, while the reverse holds for $d = 1$. In addition, as parameter $d$ increases the fraction of the pollution generated in one country that affects the other country increases. Thus, as $d$ increases, the greater output of industry under taxes leads to greater environmental damage for a low enough $\alpha$ (see Tables A1 and A2). This means that the results obtained for $d = 0$ may differ from those obtained for $d = 1$. In fact, for $d = 1$ the range of values of parameter $\alpha$ under which both governments set standards is broader than when $d = 0$, and for intermediate values of $\alpha$ just one government implements a tax, so as $d$ increases governments acquire a greater incentive to set standards rather than taxes.

Next, we present the result obtained for all values of parameter $d$.

**Proposition 3** *In equilibrium, if* $\overline{\alpha} > \alpha \ge \max\{\alpha_1(d), \alpha_2(d)\}$ *both governments set up environmental taxes; if* $\alpha_1(d) > \alpha > \alpha_2(d)$ *one government sets an environmental tax and the other an emission standard; finally, for the remaining values of parameters both governments set emission standards.*

The result in Proposition 3 is illustrated in Figure A1, which shows that when transboundary spillovers are low enough (i.e. when $d < 0.6705$) the result obtained is similar to that when $d = 0$: if $\alpha \ge \alpha_2(d)$ both governments set environmental taxes, and if $\alpha \le \alpha_1(d)$ both governments set emission standards. When $\alpha_1(d) < \alpha < \alpha_2(d)$, there are two symmetric equilibria, and the one in which both governments set standards dominates the one in which they both set taxes. As parameter $d$ increases that zone becomes smaller, and it disappears for $d = 0.6705$. This is because as $d$ increases governments have more incentives to set standards rather than taxes.

As shown in Figure A1, when transboundary spillovers are high enough (i.e. when $d > 0.6705$) the result is similar to when $d = 1$: if $\alpha \ge \alpha_1(d)$ both governments implement environmental taxes, if $\alpha_1(d) > \alpha > \alpha_2(d)$ one government sets an environmental tax and the other an emission standard, and if $\alpha \le \alpha_2(d)$ both governments set emission standards. As parameter $d$ decreases from $d = 1$ the zone where there is asymmetric equilibrium becomes smaller, and it disappears for $d = 0.6705$. This is because as $d$ decreases governments have less incentive to set standards rather than taxes.

## 5 | CONCLUSIONS

Increasing concern at the quality of the environment has led governments to implement various environmental policy tools to control pollution. The most commonly used are emissions standards and environmental taxes. The literature on the environment has extensively analysed and compared the use of these two instruments, and found that whether taxes are more efficient than standards depends on several factors. However, this literature does not consider how the ownership structure of firms may affect the choice of environmental policy tools by governments, because it has tended to assume that polluting firms are domestic-owned. Nevertheless, this is an important factor to take into account in the analysis since it is well known in economic literature that the nationality of firms that compete on international markets affects the behaviour of regulators. Moreover, in today's economy firms are owned not only by domestic investors but also by foreign investors.

To fill this gap in the literature, this paper seeks to analyse whether the ownership of firms by both domestic and foreign investors affects the design of environmental policies by governments. Specifically, a world market is assumed and it is analysed whether an environmental tax is superior to an emission standard, based on two factors. The first is the percentage of stock in domestic firms owned by foreign investors. The second is the degree to which environmental pollution spills over to trading partners. We find that governments prefer to use emission standards if the percentage of shares in the firm located abroad owned by domestic investors is low enough. When that percentage takes an intermediate value and the degree to which environmental pollution spills over to trading partners is high enough, one government sets an emission standard and the other an environmental tax. For the rest of the parameter values, both governments prefer to use environmental taxes. This result means that governments must take into account the ownership structure of firms that compete in international markets when designing their environmental policies.

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### ORCID

*María Begoña Garzón* https://orcid.org/0000-0002-5731-7581

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## APPENDIX

**Lemma A1** *When one government sets an environmental tax and the other chooses an emission standard to control pollution, in equilibrium:*

$$t^{ts} = a^{ts} = (A-c)\left(141 + 32d^3 + 6d^2(-27+\alpha) + 191\alpha - 90\alpha^2 - 4d(-27+55\alpha)\right)/H,$$

$$s^{st} = (A-c)\left(319 + d^2(44-16\alpha) - 246\alpha - 160\alpha^2 + 20d(-11+4\alpha)\right)/H,$$

$$q^{ts} = (A-c)\left(452 + 32d^3 + 6d^2(-27+\alpha) - 63\alpha - 10\alpha^2 + 4d(-40+13\alpha)\right)/H,$$

$$q^{st} = (A-c)\left(456 + 32d^3 - 59\alpha - 130\alpha^2 - 2d^2(70+\alpha) - 4d(34+11\alpha)\right)/H,$$

$$a^{st} = (A-c)\left(137 + 32d^3 + d(84-124\alpha) + 187\alpha + 30\alpha^2 + 2d^2(-92+7\alpha)\right)/H,$$

$$\pi^{ts} = \left((A-c)^2 \left(428489 + 3072d^6 + 1152d^5(-27+\alpha) - 60042\alpha + 959\alpha^2 - 31860\alpha^3 + 8300\alpha^4 \right.\right.$$
$$+ 4d^4\left(16291 - 3314\alpha + 27\alpha^2\right) - 16d^3\left(-8473 - 2450\alpha + 527\alpha^2\right)$$
$$- 4d^2\left(68929 + 22330\alpha - 22557\alpha^2 + 330\alpha^3\right)$$
$$\left.\left. + 8d\left(-32353 + 14194\alpha - 13773\alpha^2 + 4690\alpha^3\right)\right)\right) / \left(2H^2\right),$$

$$\pi^{st} = \left((A-c)^2 \left(522047 + 3072d^6 - 4476\alpha - 303673\alpha^2 - 32700\alpha^3 + 25100\alpha^4 \right.\right.$$
$$- 384d^5(70+\alpha) - 4d^4\left(-7688 + 1340\alpha + 61\alpha^2\right)$$
$$- 16d^3\left(-13822 - 824\alpha + 1367\alpha^2\right) - 4d^2\left(101006 - 36762\alpha - 28881\alpha^2 + 890\alpha^3\right)$$
$$\left.\left. + 8d\left(-28967 - 28940\alpha + 11327\alpha^2 + 7490\alpha^3\right)\right)\right) / \left(2H^2\right),$$

$$\mathrm{CS}^{st} = \mathrm{CS}^{ts} = (A-c)^2\left(454 + 32d^3 + 4d(-37+\alpha) - 61\alpha - 70\alpha^2 + d^2(-151+2\alpha)\right)^2 / H^2,$$

$$PS^{ts} = \left((A-c)^2 \left(428489 + 3072d^6 + 33516\alpha + 56525\alpha^2 - 336492\alpha^3 \right.\right.$$
$$+ 7460\alpha^4 + 16800\alpha^5 - 384d^5\left(81 - 14\alpha + 4\alpha^2\right)$$
$$+ d^4\left(65164 - 47668\alpha + 8004\alpha^2 - 352\alpha^3\right)$$
$$- 16d^3\left(-8473 - 7799\alpha + 2153\alpha^2 + 840\alpha^3\right)$$
$$- 4d^2\left(68929 + 54407\alpha - 81649\alpha^2 - 5994\alpha^3 + 560\alpha^4\right)$$
$$\left.\left. + 8d\left(-32353 + 17580\alpha - 56907\alpha^2 + 29790\alpha^3 + 2800\alpha^4\right)\right)\right) / \left(2H^2\right),$$

$$PS^{st} = \left((A-c)^2 \left(522047 + 3072d^6 - 98034\alpha - 359239\alpha^2 + 271932\alpha^3 \right.\right.$$
$$+ 25940\alpha^4 - 16800\alpha^5 + 768d^5\left(-35 - 6\alpha + 2\alpha^2\right)$$
$$+ 4d^4\left(7688 + 7263\alpha - 2035\alpha^2 + 88\alpha^3\right)$$
$$+ 16d^3\left(13822 - 4525\alpha + 259\alpha^2 + 840\alpha^3\right)$$
$$+ 4d^2\left(-101006 + 68839\alpha - 30211\alpha^2 - 7214\alpha^3 + 560\alpha^4\right)$$
$$\left.\left. - 8d\left(28967 + 32326\alpha - 54461\alpha^2 + 17610\alpha^3 + 2800\alpha^4\right)\right)\right) / \left(2H^2\right),$$

$$ED^{ts} = (A-c)^2 \left(-311 + d^2(220 - 80\alpha) + 254\alpha - 80\alpha^2 - 4d^3(11 - 4\alpha)\right.$$
$$\left. + d\left(-51 - 26\alpha + 160\alpha^2\right)\right)^2 / \left(2H^2.\right),$$

$$\mathrm{ED}^{st} = (A-c)^2\left(319 - 246\alpha - 160\alpha^2 + 32d^2(-7+8\alpha) + d\left(91 - 174\alpha + 80\alpha^2\right)\right)^2 / \left(2H^2\right),$$

$$W^{ts} = \left((A-c)^2\left(831702 + 127902\alpha - 307877\alpha^2 - 202492\alpha^3 - 3540\alpha^4 \right.\right.$$
$$+ 16800\alpha^5 - 16d^6\left(-199 - 88\alpha + 16\alpha^2\right) + 32d^5\left(-971 - 264\alpha + 32\alpha^2\right)$$
$$+ d^4\left(21782 + 3588\alpha + 16524\alpha^2 - 5472\alpha^3\right) + 80d^3\left(4811 + 517\alpha - 1559\alpha^2 + 184\alpha^3\right)$$
$$+ d^2\left(-530537 - 80992\alpha + 311256\alpha^2 + 19896\alpha^3 - 27840\alpha^4\right)$$
$$\left.\left. + d\left(-567714 - 23624\alpha - 29040\alpha^2 + 67600\alpha^3 + 48000\alpha^4\right)\right)\right) / \left(2H^2\right),$$

$$W^{st} = \left((A-c)^2\left(832518 + 5120d^6 - 51862\alpha - 437353\alpha^2 + 210292\alpha^3 + 10140\alpha^4 - 16800\alpha^5 + 128d^5\left(-361 - 34\alpha + 12\alpha^2\right) + 2d^4\left(3617 + 71522\alpha - 36834\alpha^2 + 176\alpha^3\right) - 16d^3\left(-25589 + 13022\alpha - 7509\alpha^2 + 1720\alpha^3\right) + d^2\left(-499801 + 71596\alpha - 69584\alpha^2 + 80344\alpha^3 - 4160\alpha^4\right) + 2d\left(-279281 - 29724\alpha + 184312\alpha^2 - 79160\alpha^3 + 1600\alpha^4\right)\right)\right) / \left(2H^2\right),$$

where $H = 1501 + 128d^3 + 6\alpha - 240\alpha^2 + 2d^2(-313 + 8\alpha) - 4d(87 + 40\alpha)$.

*Proof of Lemma 3* From Lemmas 1 and 2, the following is obtained:

$$W^{tt} - W^{ss} = \left((A-c)^2\left(-2 + 17\alpha - 60\alpha^2 - 12d(1+2\alpha) + d^2(-11 + 12\alpha)\right)\left(582 - 3915\alpha - 60\alpha^2 + 16d^4(-11 + 12\alpha) - 32d^3(-49 + 24\alpha) + d^2\left(5089 - 4300\alpha - 480\alpha^2\right) - 4d\left(-953 + 1646\alpha + 240\alpha^2\right)\right)\right) / \left(2(53 + 32d - 20\alpha)^2\left(33 + 16d - 4d^2 + 15\alpha\right)^2 > 0 \text{ if and only if}$$

$$\alpha > \alpha_3(d) = \left(-3915 - 6584d - 4300d^2 - 768d^3 + 192d^4 + (15466905 + 54702480d + 93994936d^2 + 89872960d^3 + 42849424d^4 + 6411264d^5 - 1399296d^6 - 294912d^7 + 36864d^8)^{1/2}\right) / \left(120\left(1 + 16d + 8d^2\right)\right).$$

Assume that $\alpha_1(d)$ is the value of parameter $\alpha$ such that $W^{tt}$- $W^{st} = 0$. From Lemmas 1 and 3 the following emerges:

$$W^{tt} - W^{st} = \frac{(A-c)^2 F_1(\alpha, d)}{2\left(33 + 16d - 4d^2 + 15\alpha\right)^2 H^2}, \tag{A1}$$

where $F_1(\alpha, d) = 512d^9\left(121 - 176\alpha + 48\alpha^2\right) + 4d^8\left(-201069 + 625888\alpha - 307280\alpha^2 + 1408\alpha^3\right) - 16d^7\left(-212959 + 1133488\alpha - 688016\alpha^2 + 39552\alpha^3\right) - 4d^6\left(-152802 - 7071670\alpha + 9341079\alpha^2 - 3485704\alpha^3 + 26624\alpha^4\right) + 8d^5\left(-3308010 + 9352812\alpha + 6246727\alpha^2 - 7612304\alpha^3 + 475776\alpha^4\right) + d^4\left(-14667135 - 98888572\alpha + 53833506\alpha^2 + 38149684\alpha^3 - 37756164\alpha^4 + 240480\alpha^5\right) - 8d^3\left(-4419385 + 1329160\alpha + 26631890\alpha^2 + 2325408\alpha^3 - 7967482\alpha^4 + 733680\alpha^5\right) - 8d\left(-1303310 + 17749257\alpha - 16561464\alpha^2 - 32282082\alpha^3 + 2798589\alpha^4 + 7400430\alpha^5 + 788400\alpha^6\right) + 2d^2\left(18472926 + 50253303\alpha + 55802692\alpha^2 - 44011480\alpha^3 - 29803470\alpha^4 + 7642620\alpha^5 + 799200\alpha^6\right) - 3\left(-301900 + 34892702\alpha + 39477798\alpha^2 - 20560500\alpha^3 - 39409941\alpha^4 - 5672820\alpha^5 + 5301900\alpha^6 + 1260000\alpha^7\right)$

Given that the denominator of Equation (A1) is always positive, $\alpha_1(d)$ is the value of parameter $\alpha$ such that $F_1(\alpha, d) = 0$. It can be seen that if $d = 0$ then $F_1(\alpha, d) = 0$ for $\alpha = 0.0085$, and if $d = 1$ then $F_1(\alpha, d) = 0$ for $\alpha = 0.3020$. Moreover, $\alpha_1(d)$ is strictly increasing in $d$ (this is proved below). It

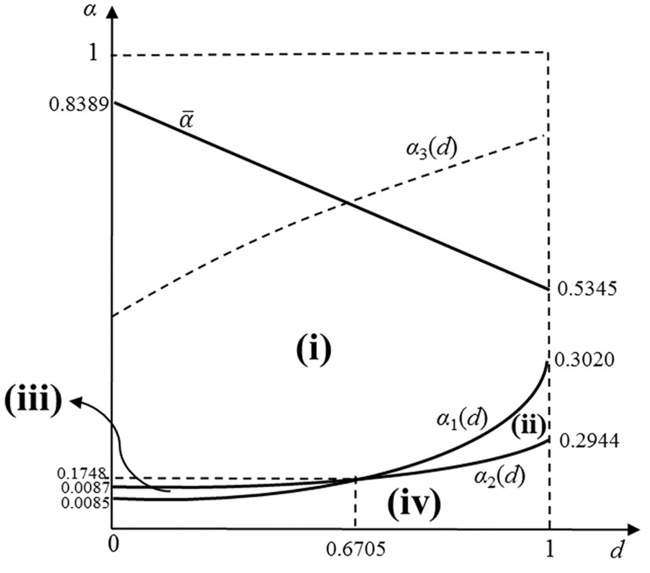


FIGURE A1 Illustration of lemma 3

can be seen that the expression $F_1(\alpha, d) = 0$ is below the line that passes through the points ($d = 0$, $\alpha = 0.0085$) and ($d = 1$, $\alpha = 0.3020$). The equation of that line is:

$$\alpha = 0.2934\,(0.0292 + d)\,. \tag{A2}$$

Moreover, for $d = 1/2$, the value of $\alpha$ obtained from Equation (A2) is greater than the value of $\alpha$ such that $F_1(\alpha, d) = 0$. This means that, in Figure A2, $F_1(\alpha, d) = 0$ is below the line given by expression (A2) for $0 < d < 1$. This in turn means that the values of parameters $\alpha$ and $d$ such that $F_1(\alpha, d) = 0$ must satisfy $\alpha \leq 0.2934\ (0.0292 + d) \leq 0.3020$.

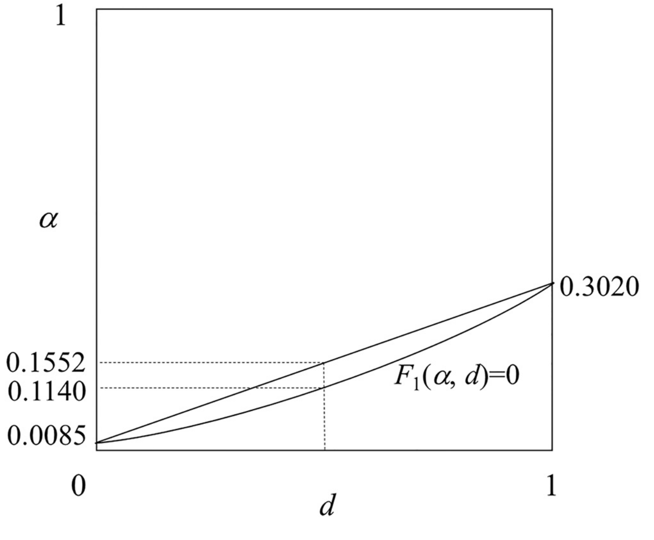


FIGURE A2 Plot of $F_1(\alpha, d) = 0$.

By differentiating $F_1(\alpha, d) = 0$ the following is obtained:

$$\frac{d\alpha}{dd} = -\frac{\frac{\partial F_1(\alpha,d)}{\partial d}}{\frac{\partial F_1(\alpha,d)}{\partial \alpha}} = -\frac{F_{1d}}{F_{1\alpha}}. \quad \text{(A3)}$$

We set out to prove that Equation (A3) is positive since $F_{1d} > 0$ and $F_{1\alpha} < 0$, so $\alpha_1(d)$ is strictly increasing in $d$. It can be seen that:

$$\begin{aligned} F_{1d} = &\left(2 + 12d + 11d^2\right)\left(1303310 + 1416603d - 2409668d^2 - 666876d^3\right.\\ &\left.+ 714380d^4 - 160056d^5 + 12672d^6\right)\\ &- \left(35498514 - 50253303d + 7974960d^2 + 98888572d^3\right.\\ &\left.- 93528120d^4 - 42430020d^5 + 31737664d^6 - 5007104d^7 + 202752d^8\right)\alpha\\ &+ 2\left(16561464 + 27901346d - 79895670d^2 + 26916753d^3 + 31233635d^4\right.\\ &\left.- 28023237d^5 + 9632224d^6 - 1229120d^7 + 27648d^8\right)\alpha^2\\ &+ 4\left(16141041 - 11002870d - 3488112d^2\right.\\ &\left.+ 9537421d^3 - 19030760d^4 + 5228556d^5 - 276864d^6 + 2816d^7\right)\alpha^3\\ &- 6\left(932863 + 4967245d - 7967482d^2\right.\\ &\left.+ 6292694d^3 - 792960d^4 + 26624d^5\right)\alpha^4\\ &+ 180\left(-82227 + 42459d - 24456d^2 + 1336d^3\right)\alpha^5\\ &+ 21600\,(-73 + 37d)\alpha^6. \end{aligned}$$

The above expression can be rewritten as $F_{1d} = \left(\left(\frac{8}{10} + 11d^2\right) + (1 + 12d) + \left(\frac{2}{10}\right)\right) A_{1d}\alpha^0 - B_{1d}\alpha^1 + C_{1d}\alpha^2 + D_{1d}\alpha^3 - E_{1d}\alpha^4 + F_{1d}\alpha^5 + G_{1d}\alpha^6$. Given that $\alpha \leq 0.2934\ (0.0292 + d) \leq 0.3020$ (see Figure A2), we obtain that: $\left(\frac{8}{10} + 11d^2\right) A_{1d}\alpha^0 - B_{1d}\alpha^1 + C_{1d}\alpha^2 > 0, (1 + 12d)A_{1d}\alpha^0 + D_{1d}\alpha^3 - E_{1d}\alpha^4 > 0$, and $\left(\frac{2}{10}\right) A_{1d}\alpha^0 + F_{1d}\alpha^5 + G_{1d}\alpha^6 > 0$, so $F_{1d} > 0$.

It can be seen that:

$$\begin{aligned} F_{1\alpha} = &\ 2(4096d^9(-11 + 6\alpha) + 64d^8\left(19559 - 19205\alpha + 132\alpha^2\right)\\ &- 128d^7\left(70843 - 86002\alpha + 7416\alpha^2\right) - 4d^6\\ &\left(-3535835 + 9341079\alpha - 5228556\alpha^2 + 53248\alpha^3\right)\\ &+ 8d^5\left(4676406 + 6246727\alpha - 11418456\alpha^2 + 951552\alpha^3\right) + d^4\\ &\left(-49444286 + 53833506\alpha + 57224526\alpha^2 - 75512328\alpha^3 + 601200\alpha^4\right)\\ &- 16d^3\left(332290 + 13315945\alpha + 1744056\alpha^2 - 7967482\alpha^3 + 917100\alpha^4\right)\\ &- 12d\left(5916419 - 11040976\alpha - 32282082\alpha^2 + 3731452\alpha^3 + 12334050\alpha^4\right.\\ &\left.+ 1576800\alpha^5\right) + d^2\left(50253303 + 111605384\alpha - 132034440\alpha^2\right.\\ &\left.- 119213880\alpha^3 + 38213100\alpha^4 + 4795200\alpha^5\right)\\ &- 3\left(17446351 + 39477798\alpha - 30840750\alpha^2 - 78819882\alpha^3\right.\\ &\left.- 14182050\alpha^4 + 15905700\alpha^5 + 4410000\alpha^6\right)). \end{aligned}$$

The above expression can be rewritten as $F_{1\alpha} = A_{1\alpha}d^9 + B_{1\alpha}d^8 - C_{1\alpha}d^7 - D_{1\alpha}d^6 + E_{1\alpha}d^5 + F_{1\alpha}d^4 - G_{1\alpha}d^3 + H_{1\alpha}d^2 - I_{1\alpha}d^1 - J_{1\alpha}d^0$. Since $\alpha \leq 0.2934(0.0292 - d) < 0.3020$, it emerges that: $A_{1\alpha}d^9 + B_{1\alpha}d^8 - C_{1\alpha}d^7 < 0, - D_{1\alpha}d^6 + F_{1\alpha}d^4 < 0$, $E_{1\alpha}d^5 - G_{1\alpha}d^3 - I_{1\alpha}d^1 < 0$ and $H_{1\alpha}d^2 - J_{1\alpha}d^0 < 0$, which means that $F_{1\alpha} < 0$. Finally, as $F_{1d} > 0$ and $F_{1\alpha} < 0$ from Equation (A3), it is obtained that $\alpha_1(d)$ is strictly increasing in $d$.

Assume that $\alpha_2(d)$ is the value of parameter $\alpha$ such that $W^{ts} - W^{ss} = 0$. From Lemmas 2 and 3 we can obtain that:

$$W^{ts} - W^{ss} = \frac{(A-c)^2 F_2(\alpha, d)}{2(53 + 32d - 20\alpha)^2 H^2}, \tag{A4}$$

where $F_2(\alpha, d) = -2364120 + 271628774\alpha - 114028069\alpha^2 - 404300820\alpha^3 + 257288028\alpha^4 + 17106560\alpha^5 - 38875200\alpha^6 + 6720000\alpha^7 + 262144d^8 \alpha(-11 + 8\alpha) + 512d^7\left(-11979 + 69096\alpha - 41136\alpha^2 + 1792\alpha^3\right) - 4d^6\left(-3734181 + 16420632\alpha - 10552528\alpha^2 + 3369728\alpha^3 + 16384\alpha^4\right) - 8d^5\left(-8700219 + 26647304\alpha - 12672976\alpha^2 + 352640\alpha^3 + 262144\alpha^4\right) + 2d^4 \left(3948021 + 73706126\alpha - 98582666\alpha^2 + 83929472\alpha^3 + 346848\alpha^4 - 1647360\alpha^5\right) + 16d^3\left(-7378173 + 7293321\alpha + 9282573\alpha^2 - 2246368\alpha^3 - 3319024\alpha^4 + 3148160\alpha^5\right) - 4d^2\left(25824150 + 4377405\alpha - 54648567\alpha^2 + 84045146\alpha^3 - 569360\alpha^4 - 7371360\alpha^5 + 710400\alpha^6\right) + 8d\left(-3474504 + 57174250\alpha - 71276525\alpha^2 - 7915478\alpha^3 + 1494576\alpha^4 - 1254880\alpha^5 + 1785600\alpha^6\right)$.

Given that the denominator of Equation (A4) is always positive, $\alpha_2(d)$ is the value of parameter $\alpha$ such that $F_2(\alpha, d) = 0$. It can be seen that if $d = 0$ then $F_2(\alpha, d) = 0$ for $\alpha = 0.0087$, and if $d = 1$ then $F_2(\alpha, d) = 0$ for $\alpha = 0.2944$. Moreover, $\alpha_2(d)$ is strictly increasing in $d$. The proof is similar to that shown for $\alpha_1(d)$, so it is omitted (though is available on request).

Finally, as both $\alpha_1(d)$ and $\alpha_2(d)$ increase strictly with $d$, $\alpha_1(d = 0) = 0.0085 < \alpha_2(d = 0) = 0.0087$ and $\alpha_1(d = 1) = 0.3020 > \alpha_2(d = 1) = 0.2944$, it is obtained that $\alpha_1(d)$ and $\alpha_2(d)$ cross only once, for $d = d^*$. Thus, $\alpha_2(d) > \alpha_1(d)$ if $d < d^*$, $\alpha_2(d) < \alpha_1(d)$ if $d > d^*$, and $\alpha_2(d) = \alpha_1(d)$ if $d = d^*$. By running simulations it can be obtained that $d^* = 0.6705$ and $\alpha_2(d^*) = \alpha_1(d^*) = 0.1748$.

**Proposition 1** *Table A1 shows the comparison of the components of social welfare and the equilibriums obtained in the game for the different intervals of parameter $\alpha$ when $d = 0$.*

**TABLE A1** Equilibriums obtained in proposition 1

| $\alpha$ | Comparison of the components of social welfare ($d = 0$) | Equilibriums |
|---|---|---|
| $\bar{\alpha} > \alpha > 0.1686$ | $CS^{tt} > CS^{st}, ED^{tt} > ED^{st}, PS^{tt} + T^{tt} > PS^{st}$,<br>$CS^{ts} > CS^{ss}, ED^{ts} > ED^{ss}, PS^{ts} + T^{ts} > PS^{ss}$. | $(t, t)$ |
| $0.1686 > \alpha > 0.1610$ | $CS^{tt} > CS^{st}, ED^{tt} > ED^{st}, PS^{tt} + T^{tt} > PS^{st}$,<br>$CS^{ts} > CS^{ss}, ED^{ts} < ED^{ss}, PS^{ts} + T^{ts} > PS^{ss}$. | $(t, t)$ |
| $0.1610 > \alpha > 0.0296$ | $CS^{tt} > CS^{st}, ED^{tt} < ED^{st}, PS^{tt} + T^{tt} > PS^{st}$,<br>$CS^{ts} > CS^{ss}, ED^{ts} < ED^{ss}, PS^{ts} + T^{ts} > PS^{ss}$. | $(t, t)$ |
| $0.0296 > \alpha > 0.0295$ | $CS^{tt} > CS^{st}, ED^{tt} < ED^{st}, PS^{tt} + T^{tt} < PS^{st}$,<br>$CS^{ts} > CS^{ss}, ED^{ts} < ED^{ss}, PS^{ts} + T^{ts} > PS^{ss}$. | $(t, t)$ |
| $0.0295 > \alpha > 0.0087$ | $CS^{tt} > CS^{st}, ED^{tt} < ED^{st}, PS^{tt} + T^{tt} < PS^{st}$,<br>$CS^{ts} > CS^{ss}, ED^{ts} < ED^{ss}, PS^{ts} + T^{ts} < PS^{ss}$. | $(t, t)$ |
| $0.0087 > \alpha > 0.0085$ | $CS^{tt} > CS^{st}, ED^{tt} < ED^{st}, PS^{tt} + T^{tt} < PS^{st}$,<br>$CS^{ts} > CS^{ss}, ED^{ts} < ED^{ss}, PS^{ts} + T^{ts} < PS^{ss}$. | $(t, t), (s, s)$ |
| $0.0085 > \alpha \geq 0$ | $CS^{tt} > CS^{st}, ED^{tt} < ED^{st}, PS^{tt} + T^{tt} < PS^{st}$,<br>$CS^{ts} > CS^{ss}, ED^{ts} < ED^{ss}, PS^{ts} + T^{ts} < PS^{ss}$. | $(s, s)$ |

**Proposition 2** *Table A2 shows the comparison of the components of social welfare and the equilibriums obtained in the game for the different intervals of parameter $\alpha$ when $d = 1$.*

**TABLE A2** Equilibriums obtained in proposition 2

| $\alpha$ | Comparison of the components of social welfare ($d = 1$) | Equilibriums |
|---|---|---|
| $\bar{\alpha} > \alpha > 0.3020$ | $CS^{tt} > CS^{st}, ED^{tt} > ED^{st}, PS^{tt} + T^{tt} > PS^{st}$,<br>$CS^{ts} < CS^{ss}, ED^{ts} > ED^{ss}, PS^{ts} + T^{ts} > PS^{ss}$. | $(t, t)$ |
| $0.3020 > \alpha > 0.2944$ | $CS^{tt} > CS^{st}, ED^{tt} > ED^{st}, PS^{tt} + T^{tt} > PS^{st}$,<br>$CS^{ts} < CS^{ss}, ED^{ts} > ED^{ss}, PS^{ts} + T^{ts} > PS^{ss}$. | $(t,s), (s,t)$ |
| $0.2944 > \alpha > 0.2408$ | $CS^{tt} > CS^{st}, ED^{tt} > ED^{st}, PS^{tt} + T^{tt} > PS^{st}$,<br>$CS^{ts} < CS^{ss}, ED^{ts} > ED^{ss}, PS^{ts} + T^{ts} > PS^{ss}$. | $(s, s)$ |
| $0.2408 > \alpha > 0.2383$ | $CS^{tt} > CS^{st}, ED^{tt} > ED^{st}, PS^{tt} + T^{tt} < PS^{st}$,<br>$CS^{ts} < CS^{ss}, ED^{ts} > ED^{ss}, PS^{ts} + T^{ts} > PS^{ss}$. | $(s, s)$ |
| $0.2383 > \alpha \geq 0$ | $CS^{tt} > CS^{st}, ED^{tt} > ED^{st}, PS^{tt} + T^{tt} < PS^{st}$,<br>$CS^{ts} < CS^{ss}, ED^{ts} > ED^{ss}, PS^{ts} + T^{ts} < PS^{ss}$. | $(s, s)$ |