Research Joint Ventures and Optimal Emissions Taxation*

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Abstract

This paper performs a comparison of two well known approaches for modelling R&D spillovers associated with investment in E-R&D, namely dAspremont-Jacquemin and Kamien-Muller-Zang. We show that there is little qualitative difference between the models in terms of total surplus delivered when selecting the optimal tax regime when there is pre-commitment under cooperative regimes in which firms coordinate expenditures to maximize joint profits. However, under non-cooperative regimes there is marked difference, with the model of Kamien-Muller-Zang leading to higher taxation rates when firms share information. Furthermore, we argue that the Kamien-Muller-Zang model is of questionable validity when modelling R&D on emissions reducing technology due to counter intuitive results showing a positive relationhip between R&D spillovers and emissions taxes.

Key Words: Research Joint Ventures, R&D Spillovers, Optimal Emissions Taxation, Precommitment

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1 Introduction

When an environmental economic policy, such as an emissions tax, is imposed on a market, each firm operating in this market has two options, either to reduce its output or to increase abatement activities by investing in activities such as R&D of emissions reducing technology (Baumol and Oates (1998)). The current thinking on the issue is that policies targeting research and development and the adoption and diffusion of emissions reducing technology offer a greater scope for achieving the objective of prolonged and sustained reduction in emissions (e.g., Jaffe et al. (2003), Jung et al. (1996), Kneese and Schultze (1975) and OECD (2010)). However, without the presence of some form of environmental economic policy to internalize the cost of pollution, the incentives are not sufficient to promote R&D in emission reducing technology. Furthermore, as first noted by Arrow (1962), any type R&D will generate social benefits that do not always accrue to the investing firm. As noted in Griliches (1984, 1992) and Jaffe (1986, 1998), many of the benefits of R&D accrue to competing firms, downstream firms who purchase the innovating firm's product and consumers.

This will be doubly so with emissions reducing technologies, because they provide two types of spillover effects. The first is an indirect spillover associated with the public good aspect associated with the knowledge generated from research, as discussed extensively in the literature on R&D, while the second effect emerges as a direct consequence of implementing an emissions reducing technology targeted at rectifying a public bad. Both of these spillover effects provide an incentive for other firms to free-ride and therefore under invest in either abatement technology or abatement effort. Hence, this can inhibit the amount of firm level spending on R&D. However, these two spillover effect can also be positive when firms are allowed to coordinate through the use of horizontal agreements, in this way the externalities associated with R&D and abatement activity can be internalized. Our paper examines this interplay between process-focused environmental R&D (henceforth, E-R&D), abatement effort and environmental economic policy, specifically emissions taxes focused on firm production.

We will provide a comparison of two approaches to modelling spillovers associated with investment in E-R&D. The first approach that has been used is based on the the seminal paper of d'Aspremont and Jacquemin (1988, 1990) (henceforth, AJ), in this approach spillovers occur in abatement effort and firms are able to free-ride from the abatement efforts of other firms. This approach has been used to model E-R&D in the papers by Scott (1996), Chiou and Hu (2001), Petrakis and Poyago-Theotoky (2002), Poyago-Theotoky (2003) and Poyago-Theotoky (2007a, 2010) and Poyago-Theotoky (2007b). The second approach is based on Kamien et al. (1992) (henceforth, KMZ), in this approach spillovers occur as a consequence of firms free riding off other firms R&D efforts and occur as a consequence of firms applying technology developed by other firms. Amir (2000) has shown for cost reducing process R&D that the two models in general are not equivalent and will only be equivalent if cost and informational associated spillovers in the two models are negligible. When spillovers do exist, the AJ model exaggerates the impact of cost reducing R&D, with the KMZ model viewed as being the better model.

In our paper, we provide a comparison of these two approaches in the context of the E-R&D model of Chiou and Hu (2001). The model presented in their paper assumes that the marginal damages associated with pollution are constant for each firm. We show that for this model, the KMZ model is not rich enough to convey the impact of free riding on emissions reduction, largely because this type of free riding cannot be incorporated into a model based on KMZ-style informational spillovers. As such the model is too conservative in predicting interplay between environmental and innovation spillovers. Hence, the AJ-style R&D spillover model could be argued as being more appropriate for modelling E-R&D. We reach this conclusion after performing a comparison between the AJ and KMZ formulations applied to the four cases explored in KMZ: non-cooperative (N), non-cooperative RJV (NJ), cooperative RJV (CJ) and the research cartel (C). We also correct an error in Chiou and Hu (2001), where AJ-style R&D spillovers are incorrectly accounted for.

In Chiou and Hu (2001), where the author's inadvertently set the spillover parameter to 0, they claim that this is case N, where there is no cooperation on research, with the RJV occuring when the spillover parameter is greater than 0. However, this is not the case.

When the R&D spillover parameter is set to 0, there are no information externalities generated from R&D. Under the R&D spillover model formulated in AJ and KMZ, the spillover parameter is always greater than 0, with the RJV occuring when firms share information completely so that the spillover parameter is set to 1. We then investigate the role that an optimal tax policy plays in this model, something that was not considered in Chiou and Hu (2001). In their paper, the environmental tax is exogenously defined; in fact, it can be shown that the tax regime selected in Chiou and Hu (2001) is not optimal for the parameters selected in that paper. However, it is important to consider what the correct tax regime is as can be understood from the current on going debate on carbon prices in Australia.

We therefore investigate what is the optimal second best emissions tax for the Chiou and Hu model. We do this for when the government makes an a priori commitment to a specific tax regime, before firms select E-R&D effort. This is consistent with the ordering of strategic interaction as presented in Chiou and Hu (2001). We then provide a comparison between the AJ and KMZ models of the non-cooperative and cooperative E-R&D models. We show that there is little qualitative difference between the AJ and KMZ models in terms of total surplus delivered when selecting the optimal tax regime. This is surprising when one considers the results presented in Amir (2000), which indicates that there are tangible differences between the KMZ and AJ models for cost reducing process R&D. Our results therefore indicate that for the case of tax pre-commitment the AJ model is the appropriate model to use when modelling E-R&D.

This paper is set out as follows: Section two sets out the model, explaining the differences between the AJ and KMZ style R&D spillovers in the Chiou and Hu model. Section three provides the comparison of the four R&D cases as laid out in KMZ for the AJ model of E-R&D as it was formulated in Chiou and Hu (2001). Section four then repeats this analysis for the KMZ model of E-R&D, providing a comparison of the each of the four R&D cases. Section five presents a welfare theoretic comparison of the optimal uniform second best emissions tax policy for this model for the case where the government pre-commits to the tax regime. Section six concludes.

2 The Model

We will begin by formulating a generalization of the model set down in Chiou and Hu (2001). As in Chiou and Hu (2001), we will consider the model of a Cournot duopoly producing a homogenous good. The inverse demand function for the market is given by

$$P(q_1, q_2) := a - Q, \quad Q = q_1 + q_2,$$

where a is the demand intercept and Q is the aggregate amount supplied by both firms. As is standard practice in the R&D spillovers literature, there are no fixed costs of production and the marginal cost of production is normalized to 0 without loss of generality. When each firm produces q_i, they also emit pollution at the rate of $\bar{e}$ per unit of production. The cost of pollution is imposed on the firm by a linear emissions tax t.

However, the profit function for firm i is given by

$$\pi_i = \left(P(q_i, q_{-i}) - t\left(\bar{e} - s\left(r_i, r_{-i}; \beta\right)\right)\right) q_i - c(r_i), \quad i = 1, 2 \tag{1}$$

where $s\left(r_i, r_{-i}; \beta\right)$ are spillovers expressed as a function of firms' abatement technology level and $c(r_i)$ denotes R&D costs associated with applying the abatement technology. The parameter β in the spillover function denotes the degree with which each firm can benefit from their rival's research. We use a general R&D spillover function to capture the possibility of either AJ or KMZ style R&D spillovers.

For both the AJ and KMZ R&D spillover models, we explore the following four scenarios as set down in KMZ. Note that because, in the final stage of the game, Cournot competition always prevail, we will use the behavior of firms in the research stage game to describe each of these scenarios:

1. **Case N:** Firms behave noncooperatively in choosing R&D levels, choosing neither to coordinate on R&D expenditure nor share information. The N stands for **noncooperative R&D**.

2. **Case C:** Firms firms choose to coordinate R&D expenditure levels, by choosing r_i to maximize the sum of their profits $\pi_1 + \pi_2$. The C stands for **cartelized (or collusive) R&D**.
3. **Case CJ:** Firms behave as in Case C, choosing r_i to maximize their joint profits. In addition, they also share information, so that the R&D spillover parameter β is set equal to 1. The CJ stands for **cartelized research joint venture**.
4. **Case NJ:** Firms behave as in Case N, choosing r_i separately. However, they share information, so that the R&D spillover parameter β is set equal to 1. The NJ stands for **non-cartelized research joint research**.

The other feature in this model, which is different from Chiou and Hu (2001), is the role that the government has in selecting the emissions tax. We consider the situation where there are two possible emissions tax policies that are open for the government. In the first policy option the government decides to pre-commit to an emissions tax regime. In this model, the sequence of decisions is as follows: (1) the government first decides on emissions taxes; (2) firms then decide on their R&D expenditure depending on the type of R&D organization that they have committed to; and (3) firms then choose their output inorder to compete in the product market, which in turn gives the level of emissions imposed on society.

Alternatively, the government does not precommit, but instead makes an interim decision regarding the level of emissions taxes after firms have made their E-R&D decisions. In this case the sequence of decisions will be made as follows: (1) in the first stage each firm will commit to a level of R&D investment, depending on the type of R&D organization that they have committed to; (2) in the second stage, the government decides on its tax policy; and (3) in the final stage, firms will then engage in Cournot competition. This paper will only examine the case where there is government pre-commitment to emissions taxes. We do this to be consistent with the structure of the model in Chiou and Hu (2001).

In that paper the decision structure was consistent with the ordering in the AJ model, so firms first choose their levle of cost reducing R&D expenditure and then decide on output in the product market. Altough taxes are included in Chiou and Hu (2001), they are not optimal (as can be seen from our results in section four of this paper), as they are modelled as an exogenous parameter. Under government precommitment to tax, the ordering of decisions in our R&D model is therefore identical to Chiou and Hu (2001), with the exception that in our model the government will not choose its taxes to optimize total welfare. The non-precommitment case, will not be examined in this paper; it has been examined elsewhere in Poyago-Theotoky (2007a, 2010), albeit for a slightly different emissions structure.

The decision structure of our model is therefore ordered into three stages:

1. **Stage 1:** The government decides on emissions taxes τ, choosing the taxes in order to maximize the welfare equation

$$W = CS + PS + T - D,$$

   where CS denotes consumer surplus, PS denotes producer surplus, T denotes aggregate revenues from emissions taxes and D denotes the social cost of environmental damages.

2. **Stage 2:** Given the proposed tax regime t of the government and the level of R&D spillover β, firms choose their E-R&D expenditure x_i based on whether they are behaving non-cooperatively or whether they are participating in a research cartel and coordinating their costs.

3. **Stage 3:** In the final stage firms then engage in Cournot competition in the product market, choosing their output q_i accordingly. The production decisions made in this market, in turn, determine the level of emissions imposed on society.

3 Cournot Market Stage Game

In this section we derive the equilibrium of the Cournot market stage game for both the AJ and KMZ models. The results for the AJ - equilibrium outputs, profits and comparative statics - align with the results presented in Chiou and Hu (2001), with the exception that there they assume that the R&D spillover term $\beta \in [0,1)$, where $\beta = 0$ corresponds to the competitive case and $0 < \beta < 1$ for RJVs. This is incorrect - the R&D spillover term $\beta \in (0,1]$, where $\beta = 1$ corresponds to the case where there is a RJV and there is complete disclosure of information between the two firms.

The case when $0 < \beta < 1$ corresponds to the non-competitive case, as can be seen from AJ and KMZ, respectively. This is because the spillover parameter β establishes the degree with which intellectual property rights are observed. When $\beta = 0$, intellectual property rights are at their strongest and any form of imitation or patent versioning is not tollerated under the law. When $0 < \beta < 1$, this corresponds to the case where firms are working non-cooperatively, but intellectual property rights are weaker and so patent versioning and imitation are tolerated. When $\beta = 1$ there is full disclosure of R&D, which corresponds to the case of a RJV where firms would share the rights to any patentable technology.

The reader should note that in the analysis that follows, we use $\tilde{\beta}$ and $\bar{\beta}$ to denote R&D spillovers in the AJ and KMZ models. We use this notation because, as we will show, the spillovers are not equivalent in the two models and act in different ways. Note that β is being used in this section to denote a generic R&D spillover parameter.

3.1 The Linear Quadratic Model (AJ)

In this model, spillovers are regarded as leakages in technological know-how and take place in final outcomes. Hence each firms final cost reduction is the sum of its autonomously acquired part and a fraction (equal to the spillover parameter β) of all other firms parts. If we consider the profit function as given by equation (1), the spillover function is defined by

$$s\left(r_i, r_j; \tilde{\beta}\right) = r_i + \tilde{\beta} r_j, \quad i, j = 1, 2. \tag{2}$$

Hence each firm can reduce the level of their marginal emission rate $\bar{e}$, and in turn its payments of emissions taxes, by applying a quantity r_i of emissions reducing abatement technology.

For the final stage of the game, the ith firm's equilibrium profit function can be derived from the Cournot stage game as follows:

$$\pi_i(r_i, r_j) = \frac{1}{9}\left(a - t\left(\bar{e} - r_i\left(2 - \tilde{\beta}\right) + r_j\left(1 - 2\tilde{\beta}\right)\right)\right)^2 - \frac{\gamma}{2}r_i^2, \quad i, j = 1, 2 \tag{3}$$

The cost of producing this technology is given by $c(r_i) = \gamma r_i^2/2$ inorder to model the effect that research costs are convex (i.e., to create greater emissions reduction, firms must invest in better and more costly scientists and equipment). The spillover parameter $\tilde{\beta}$ captures the degree with which it is possible for firm i to free ride off the technological investments of the other firm, thereby reducing their expenditure on E-R&D.

The following two propositions can now be derived. Proposition 1 shows, that firm i's pollution abatement R&D has two effects. Firstly, firm is pollution abatement R&D lowers its per output emission tax payment and thus increases its output. Secondly, firm is pollution abatement R&D spills over to the opponent, making the opponents emission tax payments decrease (increase) and thus the opponents output increase (decrease) depending on whether the spillover effect is less (greater) than 1/2.

Proposition 1 *For any emission tax t, if spillovers parameter $\tilde{\beta} > 1/2$, then firm j increasing its research will have a positive effect on firm i's output (and negative otherwise); and for firm i increasing its own research always leads to higher output for all $\tilde{\beta}$.*

Proof. The equilibrium output for each firm in the product market stage game may be derived as follows by solving the Cournot stage game:

$$q_i = \frac{1}{3}\left(a - t\left(\bar{e} - x_i\left(2 - \tilde{\beta}\right) + x_j\left(1 - 2\tilde{\beta}\right)\right)\right), \quad i, j = 1, 2$$

Taking the first partial derivatives of firm i's equilibrium output function q_i with respect to r_i and $r_j$gives:

$$\frac{\partial q_i}{\partial x_i} = \frac{t\left(2-\tilde{\beta}\right)}{3} > 0, \quad 0 \leq \tilde{\beta} < 1$$

$$\frac{\partial q_i}{\partial x_j} = -\frac{t\left(1-2\tilde{\beta}\right)}{3} \gtreqless 0, \quad \tilde{\beta} \lesseqgtr 1/2$$

■

The strategic effect shown in Proposition 1 is important: If $\beta < 1/2$, then the first effect dominates the second effect and firm i's pollution abatement R&D makes its opponents output decrease. If $\beta \geq 1/2$ the the opposite effect occurs so that firm is pollution abatement R&D makes its opponents output increase. Hence, as shown in Proposition 2, below, as the spillover effect increases, the marginal effect of the abatement level on q_i decreases. This is because as the spillover effect increases, the opponents tax payments will also decrease with firm is pollution abatement level.

Proposition 2 *For any emission tax t, an increase in* $\tilde{\beta}$ *will give a positive change in output for* $x_i \leq 2x_j$ *(otherwise output will fall).*

Proof. Taking the first partial derivative of q_i with respect to β, it can be seen that

$$\frac{\partial q_i}{\partial \beta} = -\frac{1}{3}t(x_i - 2x_j) > 0, \quad i, j = 1, 2$$

will be non-negative if $x_i \leq 2x_j$ and will be negative otherwise. ■

3.2 The KMZ Model

In this model, the firm can reduce their marginal rate of emissions $\bar{e}$, by investing the amount y_i in emissions reducing abatement technology. Hence, the cost of producing this technology for firm i is given by $c(y_i) = y_i$.The spillover function is given by

$$s\left(y_i, y_{-i}; \bar{\beta}\right) = \sqrt{2(y_i + \bar{\beta} y_j)/\gamma}. \tag{4}$$

There is also a positive spillover effect from applying this technology, which is given by $\bar{\beta} y_j$, $0 \leq \bar{\beta} \leq 1$. The purpose of this spillover parameter $\bar{\beta}$ is to capture the degree to which it is possible for firm i to free ride off the technological investments of other firms.

This is a different interpretation to that of the AJ model. Here, each firms final (or effective) R&D investment in emission reduction is the sum of its own (autonomous) expenditure and a fixed fraction (given by the spillover parameter) of the sum of other firms expenditures. Hence, all spillovers are purely technological. As first noted in Amir (2000), it is easy to see for both models that when $\tilde{\beta} = \bar{\beta} = 0$, the following monotone transformation holds

$$r_i = \sqrt{\frac{2}{\gamma} y_i} \iff y_i = \frac{\gamma}{2} r_i^2, \quad i = 1, 2,$$

allowing either payoff function to be recovered from the other. Hence, when $\beta = 0$ the AJ and KMZ models are equivalent. This explains the point made earlier regarding the notational distinction being made in this paper, between these two spillover parameters.

In the presence of spillovers, it can be seen by inspection that for the profit functions given in equations (eq:prof-AJ) and (eq:prof-KMZ) that the above transformation would not work, and no other transformation can be found. Hence, the two games are not generally equivalent. The equilibrium profit for firm i, once again can be derived by solving the Cournot stage game and is given as follows:

$$\pi_i = \frac{1}{9}\left(a - t\left(\bar{e} + \sqrt{\frac{2}{\gamma}\left(\bar{\beta} y_i + y_j\right)} - 2\sqrt{\frac{2}{\gamma}\left(y_i + \bar{\beta} y_j\right)}\right)\right)^2 - y_i, \quad i, j = 1, 2 \tag{5}$$

We now require similar propositions to Propostion 1 and 2 of the previous subsection, to show what happens to the output of firm i, if levels of E-R&D expenditure y_i and y_j change and if the spillover parameter β changes.

Proposition 3 *For any emission tax t:*

1. *If the spillover parameter*

$$\bar{\beta} < 1/2\sqrt{(y_i + \bar{\beta} y_j)/(y_j + \bar{\beta} y_i)},$$

   then firm j increasing its research will have a positive effect on firm i's output (and negative otherwise).

2. *For all levels of R&D spillover $\bar{\beta}$, increasing research expenditure always leads to higher output for firm i.*

Proof. The equilibrium output for firm i in the product market stage game is given by

$$q_i = \frac{1}{3}\left(a - t\left(\bar{e} - \sqrt{2}\sqrt{\frac{y_j + \bar{\beta} y_i}{\gamma}} + 2\sqrt{2}\sqrt{\frac{y_i + \bar{\beta} y_j}{\gamma}}\right)\right), \quad i, j = 1, 2$$

Taking the first partial derivatives of firm i's equilibrium output function q_i with respect to y_i and y_j gives:

$$\frac{\partial q_i}{\partial y_i} = \frac{t}{3\sqrt{2}\gamma}\left[\frac{2}{\sqrt{\frac{y_i + \bar{\beta} y_j}{\gamma}}} - \frac{\bar{\beta}}{\sqrt{\frac{y_j + \bar{\beta} y_i}{\gamma}}}\right] > 0, \quad 0 < \bar{\beta} \geq 1$$

and

$$\frac{\partial q_i}{\partial y_j} = \frac{t}{3\sqrt{2}\gamma}\left[-\frac{1}{\sqrt{\frac{y_j + \bar{\beta} y_i}{\gamma}}} + \frac{2\bar{\beta}}{\sqrt{\frac{y_i + \bar{\beta} y_j}{\gamma}}}\right] \gtreqless 0, \quad \bar{\beta} \lesseqgtr \frac{1}{2}\sqrt{\frac{y_i + \bar{\beta} y_j}{y_j + \bar{\beta} y_i}}$$

We note that the conclusions are identical to the AJ model, if expenditures are identical for each firm, so that $y_i = y_j$ for all firms i, j. ■

Proposition 3 indicates that for the KMZ model, the same relationship will hold as in AJ in that there are both direct and indirect effects on output depending on the size of the spillover parameter. The major difference being that this depends on the relative size of each firm's effective expenditure on E-R&D. This is made clear in the following proposition.

Proposition 4 *For any emission tax t, an increase in $\tilde{\beta}$ will give a positive change in output whenever*

$$\frac{y_i}{y_j} < \frac{1}{2}\sqrt{\frac{y_i + \bar{\beta} y_j}{y_j + \bar{\beta} y_i}}, \quad 0 < \beta \leq 1,$$

otherwise output will fall.

Proof. Taking the first partial derivative of q_i with respect to β, it can be seen that

$$\frac{\partial q_i}{\partial \bar{\beta}} = -\frac{t}{3\sqrt{2}\gamma}\left(-\frac{y_i}{\sqrt{\frac{y_j+\bar{\beta}y_i}{\gamma}}} + \frac{2y_j}{\sqrt{\frac{y_i+\bar{\beta}y_j}{\gamma}}}\right) > 0, \quad i, j = 1, 2$$

only if

$$\frac{y_i}{y_j} < \frac{1}{2}\sqrt{\frac{y_i + \bar{\beta} y_j}{y_j + \bar{\beta} y_i}}, \quad 0 < \beta \leq 1$$

and is negative otherwise. ■

One interesting consequence of Proposition 4, is that $\partial q_i / \partial \bar{\beta} > 0$ will hold if and only if $\partial q_i / \partial y_j > 0$. This is a stronger result than what is implied under the AJ model, it indicates that under the KMZ model the spillover from the other firm's investment in E-R&D is crucial in determining whether or not the firm will be able to expand production. It is therefore important to reemphasize that the differences between the AJ and KMZ formulations cannot be reconciled by the assumption of symmetric expenditures, as might be suggested by the similarities between Propositions 1 and 3.

4 E-R&D Stage Game

In this section, we derive the E-R&D effort/expediture for the firms under cases N, NJ, C and CJ as set down in KMZ. In addition we derive the optimal second best emissions tax regime for this market. We do this analytically for the AJ linear quadratic model and the KMZ model in Sections 2.1 and 2.2 respectively. We provide a comparison between these models. The purpose for doing this is to ask which of the two models is the most appropriate one when modelling E-R&D. The other natural question we wish to answer, when making this comparison, is whether or not it is possible to reconcile these two models. That is, are there some parameter values for which the AJ and KMZ models can be reconciled.

We note that Chiou and Hu (2001) also consider the four cases provided in KMZ for the AJ linear quadratic model. However, the non-cooperative model (N) and the research cartel (C) they consider assume the non-existence of spillovers (i.e. $\beta = 0$), while the non-cooperative RJV (NJ) and RJV cartel (CJ) have positive R&D spillovers that are less than 1. This is not correct, as the point of the R&D spillover models (AJ and KMZ) is that there are always spillovers from R&D (positive and negative), these give a firm the incentive to under invest in research. In the RJV, this coordination failure is corrected and the spillover parameter is set to 1. This signifies that under the RJV, participating firms are sharing information. As such, cases NJ and CJ in Chiou and Hu correspond to the N and C cases from AJ and KMZ. In actual fact, NJ and CJ occur when the spillover parameter is set equal to one. In this section, we set out the AJ model following exactly the formulation of each of the cases as provided in KMZ.

4.1 Linear-Quadratic Model (AJ)

Case N and NJ: We now find the subgame perfect equilibrium (SGPE) of the E-R&D stage game. The equilibrium abatement effort of both firms is given by

$$r_1^N = r_2^N = r^N = \frac{(2-\beta)(a-\bar{e}t)t}{9\gamma - 2(2-\beta)(1+\beta)t^2} \tag{6}$$

The equilibrium outputs are given as follows:

$$q_1^N = q_2^N = q^N = \frac{3\gamma\,(a-\bar{e}t)}{9\gamma - 2(2-\beta)(1+\beta)t^2} \tag{7}$$

These lead to the following total emissions

$$E^N = Q^N \left(1 - (1+\beta) r^N\right) = \frac{6\gamma(a - t\bar{e})[9\gamma\bar{e} - 2(2-\beta)(1+\beta)at]}{\left(9\gamma - 2(2-\beta)(1+\beta)t^2\right)^2} \tag{8}$$

The necessary second order condition for the SGPE is $9\gamma > 2(2-\beta)^2 t^2$. The stability condition on the Nash equilibrium is given

$$2(2-\beta)(2\beta - 1)t^2 < 9\gamma - 2(2-\beta)^2 t^2.$$

This is satisfied when $\gamma > 4/3$, which also satisfies the second order condition.

The following proposition shows that in the AJ model, costs of R&D will go down as the spillovers increase. This points to pivotal role that RJV have in the AJ model:

Proposition 5 *Given the same emission tax rate and provided that firms engage in Cournot output competition, increasing the spillover β has the effect of lowering R&D efforts, for* $0 \leq \beta < 1$.

Proof. Differentiating equation (eq: abatementN) and assuming that the second order conditions hold, then

$$\frac{-2t(a - t\bar{e})}{(9\gamma - 2(2-\beta)(1+\beta)t^2)^2}[9\gamma - 2(2-\beta)^2 t^2] < 0, \quad 0 \leq \beta < 1.$$

Hence, as β increases the costs of abatement becomes smaller. ■

Not surprisingly we find that when $\beta = 1$, which occurs when firms share research labs under a joint venture that equilibrium abatement expenditure of both firms is given by

$$r_1^{NJ} = r_2^{NJ} = r^{NJ} = \frac{t(a - t\bar{e})}{9\gamma - 4t^2} \tag{9}$$

The equilibrium outputs are given as follows:

$$q_1^{NJ} = q_2^{NJ} = q^{NJ} = \frac{3\gamma(a - t\bar{e})}{9\gamma - 4t^2} \tag{10}$$

These lead to the following total emissions

$$E^{NJ} = Q^{NJ}\left(\bar{e} - 2r^{NJ}\right) = \frac{6\gamma(a - t\bar{e})[9\gamma\bar{e} - 4at]}{9\gamma - 4t^2} \tag{11}$$

Cases C and CJ: Under the research cartel, both firms choose their abatement level x_i to maximize the joint profit function

$$V = \sum_{i=1}^{2} \pi_i \left(q_1(r_1, r_2), q_2(r_1, r_2), r_i; \beta\right)$$

Then depending or whether or not firms are participating in an RJV, β is either set to 1 (Case CJ) or is left to be a positive value less than 1 (Case C).

Solving this maximization problem, we obtain the optimal levels of abatement for the cartel

$$r_1^C = r_2^C = r^C = \frac{2t(1+\beta)(a - t\bar{e})}{9\gamma - 2(1+\beta)^2 t^2}, \tag{12}$$

The equilibrium output in the non-cooperative stage game is given by

$$q_1^C = q_2^C = q^C = \frac{3\gamma(a - t\bar{e})}{9\gamma - 2(1+\beta)^2 t^2}, \tag{13}$$

leading to the following total emissions under the research cartel:

$$E^C = Q^C\left(\bar{e} - (1+\beta)r^C\right) = \frac{6\gamma(a - t\bar{e})[9\gamma\bar{e} - 2t(1+\beta)(a + \beta t\bar{e})]}{9\gamma - 2(1+\beta)^2 t^2}, \tag{14}$$

The necessary second order condition for the existence of an equilibrium under a research cartelization is $9\gamma > 2(5 - \beta(8 - 5\beta))t^2$.

Proposition 6 *Given the same emission tax rate and provided that firms engage in Cournot output competition, increasing the spillover β has the effect of lowering R&D efforts, for $0 \leq \beta < 1$.*

Proof. Differentiating equation (eq:abatementC) with respect to β and assuming that the second order conditions hold, then

$$\frac{2t(a-\bar{e}t)(9\gamma+2(1+b)^2t^2)}{(9\gamma-2(1+b)^2t^2)^2} > 0, \quad 0 \leq \beta < 1.$$

This indicates that as β moves towards 1, abatement efforts will also increase. ■

When the RJV cartel is present, so that firms both coordinate abatement efforts and share information, we obtain the optimal levels of abatement for the cartel

$$r_1^{CJ} = r_2^{CJ} = r^{CJ} = \frac{4t(a-t\bar{e})}{9\gamma-8t^2},$$

The equilibrium output in the non-cooperative stage game is given by

$$q_1^{CJ} = q_2^{CJ} = q^{CJ} = \frac{3\gamma(a-t\bar{e})}{9\gamma-8t^2},$$

leading to the following total emissions under the research cartel:

$$E^{CJ} = Q^{CJ}\left(\bar{e}-(1+\beta)r^{CJ}\right) = \frac{6\gamma(a-t\bar{e})[9\gamma\bar{e}-4t(a+t\bar{e})]}{9\gamma-8t^2},$$

4.2 KMZ Model:

Cases N and NJ We now find the SGPE equilibrium; this is found by deriving the Nash equilibrium of the E-R&D stage game. Under the KMZ model, both firms choose their level of expenditure in E-R&D y_i to maximize their profit functions. The equilibrium E-R&D expenditure of both firms is given by

$$y_1^N = y_2^N = y^N = \frac{2t^2(a-t\bar{e})^2(2-\beta)^2\gamma}{(1+\beta)\left(9\gamma-2(2-\beta)t^2\right)^2} \tag{15}$$

The equilibrium outputs are given as follows:

$$q_1^N = q_2^N = q^N = \frac{(a-\bar{e}t)\left(9\gamma-4(2-\beta)t^2\right)}{3\left(9\gamma-2\left(2-\beta\right)t^2\right)} \tag{16}$$

These lead to the following total emissions

$$E^N = \frac{2\,(a-\bar{e}t)\,(9\gamma-4(2-\beta)t^2)\,(9\gamma\bar{e}+2t(2-\beta)(a-2\bar{e}t)}{3\,(9\gamma-2\,(2-\beta)\,t^2)} \tag{17}$$

The necessary second order condition is $9\gamma > (2-\beta)^2 t^2$.

The following proposition shows that in the KMZ model, costs of R&D will go down as the spillovers increase. This points to privotal role that RJV have in this model.

Proposition 7 *Given the same emission tax rate and provided that firms engage in Cournot output competition, increasing the spillover β has the effect of lowering R&D efforts, for $0 \leq \beta < 1$.*

Proof. Differentiating equation (eq: abatementN) and assuming that the second order conditions hold, then

$$\frac{-2t(a-t\bar{e})}{(9\gamma-2(2-\beta)(1+\beta)t^2)^2}[9\gamma-2(2-\beta)^2t^2] < 0, \quad 0 \leq \beta < 1.$$

Hence, as β increases the costs of abatement becomes smaller. ■

Not surprisingly, we find that when $\beta = 1$, which occurs when firms share research labs under a joint venture that equilibrium research expenditure of both firms is given by

$$y_1^{NJ} = y_2^{NJ} = y^{NJ} = \frac{2t^2(a-t\bar{e})^2\gamma}{2\,(9\gamma-2t^2)^2} \tag{18}$$

The equilibrium outputs are given as follows:

$$q_1^{NJ} = q_2^{NJ} = q^{NJ} = \frac{(a-\bar{e}t)\,(9\gamma-4t^2)}{3\,(9\gamma-2t^2)} \tag{19}$$

These lead to the following total emissions

$$E^{NJ} = Q^{NJ}\left(\bar{e}-2r^{NJ}\right) = \frac{2\,(a-\bar{e}t)\,(9\gamma-4t^2)\,(9\gamma\bar{e}+2t(a-2\bar{e}t))}{3\,(9\gamma-2t^2)} \tag{20}$$

Cases C and CJ: Under the research cartel, both firms choose their investmet expenditure y_i inorder to maximize their joint profit function, then depending or whether or not firms are participating in an RJV, β is either set to 1 (Case CJ) or is left to be a positive value less than 1 (Case C). Solving this maximization problem for Case C, we obtain the optimal levels of research expenditure for the cartel:

$$y_1^C = y_2^C = y^C = \frac{2t^2(1+\beta)(a-t\bar{e})^2\gamma}{(9\gamma - 2(1+\beta)t^2)^2}, \tag{21}$$

The equilibrium output in the non-cooperative stage game is given by

$$q_1^C = q_2^C = q^C = \frac{(a-t\bar{e})\,(9\gamma - 4(1+\beta)t^2)}{3\,(9\gamma - 2(1+\beta)t^2)}, \tag{22}$$

leading to the following total emissions under the research cartel:

$$E^C = \frac{2(a-\bar{e}t)(9\gamma - 4t^2(1+\beta))(9\bar{e}\gamma + 2t(a-2\bar{e}t)(1+\beta))}{3(9\gamma - 2t^2(1+\beta)} \tag{23}$$

The necessary second order condition for the existence of an equilibrium under a research cartelization is $9\gamma > 2(5-\beta(8-5\beta))t^2$.

The optimal levels of research expenditure for the RJV cartel (Case CJ) can now be obtained by setting $\beta = 1$ and are given as follows:

$$y_1^{CJ} = y_2^{CJ} = y^{CJ} = \frac{4t^2(a-t\bar{e})^2\gamma}{(9\gamma - 4t^2)^2}, \tag{24}$$

The equilibrium output is given by

$$q_1^{CJ} = q_2^{CJ} = q^{CJ} = \frac{(a-t\bar{e})\,(9\gamma - 8t^2)}{3\,(9\gamma - 4t^2)}, \tag{25}$$

leading to the following total emissions under the RJV cartel:

$$E^{CJ} = \frac{2(a-\bar{e}t)(9\gamma - 8t^2)(9\bar{e}\gamma + 4t(a-2\bar{e}t))}{3(9\gamma - 4t^2)} \tag{26}$$

5 Optimal Emissions Taxes with Precommittment

In this section we derive the optimal emission tax policy for this market. As stated earlier, we will assume that the government opts to make an ex ante commitment at the beginning of the E-R&D to a particular emissions tax regime. Hence, in our paper the government removes itself from being a strategic entity in determining the level of E-R&D, as would be the case if the govenment decided for emissions taxes that were time consistent (i.e. sub game perfect) and announced their tax policy in the second stage of the game (after firms chose their E-R&D levels).

This is the natural starting point for a comparison between the results appearing here in our paper and those in the paper by Chiou and Hu (2001), because the sequencing of decisions is the same. The only difference being that in Chiou and Hu the tax regime is not optimal - they choose to nominate a tax regime rather than derive it by solving a social welfare equation. Hence, R&D levels in their analysis are expressed as a function of t. While they do conduct some analysis of what happens when the taxation rate is changed, no results are given pertaining to the optimal level of emissions taxation.

In our paper, the government will select the optimal emissions tax regime by maximizing total welfare (SW) with respect to the emissions tax rate t; hence emissions taxation will be optimal in a second best sence, which is consistent with the welfare analysis of R&D in Suzumura (1992). The social welfare equation is given as follows:

$$SW(t;\beta,\gamma) = CS(t;\beta,\gamma) + PS(t;\beta,\gamma) + T(t;\beta,\gamma) - D(t;\beta,\gamma).$$

Here, consumer surplus $CS = \frac{1}{2}Q^2$, producer surplus $PS = \pi_1 + \pi_2$ and T is the aggregate emissions tax revenue. Environmental damages D are assumed to be a function of the total emission, $D(E)$, with $D(0) = 0, D' > 0, D'' > 0$ for $E > 0$. The quadratic function is used to model damages, i.e.

$$D(t;\beta,\gamma) = \frac{1}{2}E^2,$$

where $E = e_1 + e_2$ is the level of aggregate emission attributable to firms in this industry.

It will be assumed that $T = tE$, where $t \in [0,1]$ is the tax rate. A common tax rate is used because we will be focusing only on the symmetric equilibrium. The other aspect to note is that the welfare equation must be solved numerically.

We choose the following parameter values that are permitted within the second order conditions provided by both the AJ and KMZ models under all regimes: $A = 20$ and $\gamma = 8$. We do this because it allows us to compare not only the optimal tax rate, but also maximum level of social welfare that this generates. The other parameter of importance is $\bar{e}$, which must be less than or equal to 1 for both the AJ and KMZ models. The reason that this must be so, is that $\bar{e}$ is the parmater governing the marginal rate of emissions by each of the firms. When $\bar{e} > 1$, the optimal rate of taxation is always to set the emissions tax rate $t = 1$ and there is never any interaction or offset from the E-R&D spillover term. This occurs across non-cooperative and cooperative regimes for both the AJ and KMZ models. Hence, we avoid examining this case and instead focus on $\bar{e} \leq 1$, where the optimal tax rate $t < 1$ and interesting trade-offs occur between t and the respective spillover parameters used each model.

5.1 The Linear Quadratic Model (AJ)

Table 1 sets out the main components of the social welfare equation for the AJ model. We include only aggregate emissions E in this table as damages D and the emissions taxes T are functions of E and can be computed with little effort.

Cases	Consumer Surplus (CS)	Producer Surplus (PS)	Emissions (E)
N	$\frac{18\gamma^2(a-\bar{e}t)^2}{\left(9\gamma-2(2-\tilde{\beta})(1+\tilde{\beta})t^2\right)^2}$	$\frac{\gamma\left(a-\bar{e}t\right)^2\left(9\gamma-2(2-\tilde{\beta})^2t^2\right)}{\left(9\gamma-2(2-\tilde{\beta})(1+\tilde{\beta})t^2\right)^2}$	$\frac{6\gamma\left(9\gamma\bar{e}-2a(2-\tilde{\beta})(1+\tilde{\beta})t\right)(a-\bar{e}t)}{\left(9\gamma-2(2-\tilde{\beta})(1+\tilde{\beta})t^2\right)^2}$
NJ	$\frac{18\gamma^2(a-\bar{e}t)^2}{(9\gamma-4t^2)^2}$	$\frac{\gamma\left(a-\bar{e}t\right)^2\left(9\gamma-2t^2\right)}{(9\gamma-4t^2)^2}$	$\frac{6\gamma(9\gamma\bar{e}-4at)(a-\bar{e}t)}{(9\gamma-4t^2)^2}$
C	$\frac{18\gamma^2(a-t\bar{e})^2}{\left(9\gamma-2(1+\tilde{\beta})^2t^2\right)^4}$	$\frac{2\gamma(a-t\bar{e})^2}{9\gamma-2(1+\tilde{\beta})^2t^2}$	$\frac{18\gamma^2\left(9\gamma\bar{e}-2a(1+\tilde{\beta})^2t\right)^2(a-t\bar{e})^2}{\left(9\gamma-2(1+\tilde{\beta})^2t^2\right)^4}$
CJ	$\frac{18\gamma^2(a-t\bar{e})^2}{(9\gamma-8t^2)^4}$	$\frac{2\gamma(a-t\bar{e})^2}{9\gamma-8t^2}$	$\frac{18\gamma^2(9\gamma\bar{e}-8at)^2(a-t\bar{e})^2}{(9\gamma-8t^2)^4}$

Table 1: Components of the Social Welfare Equation for the AJ Model

For the non-cooperative regimes we find that when $\bar{e} \leq 1$ and $A = 20$ and $\gamma = 8$, that the optimal rate of taxation occurs in the ranges from 0.4 to 0.6. Figure 1 provides an example. The spillover effect in the AJ model has no impact on the level of taxation, with the same tax rate being optimal across the entire spillover range. Hence, sharing information has a neutral welfare effect in terms of increasing E-R&D and reducing emissions. By comparison, emissions taxes look to be an effective means of encouraging E-R&D and reducing emissions.

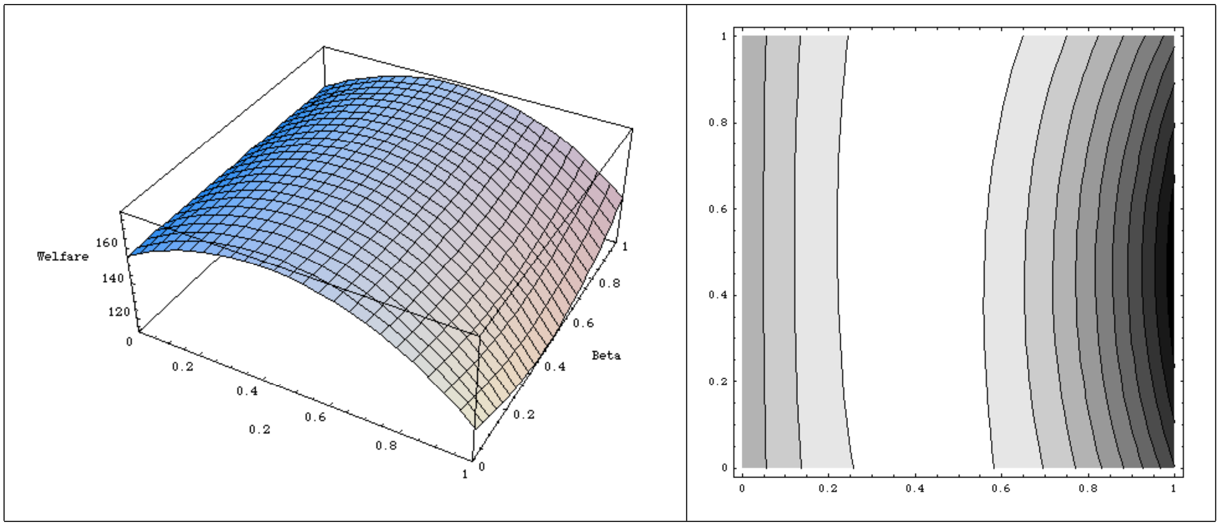

Figure 1: Impact of Taxes vs. Information Spillovers for Non Cooperative Regimes in the AJ Model ($A = 20, \gamma = 8$, $\bar{e} = 0.5$)

By comparison, for the cooperative regimes (where firms participate in a research cartel and choose R&D effort to maximize joint profits), we find that there is a trade-off between information spillovers and emissions taxes t. Figure 2 depicts one such relationship; the contour plot shows the spillover parameter $\tilde{\beta}$ when firms engage in the cartel. As a consequence, tax rates are at their lowest when $\tilde{\beta} = 1$ and firms are engaging in a RJV Cartel (i.e. when firms coordinate. In fact for parameter values $A = 20$, $\gamma = 8$ and $\bar{e} = 0.5$, when $\tilde{\beta} = 1$ the optimal tax rate $t = 0.2$, with the emissions tax rate $t \rightarrow 1$ when $\tilde{\beta} \rightarrow 0$.

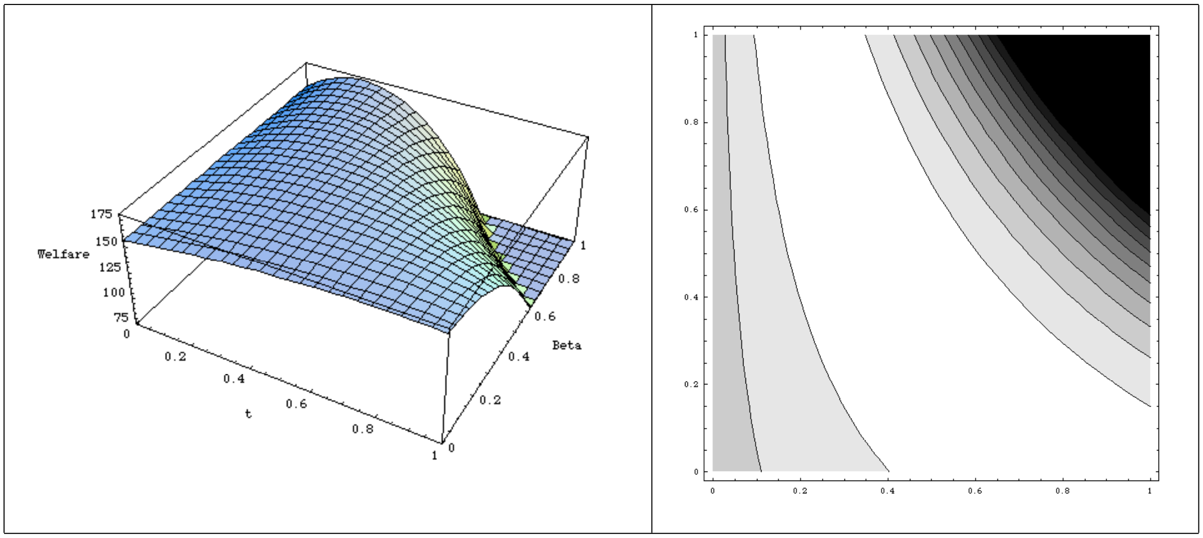

Figure 2: Impact of Taxes vs. Information Spillovers for Cooperative Regimes in the AJ Model ($A = 20, \gamma = 8, \bar{e} = 0.5$)

5.2 KMZ Model

Table 2 (located at the end of the paper) sets out the main components of the social welfare equation for the KMZ model. As for Table 1, we include only aggregate emissions E in this table as damages D and the emissions taxes T are functions of E and can be computed with little effort.

One interesting feature, which is true for both the non-cooperative and cooperative regimes, is that both the AJ and KMZ report similar levels of aggreagate social welfare. However, the relationship between the R&D spillover parameter and optimal emissions tax rate are different when comparing the two models across both regimes. This can be seen by comparing Figure 1 with Figure 3 and Figure 2 with Figure 4. The greatest difference is between the AJ and KMZ models under the non-cooperative regimes. The surface plot shown in Figure 3 indicates that relationship between emissions taxes and social welfare is similar to that shown in the AJ model.

However, the contour plot in Figure 3 shows that emissions taxes rate t and R&D spillovers $\bar{\beta}$ in the KMZ have a positive relationship. This is counter intuitive. However,

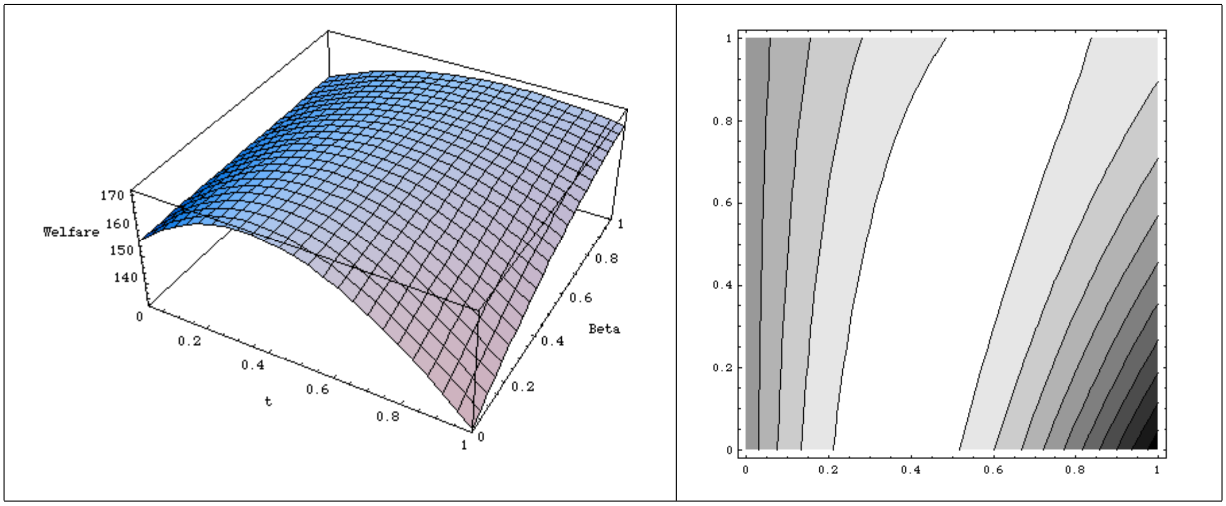

Figure 3: Impact of Taxes vs. Information Spillovers for Non Cooperative Regimes in the KMZ Model ($A = 20, \gamma = 8$, $\bar{e} = 0.5$)

as shown in Proposition 3 there exists both a positive and negative relationship between R&D spillovers and firm-level output in the KMZ model. A similar relationship exists in the AJ model, as shown in Proposition 1; the positive relationship between the spillover term and output may be a driver for the neutral effect in the AJ model. Similarly, if the positive effect were large enough in the KMZ model, then this would lead to an increase in output and therefore taxes would also be required to increase. This could give rise to the positive relationship between taxes and R&D spillovers shown in the contour plot of Figure 3.

For the cooperative regimes, Figure 4 shows a similar trade-off between $\bar{\beta}$ and t in the KMZ model as the one that was shown in Figure 3 between $\tilde{\beta}$ and t for the AJ model. Once again, optimal tax rates are lowest ($t = 0.5$) when the E-R&D spillover parameter $\bar{\beta} = 1$ and highest ($t = 1$) when $\bar{\beta} = 0$. Hence, for both models, Figures 2 and 4 illustrate that policy makers have a range of options open to them if collaborative research in the form of a research joint venture, where firms are able to share costs of R&D, is permitted. For both the AJ and KMZ models, the degree of the environmental tax burden can be reduced by increasing or decreasing degree with which collaborative firms can appropriate intellectual property rights from research where costs are shared.

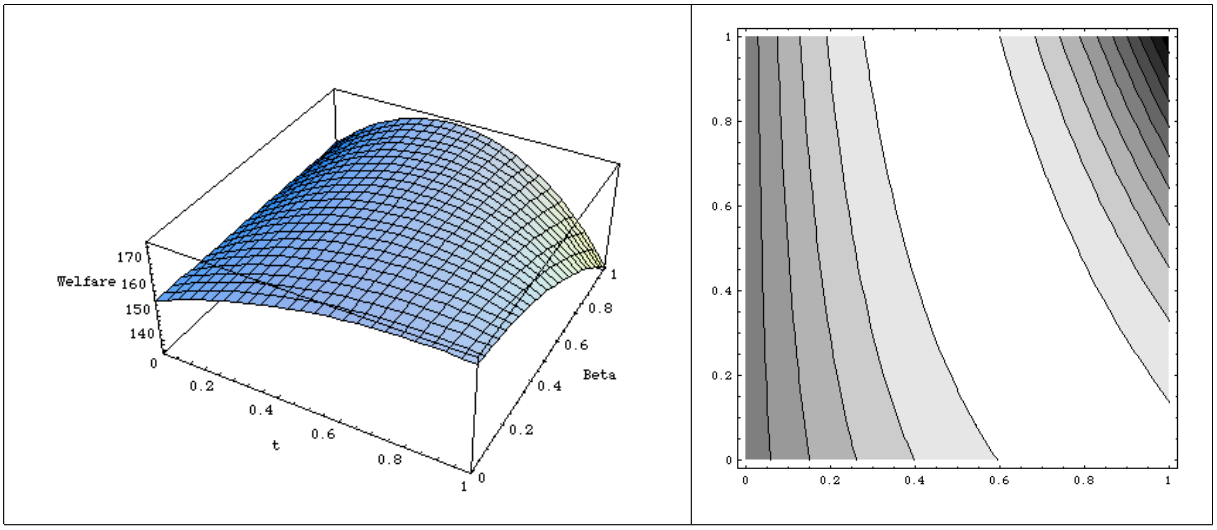

Figure 4: Impact of Taxes vs. Information Spillovers for Cooperative Regimes in the KMZ Model ($A = 20, \gamma = 8$, $\bar{e} = 0.5$)

The other point to note is that the scope of this trade-off between R&D spillovers and taxes is greatly reduced under the KMZ model. The reason being that under the KMZ model firms cannot free-ride off the emission efforts of other firms. This is not the case in the AJ model, where R&D effort is assoicated directly with emissions reduction. As such, firms in the AJ model can benefit not only from the R&D effort of other firms, but also by free-riding off the other firms' efforts to reduce emissions. This cannot occur in the KMZ models because R&D spillovers are embedded within a function and the effect of R&D on emissions is directly attributable to the firm that made the investment.

6 Conclusion

This paper performs a comparison of two approaches to modelling spillovers associated with investment in E-R&D. The major conclusions of this paper can be summarized as follows: We show that there is little qualitative difference between the models in terms of total surplus delivered, when selecting the optimal tax regime when there is pre-commitment under cooperative regimes in which firms coordinate expenditures to maximize joint profits. However, under non-cooperative regimes there is marked difference, with the model of Kamien et al. (1992) leading to higher taxation rates when firms share information.

This is surprising when one considers the results presented in Amir (2000) in the context of cost reducing process R&D, where models based on the approach of d'Aspremont and Jacquemin (1988) exaggerate the benefits associated with process R&D. We show the opposite result: that models based on Kamien et al. (1992) lead to over investment in E-R&D, higher output and higher taxes. Furthmore results under the non-cooperative regime for the KMZ model indicate that there is cause for concern regarding a counter intuitive relationship between R&D spillovers and emissions tax rates. For this reason the AJ model is seen to be better for modelling R&D on emission reducing technology.

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Regime	Consumer Surplus (CS)	Producer Surplus (PS)	Emissions (E)
N	$\frac{2(a-\bar{e}t)^2\big(9\gamma-4(2-\beta)t^2\big)^2}{9(9\gamma-2(2-\beta)t^2)^2}$	$\frac{2(a-\bar{e}t)^2\big((1+\beta)\big(9\gamma-4(2-\beta)t^2\big)+18\gamma(2-\beta)^2t^2\big)}{9(1+\beta)(9\gamma-2(2-\beta)t^2)}$	$\frac{2(a-\bar{e}t)(9\gamma-4t^2(2-\beta))(9\gamma\bar{e}-2t(2-\beta)(a-\bar{e}t))}{243\gamma^2+12(2-\beta)^2t^4}$
NJ	$\frac{2(a-\bar{e}t)^2\big(9\gamma-4t^2\big)^2}{9(9\gamma-2t^2)^2}$	$\frac{2(a-\bar{e}t)^2\big(\big(2(9\gamma-4t^2\big)+18\gamma t^2\big)}{18(9\gamma-2t^2)}$	$\frac{2(a-\bar{e}t)(9\gamma-4t^2)(9\gamma\bar{e}-2t(a-\bar{e}t))}{243\gamma^2+12t^4}$
C	$\frac{2(a-t\bar{e})^2(9\gamma-4(1+\beta)t^2)}{(9\gamma-2(1+\beta)t^2)^2}$	$\frac{2(a-\bar{e}t)^2(9\gamma-8t^2(1+\beta))}{9(9\gamma-2t^2(1+\beta)}$	$\frac{2(a-t\bar{e})^2(9\gamma-4(1+\beta)t^2)(9\gamma\bar{e}+2t(1+\beta)(a-2\bar{e}t))}{3(9\gamma-2(1+\beta)t^2)^2}$
CJ	$\frac{2(a-t\bar{e})^2(9\gamma-8t^2}{(9\gamma-4t^2)^2}$	$\frac{2(a-\bar{e}t)^2(9\gamma-16t^2)}{9(9\gamma-4t^2}$	$\frac{2(a-t\bar{e})^2(9\gamma-8t^2)(9\gamma\bar{e}+4t(a-2\bar{e}t))}{3(9\gamma-4t^2)^2}$

Table 2: Components of the Social Welfare Equation for the KMZ Model