Environmental Regulation and Technological Innovation with Spillovers

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Abstract

We present a two-period dynamic model of standard setting under asymmetric information to model the attempts by the Califormia Air Resources Board (CARB) in getting car manufacturers to comply with its phase-in of stringent emissions standards. After CARB chooses an initial emissions standard that firms are required to comply with, automakers respond by choosing R&D investment and production levels which provide CARB an imperfect signal whether they are more or less capable of complying with the standard. CARB resets the environmental standard and the firms once again choose research and production levels. Firms are Cournot duopolists in the product market and can choose to do research noncooperatively or cooperatively in the presence of spillovers. We show that firms will behave strategically and underinvest in research both under competitive and cooperative R&D, though the level of underinvestment — the ratchet effect — is greater under cooperative R&D when spillovers are large. We uncover a fundamental conflict between the incentives of firms to do cooperative research and social welfare: that firms will want to engage in cooperative (resp. noncooperative) R&D only when spillovers are low (resp. high) while social welfare is greater under noncooperative (resp. cooperative) research.

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1 Introduction

Technology-forcing regulation is intended to correct market failures involving externalities by forcing firms to innovate, the underlying belief being that socially beneficial technologies might remain undeveloped or under-developed in a free market environment, especially if anticipated development costs exceed the private benefits of the developer at the margin. In the specific context of automobile emissions control in the U.S. which is our focus, the California Air Resources Board (CARB) in 1990 passed a stringent set of emissions standards which now cover over 40% of the US automobile market. But even though the California plan required auto manufacturers to produce and sell an increasing percentage of zero-emissions vehicles (ZEVs or electric cars),[1] automobile companies have argued strenuously that these emissions targets are impossible to meet because of technological impediments.[2] Over several years, CARB has had to successively relax its standards.[3] Our objective in this paper on the one hand is to model this market as an explicit dynamic game between car manufacturers and CARB; on the other, we ex-

[1]These were 2% in 1998, 5% by 2001, 10% by 2003; the corresponding numbers for low emission vehicles were 48%, 90% and 95%, while for ultra-low emission vehicles were 2%, 5% and 15%. The low and ultra-low emission categories necessitate substantial improvements in catalytic converter efficiency, the use of reformulated fuel and the use of alternative fuels such as methane and compressed natural gas, or hybrid (fuel and electric-powered) vehicles.

[2]For instance, many viewed the launch of EV1 in 1996, General Motors' electric car with its price tag of $35,000, a maximum speed of 80 mph, a running distance of 70-90 miles, and a recharging process of around 15 hours without a high-speed charger as an attempt to convince the regulators that the company was genuine in its attempt to meet the emission standard but that technological impediments made this impossible. See *The Economist*, January 13, 1996.

[3]In 1996, CARB was convinced of the impracticality of the 2% and 5% mandates for 1998 and 2001, which were then relaxed leaving in place only the standard for 2003. It also relented in its 2003 ZEV standard of 10%, reducing it to 4%, with the remaining 6% being met by near-ZEVs such as extremely clean burning gasoline engines, natural gas engines, or hybrid gasoline-electric vehicles. At a January 25, 2001 hearing, CARB approved major changes to the ZEV regulations that will significantly reduce the number of ZEVs required during the near term. See the CARB website at http:\\www.arb.ca.gov for further details.

plore the role of noncooperative and cooperative pre-competitive R&D in the presence of spillovers in meeting CARB's regulatory objectives.

Our model is based on the classic paper on horizontal R&D of d'Asprémont and Jacquemin (1988) — henceforth D'A&J — and Yao's (1988) model of standard setting under asymmetric information. We consider a duopoly of automakers and a regulator (CARB) facing a market demand where consumers are assumed to be willing to pay more for cars meeting higher emissions standards.[4] Firms know their technological ability to comply with an emissions standard at a low or high cost (i.e., whether they are 'low-cost' or 'high-cost' types) but CARB does not. In the first period, CARB chooses an initial emission standard which the firms are required to comply with. Automakers respond by choosing R&D investment levels, followed by their production decisions which provide an imperfect signal to CARB regarding their types. Based on this signal, CARB resets the environmental standard at the beginning of the second period and the firms once again choose research and production levels. Firms can choose to do research noncooperatively or cooperatively in the presence of technological spillovers and are Cournot duopolists in the product market.

We find that low-cost firms will behave strategically and underinvest in research in the first period, both under competitive and cooperative R&D. The rationale for this is that by underinvesting, firms are able to preempt CARB from raising the emissions standard in the second period, leading to substantial gains in second period profits that more than compensate for lower first-period profits. The level of underinvestment (the *ratchet effect*)

[4]The Edmonton Sun in an online article dated May 4, 2001 reports on a Cap Gemini and Maritz Automotive Research Group study titled 'Green At What Cost?'. In a follow-up to a study done in 1999 that showed that 35% of Canadians were willing to pay an average of $1750 more for "green" vehicles, they found that 42% of the more than 2000 Canadians surveyed were willing to pay an average of $1820 more for a vehicle with lower greenhouse gas emissions in 2001; 82% said they were concerned about the environmental impact of cars, up from 80% in 1999. See http:\\autonet.ca/edmontondrive/stories.cfm?storyid=2116 for details.

is greater under cooperative R&D when spillovers are large. While it is to be expected that society's goals may be at odds with private incentives in this setting — indeed, that is often the justification for technology-forcing regulation in the first place — we find that when spillovers are high, social welfare is greater when firms engage in cooperative R&D but firm profits are greater if they do not cooperate in research. Therefore if spillovers are high, firms may need additional inducement to engage in cooperative R&D.

Although Yao (1988) has also shown that when product standards are imposed by regulation, car makers have the incentive to underinvest in R&D,[5] our model differs significantly from his in several respects. In Yao's work, the industry is modeled as a reduced-form entity whose only decision is how much to invest in R&D in both periods, and research success (i.e., low-cost compliance) is probabilistic. We consider a duopoly where each firm decides not only how much to invest in R&D in both periods, but also how much to produce in both periods within a Cournot framework since firms have to produce the cars meeting the current emissions standard in each period. Research, be it cooperative or non-cooperative, is deterministic. Furthermore, while Yao has a constant marginal benefit from the emissions standard, in our case cleaner cars are of additional value to consumers which changes the potential gains from trade (and hence the marginal benefit) as the standard changes. This marginal benefit is also affected by the strategic production decisions of the firms which determine the market equilibrium price, a channel of influence that is missing in Yao.

The paper is organized as follows. In Section 2 we describe the basic model, followed by a derivation of the full-information benchmark in Section 3. Section 4 comprises the main results of the paper in analyzing the no-precommitment asymmetric information case. Section 5 presents a pre-

[5]Unlike our ratchet effect, in his model it is the *high-cost* firm that chooses to underinvest because initial-period investment increases the expected future costs for high-cost firms more than it does for low-cost firms.

commitment and self-regulation scenarios. Conclusions and other comments are in Section 6.

2 The basic model

We model a two-period extensive form game with three players, CARB and two identical firms, i and j. In each period t, the firms face an inverse demand $p_t = a + \eta_t - (q_t^i + q_t^j)$, where p_t is the output price, $\{q_t^i, q_t^j\}$ denotes the output produced by each firm, and η_t is an emissions or environmental standard chosen by CARB that increases the potential social surplus by shifting the demand curve outward — consumers value cars meeting higher emissions standards and are willing to pay more for them. The per-unit cost of production for firm i at time t is given by $c_t^i = k\eta_t - x_t^i - \sigma x_t^j$,[6] where $k \in \{k_L, k_H\}$ is a cost parameter ($0 < k_L < k_H < 1$) which reflects the inherent productive capability of a firm and influences how the emissions standard impacts costs, $\{x_t^i, x_t^j\}$ are the research expenditures of both firms which measures their R&D efforts and lowers their unit cost of production, and $\sigma \in [0, 1]$ is an exogenously given research spillover parameter. Note that for any emission standard level η, a firm with a low k value (henceforth, a *low-cost* firm) indicates a more productive firm capable of complying with the environmental standard at a lower per-unit production cost than a high-cost firm. Firms are both either low-cost or high-cost.

In each period t, and following Yao and D'A&J, a firm's profit is given by $\pi_t = (p_t - c_t)\, q_t - \frac{\gamma}{2} x_t^2 - \frac{\mu}{2}\eta^2$, where the second term on the righthand side reflect increasing research costs, and the third term is a fixed cost of attaining the prevailing emissions standard which increases with the standard. Firm i (similarly, j) maximizes the discounted sum of two-period profits $\Pi^i = \pi_1^i + \delta\pi_2^i$, where δ is a discount factor that is common to both firms and CARB.

[6] Here and later, the corresponding derivation for firm j can be found by transposing i's and j's.

Henceforth, we will set $\delta = 1$; the implications of relaxing this assumption are discussed in Section 5. Under noncooperative R&D, firms initially choose research levels non-cooperatively and subsequently compete *à la* Cournot in the product market. Under cooperative R&D, firms first choose R&D levels so as to maximize joint industry profits and subsequently choose output levels noncooperatively.

Except under the full information scenario, we suppose that CARB cannot observe k but believes that it is either low (k_L) with probability θ or high (k_H) with probability $(1-\theta)$. The value of θ is unknown but is believed to be uniformly distributed over the interval $[0, 1]$.[7] At the end of the first period, CARB may choose to audit the first-period cost and update its prior regarding θ before setting the second period emission standard. CARB's auditing effort is assumed to be costless.

Using this basic model, we start with a benchmark full information scenario followed by an asymmetric information scenario, each under both noncooperative and cooperative R&D. In the asymmetric information scenario which is the main focus of this paper, CARB sets a standard in the first period, gathers information on first-period costs and updates its prior on both firms' type before setting a second period emission standard. In Section 5, we briefly discuss a precommitment scenario (when CARB is able to credibly precommit to an emission standard which prevails for both periods at the start of the game) as well as a self-regulation scenario (when firms are allowed to cooperatively choose an emissions standard that applies to both periods, before knowing their true type).

[7]More generally, one may assume that θ follows a beta distribution with parameters $\beta_1$and β_2. Then the initial probability of k_L is $\beta_1/(\beta_1 + \beta_2)$ and that of k_H is $\beta_2/(\beta_1 + \beta_2)$. The uniform distribution case is a beta distribution with $\beta_1 = \beta_2 = 1$.

3 Emissions standard under full information

3.1 Non-cooperative R&D

If CARB can observe $k \in \{k_L, k_H\}$, no updating is necessary and all time period subscripts can be dropped because the solution to the two-period problem is merely the solution to the one-period problem repeated twice. Given the chosen emission standard η, research levels $\{x^i, x^j\}$, and taking q_j as given, firm i chooses q^i to maximize its profit function:

$$\pi^i(q^i, q^j; x^i, x^j) = (p - c)q^i - \frac{\gamma}{2}(x^i)^2 - \frac{\mu}{2}\eta^2$$

where $p = a + \eta - (q^i + q^j)$ and $c = k\eta - x^i - \sigma x^j$. The Nash equilibrium output level of firm i is given by $q^i = [a + \eta(1-k) + (2-\sigma)x^i + (2\sigma - 1)x^j]/3$. Plugging the values of q^i and q^j into the profit function above yields a reduced-form profit function, $\pi^i(x^i, x^j)$. Then, at the preceding stage, firm i chooses an R&D level by maximizing $\pi^i(x^i, x^j)$ with respect to x^i.[8] Solving this maximization problem assuming symmetry, each firm's one-period Nash equilibrium research and production levels under noncooperative R&D (indexed by the superscript N) are given by:

$$x^N = \frac{(2-\sigma)[a + \eta(1-k)]}{D} \quad \text{and} \quad q^N = \frac{1.5\gamma[a + \eta(1-k)]}{D}, \tag{1}$$

where $D = 4.5\gamma - (2-\sigma)(1+\sigma)$; we assume $\gamma > 1$ which ensures $D > 0$. Note that the output and research levels are higher if the firms are low-cost, i.e., if $k = k_L$.

CARB's objective is to maximize the one-period social surplus by choosing η appropriately. This second best surplus is simply the sum of consumer and producer surpluses at the aggregate output level Q^N, given by the Nash equilibrium production levels, i.e., $Q^N = 2q^N$. The one period social surplus

[8] This derivation follows D'A&J.

is then

$$W^N(x^N,Q^N,\eta)=\int_0^{Q^N}(a+\eta-Z)dZ-\left[k\eta-(1+\sigma)x^N\right]Q^N-\gamma(x^N)^2-\mu\eta^2 \quad (2)$$

where the term under the integral is the area under the demand curve and all the other terms are aggregate costs of production and research.[9] Making use of (1) and then maximizing $W^N(x^N,Q^N,\eta)$ with respect to η yields:

$$\eta^N=\frac{a\gamma(1-k)A}{2\mu D^2-(1-k)^2\gamma A}, \quad (3)$$

where $A=18\gamma-2\left(2-\sigma\right)^2>0$ for $\gamma>1$.[10] Note that η^N decreases with k, i.e., the emission standard will be higher if both firms are low-cost ($k=k_L$). Finally, each firm's equilibrium profit level is given by:

$$\pi^N=\frac{1}{9}\left[a+\eta^N(1-k)+(1+\sigma)x^N\right]^2-\frac{\gamma}{2}(x^N)^2-\frac{\mu}{2}(\eta^N)^2. \quad (4)$$

3.2 Cooperative R&D

As in the previous case, firm i chooses q^i non-cooperatively in the second stage and similarly for firm j. But now, in the preceeding stage firms maximize joint profits $\pi^i(x^i,x^j)+\pi^j(x^i,x^j)$ with respect to x^i and x^j, internalizing the R&D spillovers. The one-period equilibrium solutions for research and production levels under cooperative R&D (indexed by the superscript C) are given by:

$$x^C=\frac{(1+\sigma)[a+\eta(1-k)]}{D'} \quad \text{and} \quad q^C=\frac{1.5\gamma[a+\eta(1-k)]}{D'}, \quad (5)$$

where $D'=4.5\gamma-(1+\sigma)^2>0$. Note that $D>D'$ for $\sigma>0.5$, so for high spillovers both output and research levels are higher under cooperative than

[9] Note that in this measure of social surplus, CARB takes the duopolistic market structure as given, i.e., it corresponds to Suzumura's (1992) 'second-best welfare function'.

[10] The second order sufficient condition is that the denominator of η^N be positive, which is certainly feasible for appropriate parameter values.

under non-cooperative R&D. Given the aggregate output level $Q^C = 2q^C$, CARB maximizes the one-period social surplus $W^C(x^C, Q^C, \eta)$ with respect to η, to obtain:

$$\eta^C = \frac{a\gamma(1-k)A'}{2\mu(D')^2 - (1-k)^2\gamma A'} \tag{6}$$

where $A' = 18\gamma - 2(1+\sigma)^2 > 0$. Given the emissions standard η^C, each firm will maximize its profit level $\pi^C(x^C, q^C, \eta^C)$.

3.3 Full information R&D, profit, and social welfare

The following two propositions follow from the derivations in the previous two subsections:

Proposition 1 *Under full information and either noncooperative or cooperative R&D, the output and research levels as well as the optimal emission standard will be higher for low-cost firms (i.e., $k = k_L$) than for high-cost firms.*

Proposition 2 *Under full information and for any given firm type (k_H or k_L), a high level of research spillover (i.e., $\sigma > 0.5$) implies a higher output and research level as well as a higher optimal emission standard under cooperative R&D, as compared to non-cooperative R&D. A low level of research spillover (i.e., $\sigma < 0.5$) implies higher output and research levels as well as a higher optimal emission standard only under non-cooperative R&D.*[11]

Proposition 1 is easy to understand: when firms are low-cost and therefore more productive, they produce more and undertake more research. It is also socially optimal to set a higher emission standard in this case since the marginal social cost of meeting this standard by low-cost firms is lower.

[11] The split between high and low spillover rate, defined by the value $\sigma = 0.5$, mirrors D'A&J.

Regarding Proposition 2, when spillovers are low (i.e., $\sigma < 0.5$), and for any given emissions standard η, although an increase in a firm's R&D investement, say firm i, will lower both firms unit production costs, it will lower firm i's unit cost sufficiently more than firm j's unit cost so as to give firm i a competitive edge over firm j in the output market, which is larger than the competitive edge firm i would obtain if spillovers were high. Hence, when spillovers are low, R&D investment and output levels are higher under non-cooperation than under cooperation. CARB will then set a higher standard η when spillovers are low and firms do not cooperate in R&D, because under this scenario firms tend to invest more in R&D than under the cooperative scenario. The reverse is true under the cooperative scenario.

Because of the complex interplay between R&D choice, output levels and the optimal emission standard, analytical results are very difficult to obtain; therefore, we have resorted to simulations to gain additional insights into this model. Our benchmark parameter values are $\gamma = 5.5$, $k_L = 0.45$, $k_H = 0.6$, $\mu = 0.4$, and with σ ranging between 0.33 and 0.9.[12]

Simulation Result 1 *Under cooperative R&D, firm profits are higher when σ is low (e.g., for $0.33 \leq \sigma < 0.5$) and lower when σ is high (e.g., for $0.5 < \sigma \leq 0.9$) relative to the non-cooperative R&D scenario, and regardless of whether both firms are high or low cost.*

To understand this result, note that from Proposition 2, a low σ means a higher output level (and hence higher gross profits) under noncooperation, but the higher emission standard imposes a large enough cost that noncooperation profits are smaller than those under cooperation. Thus if σ were low, firms would prefer cooperation over noncooperation. For analogous reasons, firms would prefer noncooperation over cooperation for a high σ.[13]

[12] An Excel simulation file is available from the authors upon request.

[13] This is a departure from D'A&J, where firms earn higher profits under cooperation than under noncooperation if and only if σ is high.

Simulation Result 2 *Under cooperative R&D, social welfare (and consumer surplus) is higher when σ is high (for $0.5 < \sigma \leq 0.9$) and lower when σ is low (for $0.33 \leq \sigma < 0.5$) relative to the non-cooperative R&D scenario, and regardless of whether both firms are high or low cost.*

The second simulation result indicates that even though firm profits are lower under cooperation when spillovers are high, the higher emission standard increases consumer surplus sufficiently that welfare levels are higher than under noncooperation. Hence, even though R&D cooperation is socially desirable in that it results in higher welfare, firms do not have an incentive to engage in it. This fundamental conflict between the private incentives of firms and what is socially desirable, even under full information, is an interesting and unique feature of our model with policy consequences: even if spillovers are high, firms may need external inducements in order to undertake cooperative R&D. It should be noted that this result is quite different from D'A&J where social and private incentives coincide.

4 Emissions standard without pre-commitment

4.1 Non-cooperative R&D

In this scenario, there is information asymmetry between the regulator, CARB, and the regulated firms. CARB cannot observe k but believes that it is either low (k_L) with probability θ or high (k_H) with probability $(1-\theta)$. The value of θ is unknown but is believed by CARB to be uniformly distributed over the interval [0.1], i.e., at first, CARB presumes that k_L and k_H are equally likely. But after observing the first-period cost, it updates its prior regarding θ. Under noncooperative R&D, the two-period problem consists of 6 steps as in Yao (1988):

1. CARB chooses η_1 based on its prior about θ,
2. firms choose$\{x_1^i, x_1^j\}$ noncooperatively given η_1,

3. firms choose $\{q_1^i, q_1^j\}$ given η_1 and $\{x_1^i, x_1^j\}$,

4. CARB observes (audits) the cost c_1 and chooses η_2 based on updated prior about θ,

5. firms choose $\{x_2^i, x_2^j\}$ noncooperatively given η_2, and

6. firms choose $\{q_2^i, q_2^j\}$ given η_2 and $\{x_2^i, x_2^j\}$.

This sequence of moves resembles reality in two critical respects. First, as discussed in the introduction, the history of emission regulations shows that although regulations are initially imposed with a specific deadline, apparently CARB has not been able to credibly hold the firms to that deadline, and in practice the standards have been revised in a dynamic interplay between the concerned parties. This feature is captured in the two-period extensive form game outlined above. Second, the actual CARB mandates are phased in gradually and dynamically over a certain number of years, and our model reflects this in that the firms have to undertake the production of vehicles meeting the current environmental standard in each period.

The game is solved backwards for a perfect Bayesian equilibrium assuming that CARB is aware of the fact that the research and production levels by the firms are symmetric in equilibrium.

Steps 5 and 6. The calculation of second period output and research levels mirrors Section 3.1, where the values of $\bar{x}_2^N$ and $\bar{q}_2^N$ are given by equation (1) with $k = k_H$ or k_L (depending on the firms' type), and $\eta = \eta_2$. Second period profits are given by equation (4) with appropriate substitutions.

Step 4. We need to consider whether low-cost firms might behave manipulatively, i.e., whether they will choose lower research levels in the first period so as to appear to be high-cost when CARB audits them at the end of the first period. Does manipulation leads to higher profits overall? In the first period, manipulation entails lowering investment in R&D which saves R&D

costs, but it raises the unit production costs in order for CARB to be unable to distinguish them from high-cost firms. Thus first period profits are not necessarily lower; however, manipulation does reduce the the second period emissions standard and thereby raises second period profits. While we were unable to resolve analytically whether overall profits were greater or not, we could not find any parameter configuration where the following simulation result did not hold:

Simulation Result 3 *Manipulation is a dominant strategy for low-cost firms for any positive discount factor δ, i.e., low-cost firms always have an incentive to manipulate their first-period costs.*

When low-cost firms manipulate in the first period, CARB learns nothing regarding the firms' true type and its prior unaffected. Consequently at the beginning of the second period in step 4, CARB chooses η_2 so as to maximize the expected social surplus

$$EW_2^N(\bar{x}_2^N, \bar{Q}_2^N, \eta_2) = E\Big[\int_0^{\bar{Q}_2^N}(a+\eta_2-Z)dZ-\left[k\eta_2-(1+\sigma)\bar{x}_2^N\right]\bar{Q}_2^N-\gamma(\bar{x}_2^N)^2-\mu\eta^2\Big]$$

where $\bar{Q}_2^N = 2\bar{q}_2^N$ and the expectation is taken with respect to the prior on k. Under the assumption that k_L and k_H are equally likely, we obtain the value $\bar{\eta}_2^N$ for the emissions standard under non-cooperative R&D:

$$\bar{\eta}_2^N = \frac{a\gamma(2-k_H-k_L)A}{2\mu D^2-\gamma\left[(1-k_H)^2+(1-k_L)^2\right]A} \tag{7}$$

where $A = 18\gamma - 2(2-\sigma)^2$.

Steps 2 and 3. When firms are high-cost ($k = k_H$), the solution for research and production levels are again given by an appropriate version of equation (1):

$$\bar{x}_{1,H}^N = \frac{(2-\sigma)[a+\eta_1(1-k_H)]}{D} \quad \text{and} \quad \bar{q}_{1,H}^N = \frac{1.5\gamma[a+\eta_1(1-k_H)]}{D}, \tag{8}$$

where η_1 is the first period emission standard set by CARB. The (observed) first-period unit production cost is then $\bar{c}^N_{1,H} = k_H \eta_1 - (1+\sigma)\bar{x}^N_{1,H}$; hence, each firm's first-period profit is given by:

$$\pi^N_{1,H} = \frac{1}{9}\left[a + \eta_1(1-k_H) + (2-\sigma)\bar{x}^N_{1,H}\right]^2 - \frac{\gamma}{2}\left(\bar{x}^N_{1,H}\right)^2 - \frac{\mu}{2}\left(\eta_1\right)^2.$$

When firms are low-cost ($k = k_L$) on the other hand, we assume (consistent with our simulation results) that each firm behaves manipulatively by choosing a research level $\tilde{x}^N_{1,L}$ so that its unit production cost is indistinguishable from that of a high-cost firm, $\bar{c}^N_{1,H}$. Therefore $\bar{c}^N_{1,H} = k_L \eta_1 - (1+\sigma)\tilde{x}^N_{1,L}$, and hence the manipulative research level is

$$\tilde{x}^N_{1,L} = \frac{k_L \eta_1 - c^N_{1,H}}{(1+\sigma)} = \bar{x}^N_{1,H} - \frac{(k_H - k_L)\,4.5\gamma\eta_1}{(1+\sigma)}, \tag{9}$$

where $\bar{x}^N_{1,H}$ is given in (8). We assume that the parameter values considered ensure $\tilde{x}^N_{1,L}$ is positive.

How does the manipulative $\tilde{x}^N_{1,L}$ compare to the research level $\bar{x}^N_{1,L}$ that would have prevailed under truthful behavior or non-manipulation? Noting that $\bar{x}^N_{1,L}$ would be given by (8) above with k_H replaced by k_L, we define the *noncooperative ratchet effect* as the difference $\left(\bar{x}^N_{1,L} - \widetilde{x}^N_{1,L}\right) = [(k_H - k_L)4.5\gamma\eta_1]/D(1+\sigma)$. The following proposition follows immediately:

Proposition 3 *The noncooperative ratchet effect is positive, increasing in the spread $(k_H - k_L)$, and decreasing in the spillover rate σ (for fixed η_1).*

Because low-cost manipulating firms have the same production cost as that of high-cost firms, their output level is also the same, i.e., $\tilde{q}^N_{1,L} = \left[a + \eta_1(1-k_L) + (1+\sigma)\tilde{x}^N_{1,L}\right]/3 = \bar{q}^N_{1,H}$. First-period profit is then:

$$\tilde{\pi}^N_{1,L} = \frac{1}{9}\left[a + \eta_1(1-k_L) + (2-\sigma)\tilde{x}^N_{1,L}\right]^2 - \frac{\gamma}{2}\left(\tilde{x}^N_{1,L}\right)^2 - \frac{\mu}{2}\left(\eta_1\right)^2.$$

The following proposition summarizes what can be concluded regarding research, output and profit levels across low- and high-cost firms keeping emission standards fixed in each period.

Proposition 4 *In the no pre-commitment scenario with asymmetric information and noncooperative R&D,*

(1) the first-period research level for a low-cost manipulating firm is smaller than that of a high-cost firm ($\tilde{x}_{1,L} < \bar{x}_{1,H}$), while the second-period research level for low-cost firms is greater ($\bar{x}^N_{2,L} > \bar{x}^N_{2,H}$);

(2) the first-period output level for a low-cost manipulating firm is the same as that of a high-cost firm ($\tilde{q}_{1,L} = \bar{q}_{1,H}$), while the second-period output level for low-cost firms is greater ($\bar{q}^N_{2,L} > \bar{q}^N_{2,H}$); and

(3) the profit of low-cost manipulating firms is higher than that of high-cost firms in both periods.

Finally, we calculate how the first-period emission standard is set by CARB in the following step.

Step 1: The expected first-period social surplus, assuming again CARB has a uniform prior and low-cost firms will manipulate, is given by:

$$EW^N_1(\eta_1) = \frac{1}{2}\left\{\int_0^{\tilde{Q}^N_{1,L}} (a + \eta_1 - Z)dZ - \left[k_L\eta_1 - (1+\sigma)\tilde{x}^N_{1,L}\right]\tilde{Q}^N_{1,L} - \gamma(\tilde{x}^N_{1,L})^2\right\} +$$
$$+\frac{1}{2}\left\{\int_0^{\bar{Q}^N_{1,H}} (a + \eta_1 - Z)dZ - \left[k_H\eta_1 - (1+\sigma)x^N_{1,H}\right]\bar{Q}^N_{1,H} - \gamma(x^N_{1,H})^2\right\} - \mu(\eta_1)^2$$

where $\tilde{Q}^N_{1,L} = 2\tilde{q}^N_{1,L} = 2\bar{q}^N_{1,H} = \bar{Q}^N_{1,H}$ from Proposition 4. Maximizing this expression with respect to η_1, we obtain

$$\bar{\eta}^N_1 = \frac{a\gamma B}{2\mu - \gamma F} \tag{10}$$

where

$$B = \frac{(1-k_H)A}{D^2} + \frac{(2-\sigma)(k_H-k_L)}{D(1+\sigma)}$$

and

$$F = \frac{(1-k_H)^2 A}{D^2} - \frac{(k_H-k_L)^2}{(1+\sigma)^2} + \frac{2(2-\sigma)(k_H-k_L)(1-k_H)}{D(1+\sigma)}.$$

Once the optimal $\bar{\eta}_1^N$ has been determined, one obtains the following summarizing simulation result (see Tables 1 and 2):

Simulation Result 4 *The first period equilibrium emissions rate increases slowly for spillover levels between 0.33-0.6, and declines slowly for spillover levels greater than 0.6. The equilibrium ratchet effect, however, declines monotonically with σ, i.e., the higher the spillover, the smaller the noncooperative ratchet effect in equilibrium.*

4.2 Cooperative R&D

Under cooperative R&D, the two-period problem consists of the same 6 steps as in Section 4.1, except at steps (2) and (5) where firms choose $\{x_{it}, x_{jt}\}_{t=1}^2$ *cooperatively*, i.e., they maximize the sum of their (reduced-form) profits. We sketch the corresponding derivations in each step.

Steps 5 and 6. The calculation of second period output and research levels are as in Section 3.2, where the values of $\bar{x}_2^C$ and $\bar{q}_2^C$ are given by equation (5) with $k = k_H$ or k_L (depending on the firms' type), and $\eta = \eta_2$. Second period profits are given by equation (4) with appropriate substitutions.

Step 4. As in the noncooperative R&D case, simulations indicate that low-cost firms will behave manipulatively in the first period. CARB maximizes the expected second-period social surplus $EW_2^C(\bar{x}_2^C, \bar{Q}_2^C, \eta_2)$, where $\bar{Q}_2^C = 2\bar{q}_2^C$ and the expectation is taken with respect to the prior on k. The optimal emissions standard $\bar{\eta}_2^C$ equals

$$\bar{\eta}_2^C = \frac{a\gamma(2-k_H-k_L)A'}{2\mu D'^2 - \gamma\left[(1-k_H)^2 + (1-k_L)^2\right]A'} \tag{11}$$

where $A' = 18\gamma - 2(1+\sigma)^2$.

Steps 2 and 3. Firms choose their first period research levels cooperatively, followed by their noncooperative output levels. When firms are high-cost, $\bar{x}^C_{1,H}$ and $\bar{q}^C_{1,H}$ are given by (5) with $k = k_H$ and $\eta = \eta_1$. When firms are low-cost and manipulate, their first period research level is

$$\tilde{x}^C_{1,L} = \bar{x}^C_{1,H} - \frac{(k_H - k_L)\, 4.5\gamma\eta_1}{(1+\sigma)} \tag{12}$$

whereas the output level $\tilde{q}^C_{1,L} \equiv \bar{q}^C_{1,H}$. Propositions analogous to Propositions 3 and 4 in the noncooperative case are easily derived here as well.

Step 1. CARB chooses an emissions standard η_1 so as to maximize the expected first-period social surplus $EW^C_1(\eta_1)$ given by

$$\bar{\eta}^C_1 = \frac{a\gamma B'}{2\mu - \gamma F'} \tag{13}$$

where

$$B' = \frac{(1-k_H)A'}{(D')^2} + \frac{(k_H - k_L)}{D'}$$

and

$$F' = \frac{(1-k_H)^2 A'}{(D')^2} - \frac{(k_H - k_L)^2}{(1+\sigma)^2} + \frac{2(k_H - k_L)(1-k_H)}{D'}.$$

4.3 No pre-commitment R&D, profit levels and social welfare

Comparing the ratchet effects as well as the first-period emission standards under the noncooperative and cooperative regimes, it is straightforward to derive that the cooperative emissions level is greater than the noncooperative one if and only if spillovers are large:

Proposition 5 *Comparing the two R&D regimes,*

(1) the cooperative emissions level $\bar{\eta}^C_1$ is greater than $\bar{\eta}^N_1$ and if and only if $\sigma > 0.5$;

(2) the cooperative ratchet effect is also larger than the noncooperative one if and only if $\sigma > 0.5$.

Proposition 6 *With high spillovers ($\sigma > 0.5$), the cooperative research levels in each period are higher than the noncooperative ones, i.e., $\bar{x}^C_{1,H} > \bar{x}^N_{1,H}$, $\bar{x}^C_{2,H} > \bar{x}^N_{2,H}$, $\tilde{x}^C_{1,L} > \tilde{x}^N_{1,L}$, and $\bar{x}^C_{2,L} > \bar{x}^N_{2,L}$.*

Simulation Result 5 *The first period equilibrium emissions rate under cooperative R&D is lower than under noncooperation for low spillover levels, and higher for high spillover levels. Similarly for the equilibrium ratchet effect under cooperative R&D as compared to the noncooperative ratchet effect.*

The result above is apparent from Tables 1 and 2. From Table 3 follows this result:[14]

Simulation Result 6 *For both high- and low-cost firms, the total cooperative research levels increase monotonically with spillover levels, while noncooperative research levels decrease monotonically, regardless of whether firms are high- or low-cost.*

Comparing total welfare and profit levels from the two periods (see Tables 4 and 5) yields the next result, an extension of the full-information Simulation Result 1 to this scenario with no pre-commitment.

Simulation Result 7 *For both high- and low-cost firms, the total social welfare levels are greater under noncooperative R&D for low spillover levels, and greater under cooperative R&D for high spillover levels. However, firm profits are higher under cooperation for low spillovers and under noncooperation for high spillovers.*

[14] An analogous result also holds in the original D'A&J paper (see p.1134): the noncooperative R&D level x_i^* changes with the spillover parameter β and $\text{sgn}(\partial x_i^*/\partial\beta) = \text{sgn}[(2-\beta) - 4.5b\gamma]$ which is always negative for the demand parameter b normalized to unity and $\gamma > 1$. Similarly for the cooperative R&D level $\hat{x}_i$, $\partial\hat{x}_i/\partial\beta$ is always positive. It should be noted that the monotonicity results in Simulation Result 6 take into account changes in the optimal emissions standard as the spillover level changes.

Unlike in D'A&J, our simulation results show that for a high spillover rate, i.e., for $\sigma > 0.5$, firms' profits are higher under non-cooperative R&D than under cooperative R&D, but social welfare is lower. The reverse is true for a low spillover rate, i.e., for $\sigma < 0.5$. Hence, a conflict arises between the firms incentive to choose a cooperative R&D regime, and society's interest.

5 Extensions

In this section, we consider two alternative scenarios, the first when CARB can precommit to an emissions standard for both periods, and the second a self-regulation scenario when firms choose the emissions standard cooperatively.

5.1 Precommitment

Under the pre-commitment scenario, CARB sets an emission standard level η at the beginning of period 1, to be complied by both firms in both periods.[15] As in the case of full information, there is no Bayesian updating of beliefs and, hence, the socially optimal solution to the two period problem is the solution to the one period problem repeated twice. The symmetric Nash equilibrium research and output levels under noncooperative R&D in both periods, $\hat{x}^N$ and $\hat{q}^N$, are given by equations (1) with appropriate substitutions for k and η. CARB choosesthe emissions standard so as to maximize the *expected* social surplus $EW^N(\hat{x}^N, \hat{Q}^N, \eta)$, where $\hat{Q}^N = 2\hat{q}^N$ and the expectation is taken with respect to the prior on k. Under the assumption that k_L and k_H are equally likely, the value $\hat{\eta}^N$ for the emisisons standard under non-cooperative R&D is identical to second period emissions standard without precommitment, i.e.,

[15] It has been widely debated whether such a commitment by the regulator is credible. It is reasonable to assume that a regulatory policy implemented under some sort of international agreement or protocol, is more likely to survive a domestic change of government. In this case, or in the alternative case of a sufficiently independent domestic regulator, a commitment by the latter could become credible.

$\hat{\eta}^N = \bar{\eta}_2^N$ from equation (7).

With cooperative R&D, the symmetric Nash equilibrium research and output levels under noncooperative R&D in both periods, $\hat{x}^C$ and $\hat{q}^C$, are given by equations (5) with appropriate substitutions for k and η. The emissions standard $\hat{\eta}^C$ is identical to the corresponding second period emissions standard without precommitment, i.e., $\hat{\eta}^C = \bar{\eta}_2^C$ from equation (11).

5.2 Self-regulation

Under self-regulation, firms set an emission standard cooperatively—in essence there is no CARB to audit firms costs and to set technology-forcing standards, and firms choose an emission level that maximizes their joint profits. The emissions standard is assumed to be chosen once, before firms know their true type.[16]

When both firms do research noncooperatively after they have chosen the emission standard, the R&D investment $\dot{x}^N$ and output $\dot{q}^N$ decisions are once again given by the equations in (1) with appropriate substitutions. Since the reduced-form profits of the firms are identical, maximizing joint profits is the same as maximizing any one firm's profit function. Straightforward calculations yield:

$$\dot{\eta}^N = \frac{a\gamma(1-k)H}{2\mu D^2 - \gamma(1-k)^2 H} \tag{14}$$

where $H = 9\gamma - 2(2-\sigma)^2$, and $k \in \{k_L, k_H\}$ depending on whether firms are low-cost or high cost.

Similar calculations for the case where firms choose their research levels cooperatively yield $\dot{x}^C$ and output $\dot{q}^C$ as given by equations (5) and the emissions standard by

$$\dot{\eta}^C = \frac{a\gamma(1-k)H'}{2\mu(D')^2 - \gamma(1-k)^2 H'} \tag{15}$$

[16]The alternative would be to allow firms to update at the beginning of the second period depending on their revealed type.

where $H' = 9\gamma - 2(2+\sigma)^2$.

6 Conclusions

The full-information scenario establishes a few benchmark results. First, low-cost firms do more research and produce a larger output than high-cost ones. At the same time, because a higher emissions standard is valued by society, CARB sets a higher standard when firms are low-cost and better able to meet that standard, resulting in lower profits. There is a fundamental conflict between firms' private incentives to conduct cooperative R&D and society's interests when consumers value vehicles with lower emissions: for high spillovers, firm profits are higher when they do not cooperate, while social welfare is higher if they do. Since the converse is true for low spillovers, firms have the incentive to engage in the opposite type of research to what is socially optimal.

When considering the asymmetric information scenario where CARB cannot credibly precommit to a single emission standard, low-cost firms always have the incentive to behave strategically and appear to CARB as if they are high-cost in attempting to keep the second period emission standard lower than what would otherwise be the case. This is achieved by lowering the research level undertaken, a ratchet effect that is larger under cooperation (noncooperation) for high (low) spillovers. As in the full-information case, social welfare is improved under cooperation for high spillovers, while firm profits are higher under noncooperation. This result indicates that the current permissive antitrust regulations that allow cooperative research efforts may not always be welfare improving — indeed, in our model, firms engage in cooperative R&D when spillovers are low and noncooperative research is socially optimal.

The emissions standard is higher under a cooperative research regime if spillovers are high, but not otherwise. Furthermore, for both low and high cost firms, simulations reveal that the emissions standard increases monotonically with the spillover level under cooperative R&D and the marginal impact of spillovers is more dramatic. But under noncooperative R&D, the marginal effect of spillovers is more muted and the level of research undertaken traces an inverted-U shape; thus high spillovers do not imply higher research levels in this case. The fact that emission levels decrease for high spillovers under noncooperation is at the heart of the conflict between firms' incentives and social welfare.

While we do not report on this extensively, we have considered two alternative scenarios, one where CARB can precomit to an emission standard, and another where firms choose an emission standard themselves so as to maximize joint profits. Comparing these four scenarios, simulations show (for the range of parameter values being considered) that social welfare is clearly (and unsurprisingly) maximized under full information, while producer surplus is minimized. Self-regulation on the other hand does the opposite: producer surplus is maximized while social welfare is minimized. Self-regulation is the worst scenario for consumers as emission standards are set too low. In between, we obtain that when firms are high cost, social welfare is lower under pre-commitment than under no-commitment even with manipulation. On the other hand, when firms are low cost, pre-commitment yields a higher level of social welfare than no-commitment with manipulation (see Table 6 for details).

Even though our results have been derived for the case of a duopoly, our results are likely to go through in a more general setting as in Suzumura (1992), who has extended D'A&J to the case of an oligopoly and general demand conditions. This is important since in the case of the California clean air mandates, the emission standards apply to the 6 largest car manufacturers. Several extensions to our model may be possible. The hardest is probably to incorporate non-deterministic R&D. Easier extensions would be to allow firms to comply partially rather than fully with CARB's standards, and to introduce audting costs for CARB. Finally, we have only considered the possibility of both firms engaging in either cooperative and non-cooperative R&D simultaneously; in reality firms will could engage in private research in addition to cooperative research.

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[2] Suzumura, K. (1992): "Cooperative and noncooperative R&D in an oligopoly with spillovers." *American Economic Review*, 82(5), pp. 1307-1320.

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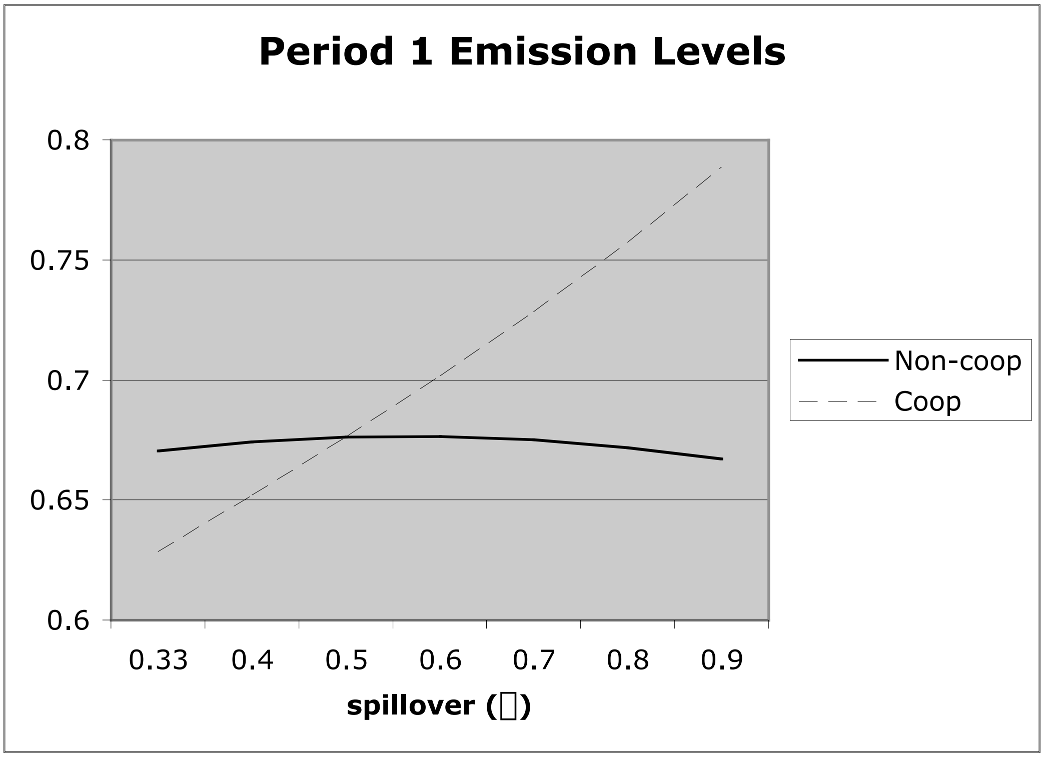

TABLE 1: Period 1 emission levels under non-cooperative and cooperative R&D

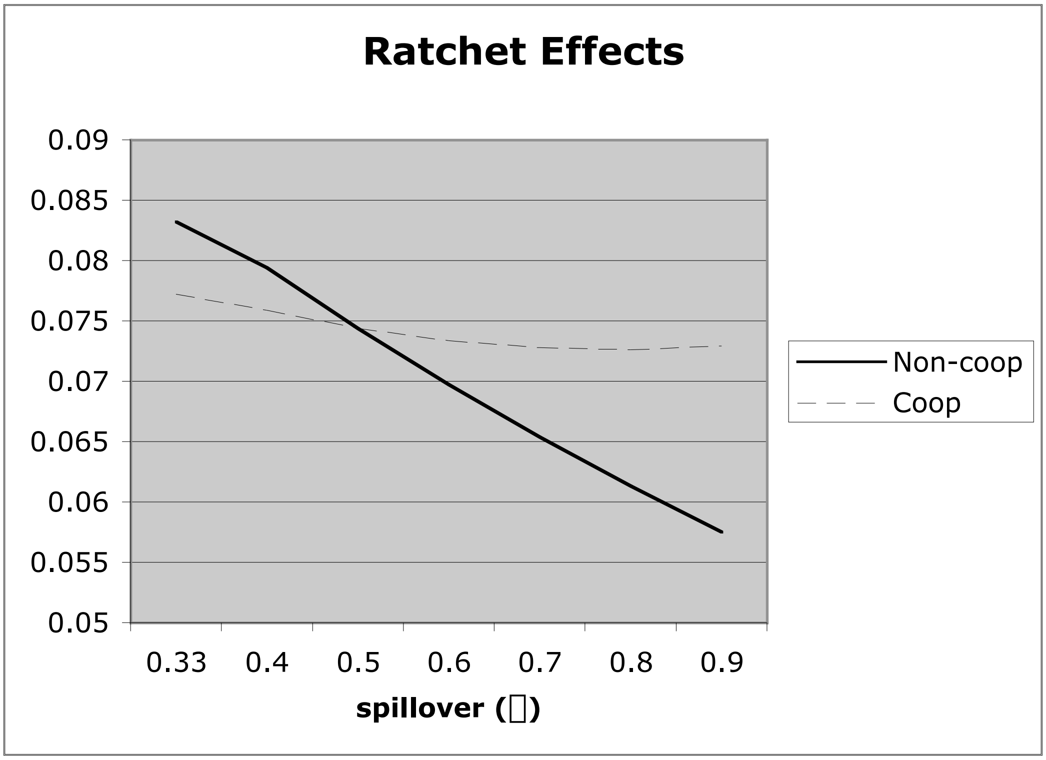

TABLE 2: Ratchet effects under non-cooperative and cooperative R&D

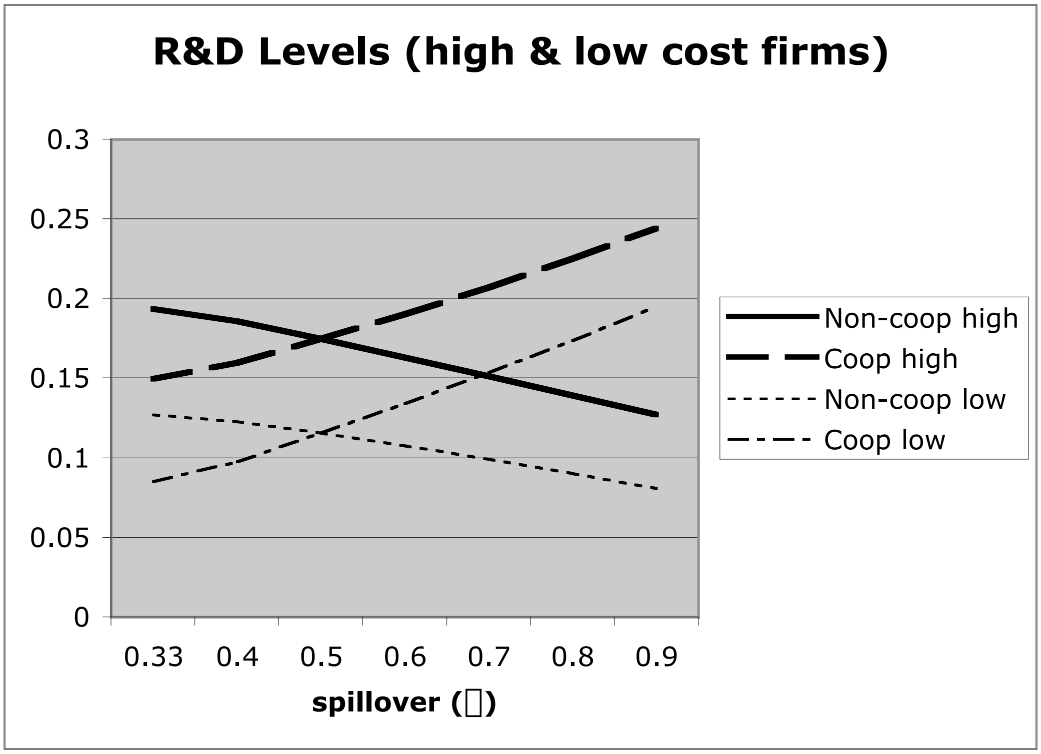

TABLE 3: Two-period research levels for high and low cost firms under non-cooperative and cooperative R&D

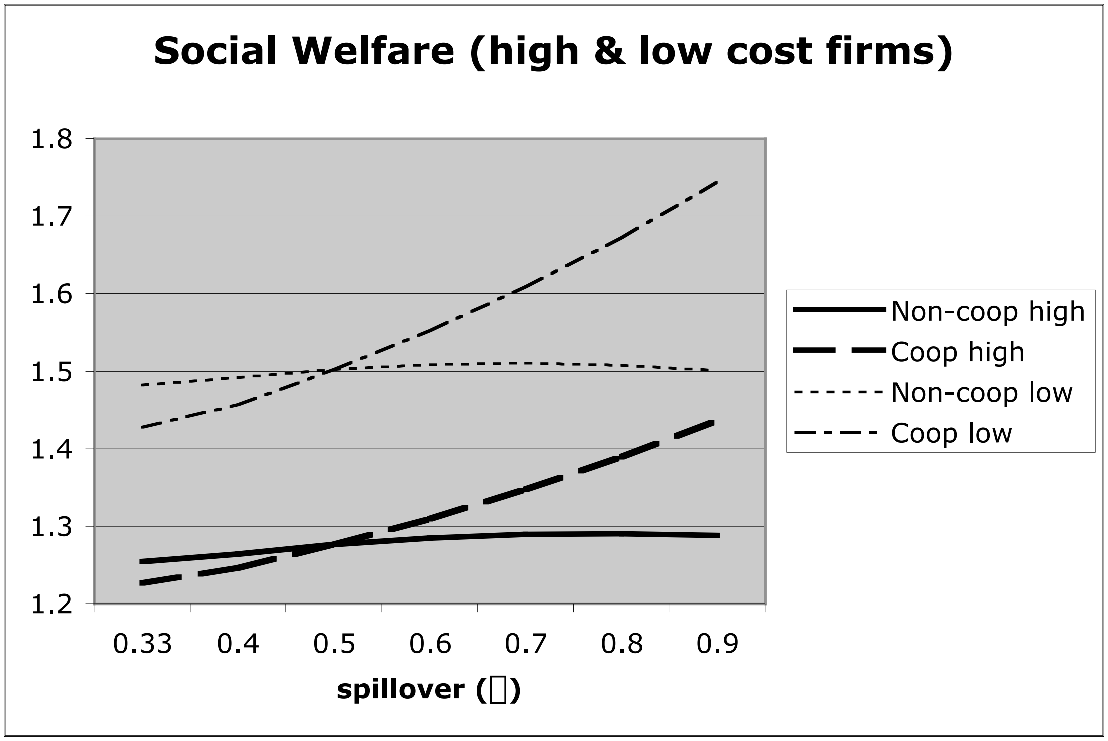

TABLE 4: Social welfare levels for high and low cost firms under non-cooperative and cooperative R&D

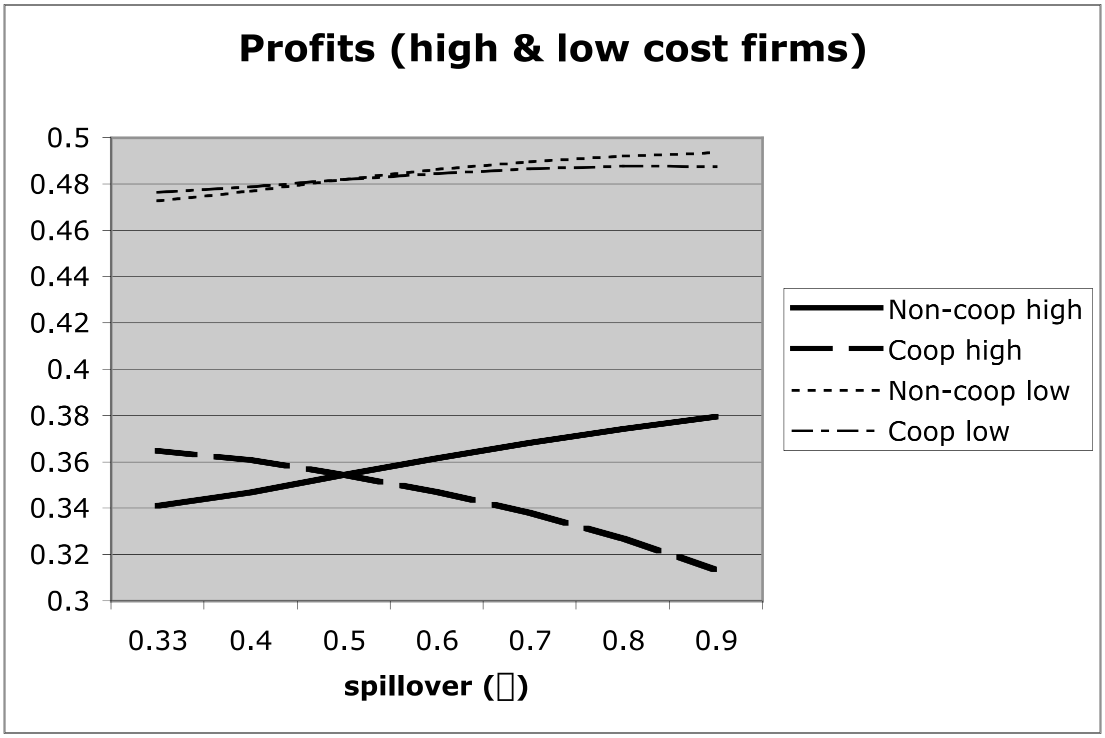

TABLE 5: Profit levels for high and low cost firms under non-cooperative and cooperative R&D

Consumer Surplus		Producer Surplus		Social Welfare	
High cost	*Low cost*	*High cost*	*Low cost*	*High cost*	*Low cost*
Pre-commitment	Full information	Self-regulation	Self-regulation	Full information	Full information
No pre-commitment	Pre-commitment	Pre-commitment	No pre-commitment	No pre-commitment	Pre-commitment
Full information	No pre-commitment	No pre-commitment	Pre-commitment	Pre-commitment	No pre-commitment
Self-regulation	Self-regulation	Full information	Full information	Self-regulation	Self-regulation

TABLE 6: Ranking of welfare measures for high and low cost firms under non-cooperative and cooperative R&D