Regulating a Stackelberg Oligopoly with Time-Persistent Pollution

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Motivation

- Naturally arises in industries with intense innovation effort.
  - The innovator becomes the leader.
  - Historically well-documented in marketing, transportation, and supply chain industries.
- Recently shown in high tech:
  - Energy storage, batteries, electric grids, robotics, pharmaceutical and healthcare products, among others.
  - Rapidly expanding.
  - Polluting.
- Can we use the same environmental policy as if firms competed simultaneously?

Motivation

- **Research questions:**
  - How to regulate firms when they compete sequentially?
  - The leader produces more units than the follower in the absence of regulation (output advantage).
    - How is this output advantage affected by regulation?
  - To which extent the change in the leader's output advantage stems from this firm's:
    - First-mover advantage or Cost advantage.
  - Role of *sequentiality* in:
    - output decisions (comparison against Cournot).
    - emission fees (comparison against inflexible fee).

Literature

- Regulation with simultaneous competition:
  - Initiated by Buchanan (1969), symmetric costs, Levin (1985), asymmetric costs, Simpson (1995), asymmetric pollution intensities, Akhundjanov and Munoz-Garcia (2016), and price competition, Kurtyka and Mahenc (2011).
- Literature on "Stackelberg games" is just fee-then-Cournot-competition, one or multiple periods.
- Effect of environmental regulation on profits:
  - Porter (1991), Porter and van der Linde (1995), and Farzin (2013): examine how regulation can promote more innovation and product quality, increasing profits.
  - CSR/public image, Baron (2001, 2008) and Calveras and Ganuza (2016).
  - Alternative channel for profit-enhancing regulation: the attenuation of the leader's first-mover and cost advantage.

Outline of the presentation

- Model
- Equilibrium behavior.
    - Without regulation (benchmark).
    - With regulation.
- Comparison with Cournot competition.
- Extensions:
    - Inflexible emission fee.
    - Several leaders and followers.
    - Product differentiation.
    - Follower's cost advantage.
    - Green leader.

Model

- Consider inverse demand function $p(Q) = 1 - Q$, where $Q = q_1 + q_2$.
- Marginal costs:
  - c_1 (leader), c_2 (follower), where $c_2 \geq c_1$, and $c_i \in [0, 1]$.
- Using c_1 to normalize costs:
  - Follower:
    $$c \equiv c_2 - c_1$$
    to denote the leader's cost efficiency.
  - Leader's cost is zero.

Model - Environmental damages

- **First period:**

$$ED_1 = d(q_1)^2,$$

where $d \geq 1/2$ represents pollution intensity.

- **Second period:**

$$ED_2 = d(\lambda q_1 + q_2)^2,$$

where $\lambda \in \left[0, \frac{1}{2}\right]$ denotes the time persistence of first-period pollution.

  - If $\lambda = 0$, $ED_2 = d(q_2)^2$.
  - If $\lambda > 0$, a share of first-period pollution still has environmental effects during the second period (common in air pollutants).

Model - Time structure

1. *First stage*:
   - The regulator sets a first-period emission fee t_1.
   - The leader responds choosing output q_1.
2. *Second stage:*
   - The regulator sets a second-period fee t_2.
   - The follower responds choosing output q_2.

- Output is sold at the end of the game.

Model - Time structure

- Second-period social welfare is

$$W_2 = CS + PS + T_2 - ED_2,$$

where:

  - $CS = \frac{Q^2}{2}$, $PS = \pi_1 + \pi_2$, and
  - $T_i = t_i q_i$ represents total tax collection.

- In the first period, the regulator anticipates W_2 and seeks to maximize

$$W_1 = -ED_1 + T_1 + W_2$$

Benchmark - No regulation

No environmental regulation

Benchmark - No regulation

- **Second stage:**
  - The follower takes q_1 as given and solves

$$\max_{q_2 \geq 0} \quad (1 - q_1 - q_2)\, q_2 - c q_2$$

  - The follower's best response function is

$$q_2(q_1) = \begin{cases} \frac{1-c}{2} - \frac{1}{2} q_1 & \text{if } q_1 < 1 - c \\ 0 & \text{otherwise.} \end{cases}$$

Benchmark - No regulation

- **First stage:**
  - Anticipating $q_2(q_1)$, the leader solves

$$\max_{q_1 \geq 0} \; [1 - q_2(q_1) - q_1]\, q_1$$

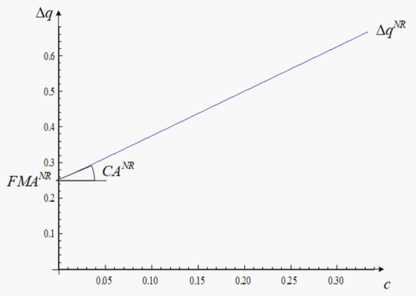
which yields $q_1^{NR} = \frac{1+c}{2}$, where NR denotes for "no regulation."

  - Therefore, the follower's output in equilibrium is $q_2^{NR} = q_2\left(q_1^{NR}\right) = \frac{1-3c}{4}$, which is positive if $c < 1/3$.

Benchmark - No regulation

- The leader's output advantage (OA) is $\Delta q^{NR} \equiv q_1^{NR} - q_2^{NR} = \frac{1+5c}{4}$ or, separating the first-mover and cost advantage:

$$\Delta q^{NR} = FMA^{NR} + CA^{NR} = \frac{1}{4} + \frac{5c}{4}$$



- How is each type of advantage affected by env. policy?

Introducing environmental regulation

Introducing environmental regulation

- **Second stage:**
  - *Lemma 1:* The follower's best response function is

$$q_2(q_1, t_2) = \frac{1-(c+t_2)}{2} - \frac{1}{2}q_1,$$

    which is decreasing in c and t_2.
- **Lemma 2:**
  - The regulator seeks to induce $q_2^{SO}(q_1) = \frac{1-c-(1+2\lambda d)q_1}{1+2d}$, which is positive for all $q_1 < \frac{1-c}{1+2\lambda d}$.
  - Setting $q_2^{SO}(q_1) = q_2(q_1, t_2)$ and solving for fee t_2, we obtain

$$t_2(q_1) = \frac{4\lambda d q_1 + (2d-1)(1-c-q_1)}{1+2d},$$

    which is positive for all parameters.

Introducing environmental regulation

- **Second stage:**
  - Fee $t_2\left(q_1\right)$ is increasing in λ, increasing in d iff $q_1 < \frac{1-c}{1-\lambda}$, but decreasing in c and q_1.
  - Intuition:
    - When pollution becomes more damaging (higher d) or more persistent (higher λ), the regulator sets a more stringent fee.
    - When the follower faces a larger cost disadvantage (higher c), the follower responds reducing q_2. Anticipating less pollution, the regulator sets less stringent fees.
  - Opposing effects from higher q_1:
    - The follower reduces its output, as without pollution.
    - But induces a less stringent fee t_2.
    - The first effect dominates in equilibrium: $q_2\left(q_1, t_2^*\right)$ decreases in q_1.

Introducing environmental regulation

- **First stage:**
  - Anticipating second-period fee and output, the leader solves

    $$\max_{q_1 \geq 0} \; (1 - q_1 - q_2^{SO}(q_1))q_1 - t_1 q_1$$

    We assume that the cost differential is not severe, to avoid corner solutions.

- **Lemma 3.** The leader's output function is

  $$q_1(t_1) = \frac{2d + c - t_1(1 + 2d)}{4d(1 - \lambda)},$$

  which is positive if $t_1 < \frac{2d+c}{2d+1}$, increasing in λ and c, and increasing in d iff $t_1 > c$.

  - *Intuition:* When d or λ increases, t_2 becomes more stringent, reducing q_2; which induces the leader to increase q_1 at this stage.

Introducing environmental regulation

- **First stage:**
  - The regulator seeks to induce $q_1^{SO} = \frac{2d(1-\lambda)+(1+2d\lambda)c}{2d[2(1+d)-\lambda(2-\lambda)]}$, which is positive for all parameters.
  - First-period emission fee is

$$t_1^* = \frac{2d\left[2d + \lambda(2-\lambda)\right] + c\left[\lambda^2 + 2d(1 - 2\lambda(1-\lambda))\right]}{(1+2d)\left[2(1+d) - \lambda(2-\lambda)\right]},$$

    which is positive, increasing in c, λ, and d.

- *Intuition:*
  - When pollution is more severe or persistent, or the leader enjoys a larger cost advantage...
  - fee t_1^* becomes more stringent.

Introducing environmental regulation

- **Fee differential (Corollary 1).**
  - The fee differential between leader and follower, $\Delta t \equiv t_1^* - t_2^*$, is

$$\Delta t = \frac{1+\lambda}{2(1+d) - \lambda(2-\lambda)} + \frac{2d\left[1+2d-3\lambda(1-\lambda)\right] - \left(1-\lambda^2\right)}{2d\left[2(1+d) - \lambda(2-\lambda)\right]}c$$

    with both terms being unambiguously positive.

- *Intuition:*
  - Positive vertical intercept:
    - When $c = 0$, $t_1^* > t_2^*$ to address the *FMA*.
  - Positive slope:
    - As c increases, t_1^* increases more rapidly than t_2^* to address the leader's *CA*.

Introducing environmental regulation

- **Leader's output advantage (Lemma 4).**

$$\begin{aligned}\Delta q^R &= FMA^R + CA^R \\ &= -\frac{\lambda^2}{2(1+d)-\lambda(2-\lambda)} + \frac{1+d(1+\lambda+\lambda^2)}{d[2(1+d)-\lambda(2-\lambda)]}c,\end{aligned}$$

  which is positive iff $c > \underline{c_R}$.

- Overall, Δq^R is unambiguously decreasing in d and in λ if and only if $\underline{c_R} \leq c < \overline{c_R}$.
- Figures should help (next).

Introducing environmental regulation

- **Leader's output advantage.**

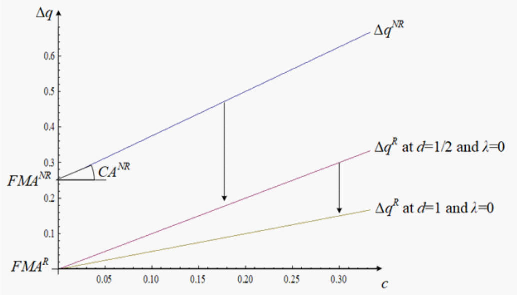


Fig 1a. Effect of d on Δq^R.

Introducing environmental regulation

- **Non-persistent pollution ($\lambda = 0$):**
  - When firms are symmetric, $c = 0$:
    - There is no CA
    - Regulation reduces FMA to zero.
    - Regulation eliminates the leader's output advantage.

Introducing environmental regulation

- **Non-persistent pollution ($\lambda = 0$):**
  - Higher c:
    - There is *CA*, but...
    - Smaller with than without regulation (flatter line).
  - In summary, it is soc. optimal for the cost-efficient leader to produce more units than the follower, but...
  - less intensively than in equilibrium.

Introducing environmental regulation

- **Non-persistent pollution ($\lambda = 0$):**
  - Higher d:
    - More stringent fees, especially on the leader, which produces more units.
    - This fee differential reduces its output advantage.
    - Regulation eliminates *FMA*, and attenuates *CA* (flatter line).

Introducing environmental regulation

- **Leader's output advantage.**

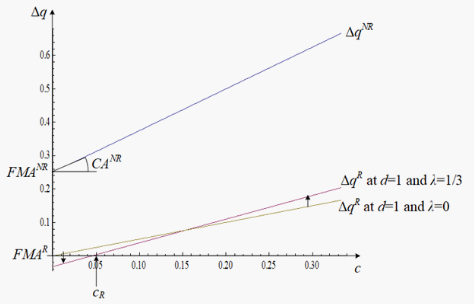


Fig 1b. Effect of λ on Δq^R.

Introducing environmental regulation

- **Persistent pollution ($\lambda > 0$):**
  - If $c = 0$, $FMA^R < 0$.
    - Follower's output advantage.
  - If $c > 0$:
    - More stringent fees on both firms, but...
    - If c is relatively low (high), the leader's fee increases more (less) than the follower, entailing an decrease (increase) in Δq^R.

Introducing environmental regulation

- **Comparing OA without and with regulation**
  - **Proposition 2:** The regulation-induced decrease in OA is

$$\Delta \equiv \Delta q^{NR} - \Delta q^{R}$$

    which is positive for all parameter values.
  - Rewriting $\Delta q^{NR} > \Delta q^{R}$, we obtain

$$\underbrace{FMA^{NR} - FMA^{R}}_{+} > \underbrace{CA^{R} - CA^{NR}}_{+ \text{ or } -},$$

    where:
    - $FMA^{NR} - FMA^{R} > 0$
    - $CA^{R} - CA^{NR} < 0$ or $CA^{R} - CA^{NR} > 0$ (but small).

Introducing environmental regulation

- **Comparing OA without and with regulation**
  - When d increases, regulation reduces OA to a larger extent.
  - Similar result when λ increases, but c needs to be low.

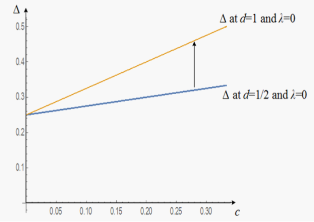


Fig. 2a. Effect of d on Δ.

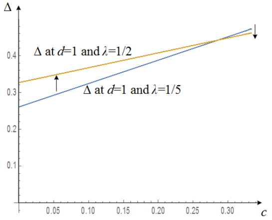


Fig. 2a. Effect of λ on Δ.

Introducing environmental regulation

- **Leader's Profits**
  - **Corollary 4.** *If the output ratio satisfies*

$$\frac{q_1}{q_2} \geq \overline{q} \equiv \sqrt{\frac{1+2d}{2d(1-\lambda)}},$$

the leader earns more profits than the follower.

- Since ratio $\frac{1+2d}{2d(1-\lambda)}$ is larger than 1, two cases arise:
  - when $1 \leq \frac{q_1}{q_2} < \overline{q}$, firm 1 produces more units but earns *lower* profits; and
  - when $\frac{q_1}{q_2} \geq \overline{q}$, the leader produces more units and earns *higher* profits.

Comparison with Cournot competition

Comparison with Cournot

- Output decisions

$$q_1^C(t_1) = \frac{1+c-t_1}{3} \text{ and } q_2^C(t_2) = \frac{1-2c-t_2}{3},$$

  where C denotes Cournot competition.

- **No regulation.** Output levels simplify to $q_1^C(0) = \frac{1+c}{3}$ and $q_2^C(0) = \frac{1-2c}{3}$, entailing that OA becomes

$$\begin{aligned} \Delta q^{NR,C} &= q_1^C(0) - q_2^C(0) \\ &= \frac{1+c}{3} - \frac{1-2c}{3} = c. \end{aligned}$$

Comparison with Cournot

- **Regulation.**
  - When $c = 0$, socially optimal output is evenly divided, $q_1^{SO} = q_2^{SO} = \frac{1}{2(1+2d)}$.
    - Induced with emission fees $t_1^C = t_2^C = \frac{4d-1}{2(1+2d)}$.
  - When $c > 0$, it is socially optimal for only firm 1 to be active, $q_1^{SO} = \frac{1}{1+2d}$ and $q_2^{SO} = 0$.
    - Induced with emission fees $t_1^C = \frac{2d(1+c)-(2-c)}{1+2d}$ and $t_2^C = 1 - 2c$.

Comparison with Cournot

- **Output advantage.**
  - When $c = 0$, the OA is $\Delta q^{NR,C} = \Delta q^{R,C} = 0$.
  - When $c > 0$, the OA is

$$\Delta q^{R,C} = q_1^C(t_1^C) - q_2^C(t_2^C) = \frac{1}{1+2d} - 0 = \frac{1}{1+2d},$$

  which is positive, and $FMA^{R,C} = 0$.

- Therefore, regulation decreases firm 1's OA if

$$\Delta^C \equiv \Delta q^{NR,C} - \Delta q^{R,C} = c - \frac{1}{1+2d} > 0$$

  which holds if $d > d_C \equiv \frac{1-c}{2c}$.

Comparison with Cournot

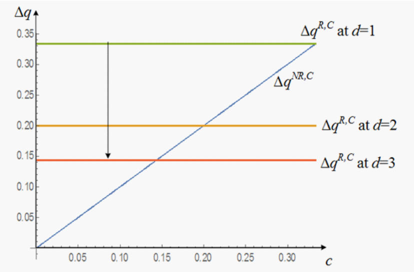


Fig 3a. Effect of d on $\Delta q^{R,C}$.

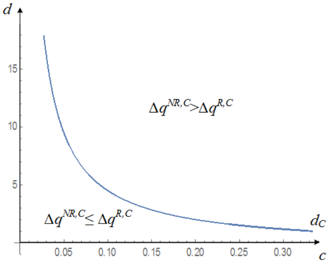


Fig. 3b. Cutoff d_C.

Comparison with Cournot

- Stackelberg, Δ, versus Cournot, Δ^C.

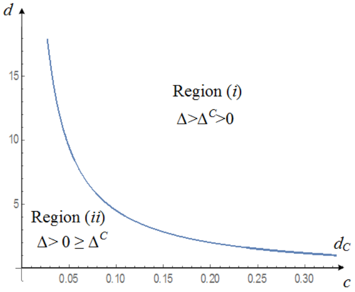


Fig 4. Change in output advantage under simultaneous and sequential competition.

Extensions

Extensions-I

- **Allowing for inflexible regulation**
  - Administrative/bureaucratic rigidities.
  - The regulator must choose a single emission fee t, solving

$$q_1(t) + q_2(t) = q_1^{SO} + q_2^{SO},$$

    where q_1^{SO} and q_2^{SO} were found in Proposition 1.
  - Intuitively, the regulator has now a single policy instrument, t, to induce firms to produce socially optimal output levels.
    - Suboptimal output levels in one or both periods.
  - **Lemma 6.** *Under an inflexible policy regime, the regulator chooses* $t^* = \frac{8d-4c(1+2d-\lambda)}{3[2(1+d)-\lambda(2-\lambda)]} - \frac{1-3c}{3}$.

Extensions-I

- **Allowing for inflexible regulation**
  - We can interpret the first-period emission fee as a function

$$\widetilde{t}_1 = \mu t_1^* + (1-\mu)t^*,$$

  where $\mu \in [0,1]$ denotes the regulator's flexibility:
    - When $\mu = 1$, she chooses fee t_1^* (see Proposition 1).
    - When $\mu = 0$, she chooses fee t^* (see Lemma 6).
  - Similarly, $\widetilde{t}_2 = \mu t_2^* + (1-\mu)t^*$.
- Then, we characterize the leader's OA as follows

$$\Delta q^{R,Inflex}(\mu) = q_1\left(\widetilde{t}_1\right) - q_2\left(\widetilde{t}_2\right)$$

which is linear in μ:

  - When $\mu = 1$, $\Delta q^{R,Inflex}(1) = \Delta q^R$.
  - When $\mu = 0$, $\Delta q^{R,Inflex}(0) = \Delta q^{R,Inflex}$.

Extensions-I

- **Allowing for inflexible regulation**
- As reg. becomes less flexible (lower μ):
  - the leader experiences a less stringent fee (relative to flexible setting),
  - the follower suffers a more stringent fee,
  - expanding the leader's output advantage.

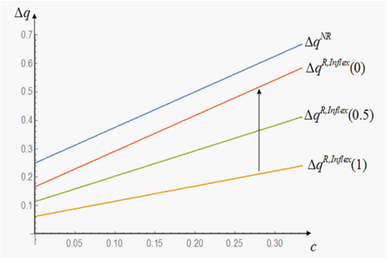


Fig. 6a. $\Delta q^{R,Inflex}(\mu)$ evaluated at $\lambda = 0$.

Extensions-II

- **Allowing for m leaders and n followers**
  - **No regulation**. Every leader's OA is decreasing (increasing) in the number of leaders (followers).
  - **Regulation.** The regulator seeks to induce the same aggreg. soc. optimal output. With more firms, she sets more stringent fees on each firm.
- Unlike with one leader and follower, we show that the OA with regulation can be negative under large parameter conditions, giving rise to a "regulation-induced follower's OA."
- Comparison:

$$\Delta(m, n) \equiv \Delta q^{NR}(m, n) - \Delta q^{R}(m, n).$$

- Overall, $\Delta(m, n)$ becomes smaller (larger) when more leaders (followers) compete, thus ameliorating (emphasizing) our previous results with a single leader and follower.

Extensions-III

- **Allowing for product differentiation**
  - $p(q_i, q_j) = 1 - q_i - \beta q_j$, where $\beta \in [0, 1]$.
  - We show that the leader's OA decreases when products are more differentiated (lower β).
  - This holds with and without regulation, but the latter falls more substantially.
  - In other words, as goods become more differentiated, the introduction of regulation produces a smaller decrease in the leader's OA.
  - We should observe stronger opposition to environmental policy when firms sell homogeneous than differentiated products.

Extensions-IV

- **Allowing for follower's cost advantage**
  - The leader only benefits from *FMA*.
  - We find that:
    - When c is low, the leader holds an OA under no regulation, but regulation switches it to the follower's OA, under all parameters.
    - When c is intermediate (large), the follower holds an OA with and without regulation, but policy emphasizes (ameliorates) its advantage.

Extensions-V

- **Allowing for a green leader**
  - The leader is not subject to regulation.
- Relative to polluting leader:
  - *FMA* increases (higher intercept).
  - *CA* increases.(steeper line).

Discussion

- **No regulation**
  - OA is larger in Stackelberg ($FMA + CA$) than in Cournot (CA only).
  - OA decreases in the number of leaders, m, increases in the number of followers, n, and shrinks when goods become more differentiated (lower β).
- **Regulation**
  - $\Delta \equiv \Delta q^{NR} - \Delta q^{R} > 0$, for all parameters, meaning that OA shrinks due to regulation.
  - Δ expands in the leader's CAs (higher c) but shrinks as pollution is more damaging or persistent (d or λ).
  - Δ decreases in the number of leaders, m, but increases in the number of followers, n.

Discussion

- **Regulation flexibility**
  - Larger flexibility shrinks Δ, making the leader more opposed to regulation.
- **A "reversal" of the leader's OA**
  - The leader had an OA before regulation, but the follower holds it after regulation.
  - This arises when:
    - Firms are relatively symmetric (low c), many leaders but few followers (high m but low n), products are highly differentiated (low β), and the follower holds a cost advantage.
  - In these contexts, we should expect strong lobbying against env policy by industry leaders.
  - Otherwise, the leader keeps a positive OA, being less resistant to regulation.

Thank you!