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Regulatory Compliance in the Automobile Industry

Bing Guo[*], Sarah Parlane[**] and Lisa Ryan[**]

[*] Universidad Carlos III de Madrid, Department of Business Administration, Spain

[**]University College Dublin, School of Economics, Ireland

Abstract: This paper considers automobile manufacturers who must comply with emission standards. True compliance is associated with some idiosyncratic losses which also depend on the extent to which the regulation is stringent and the extent to which it is technology forcing. Manufacturers invest in innovation to address compliance, but they can also install a defeat device signaling compliance without incurring any losses. Importantly, we assume that the firms have the option to remove the device once the uncertainty about innovation is resolved. We explore how these decisions depend on the policy's stringency, the firm's ability to innovate and the sector's competitiveness.

1. Introduction

In September 2015 the US EPA served a Notice of Violation on Volkswagen Group revealing that approximately 480,000 Volkswagen and Audi automobiles had an emissions-compliance "defeat device" installed. The device enabled the group to signal that its fleet complied with the regulation when its actual emissions were excessive. Whether the Volkswagen Group was the only company to rely on such a strategy is unlikely. Indeed, Reynaert and Sallee (2021) provide evidence that gaming, understood as finding a way to signal lower emissions than those occurring on-roads, has significantly increased in the automobile industry in the last 15 years.

The literature has long acknowledged that compliance is an issue when it comes to environmental regulations. Malik (1992) and Heyes (2000) assess how regulatory rules, and more specifically fines and monitoring, can be tailored to incentivize the firms to align their emission levels with the standards that are set. Macho-Stadler and Pérez-Castrillo (2006) and Macho-Stadler (2008) consider pollution taxes and emission permits in a context where emissions are self-reported. They show that non-compliant firms do not pay what they truly owe or purchase too few permits. Coria and Villegas-Palacio (2010 and 2014) consider the implication of tax based and permit based regulations on technology adoption in a context where firms also decide how much emissions to report.

Our approach is closer to Yao (1988), Malik (1990), Reynaert and Sallee (2021) and Reynaert (2021) which consider cheating as a discrete choice: the firm relies on a device, or it does not. In Malik (1990) this decision is not strategic: Firms are de-facto offenders that differ in what they stand to gain when not caught. Reynaert and Sallee (2021) and Reynaert (2021) focus on the automobile industry and consider gaming as a strategy that enables manufacturers to alter the information that consumers and regulators receive about the automobile. The message received impacts the consumers' willingness to purchase the vehicle and the overall impact of cheating on welfare is shown to be ambiguous.

Following Yao (1988), we place ourselves in a world where compliance is possible. However, compliance is subject to (possibly large) abatement costs.[1] The decision to install a cheating device is introduced as a strategic decision that enables the manufacturer to appear compliant without incurring such costs. These savings are however not guaranteed. Emissions are subjected to some scrutiny and a defeat device may be detected with some probability. When so, the firm faces penalty losses.

We consider investment in innovation as a complementary strategy enabling manufacturers to reach the emission standards and save on some of the abatement costs. The outcome of such investments is subject to uncertainty and correlated to a firm's

[1] Bresnahan and Yao (1985) explain that manufacturers must typically design cars that are either more expensive or less driveable to truly reach lower emission standards. Lemerle and Benz (2019) estimate that full compliance with CO_2 targets could increase the average cost of cars by +7% by the end of 2020 and by +15% by 2025 which could lead to a €2.9bn loss in car sales.

intrinsic ability to innovate. The consideration of innovation enables us to separate compliances losses into those incurred regardless of whether the firm innovates, and those avoided when innovating. This, in turn, enables us to capture the extent to which a regulatory policy is both stringent (high non-avoidable costs) and technology forcing (high avoidable costs).

Importantly, we not only capture the firm's initial decision to install a cheating device but also its decision to rely on the device post-innovation. More specifically, we consider that a firm may decide to keep or to remove the devise once it knows whether innovation is successful or not. This concept is motivated by a real-life observation. Ewing (2017) explains that Volkswagen decided to leave the device in place even after it had successfully developed a technology called BlueMotion. If it had not done so, no one would have ever detected the defeat device. The extent to which a firm "commits" to rely on a cheating device plays an important role because it impacts the value of the cheating device. Thereby, it influences the decision to invest, the initial decision to install the device and, ultimately, any policy recommendations.

Finally, we capture the sector's competitive pressures considering that a firm may lose some profits to its rival when it does not install a device and fails to innovate while its opponent innovates successfully or relies on a device and is not caught. When a manufacturer does not innovate and does not install a cheating device, alternative approaches must be implemented to meet the emissions standard. The losses these approaches would generate are likely to be more consequential when the rival firm innovates or appears to have been able to lower its emissions at very low cost. Indeed, some consumers care about innovation and prefer cars that rely on innovative technologies enabling them to comply with the emission standards. Alternatively, while consumers cannot verify whether a car has a cheating device installed, they can compare prices and since cheating enables a firm to avoid compliance costs it enables the same firm to set lower prices. The link between competition and cheating has received little attention in the literature.[2] Yet, Ewing (2017) highlights how the decision to rely on a cheating device was taken by Volkswagen who was struggling to retain its market share in the very competitive American market where European cars running on diesel were seen as unattractive.

We show that the firm's final decision, to keep or remove the defeat device is independent of its rival's decision. Said differently, the commitment to rely on the device forms a dominant strategy equilibrium. Broadly speaking we show that the firm relies on a cheating device when, on expectation, savings in terms of compliance losses and competitive gains are high relative to the penalty cost incurred when the device is found. When the expected savings in terms of *unavoidable* compliance losses are higher than the

[2] Using experiments, and with a focus on psychology, Gino et al. (2022) and Vedera and Pathki (2021) establish that competition can promote cheating. Reynaert and Sallee (2020) mentions the pressure than a firm would have to cheat if its competitors do so.

expected penalty losses the firm leaves the device, whether it innovates or not. In the alternative scenario, the firm only keeps the device if it fails to innovate.

The investment in innovation influences the likelihood of accessing a world where the firm can avoid part of the compliance losses. Without any device or when the firm intends to keep it regardless of the outcome of innovation, the unavoidable compliance losses and penalty incurred when caught cheating, have no impact on the investment. In these cases, the firm either faces these compliance losses or, when it keeps the device, incurs one or the other depending on whether the device is found, irrespectively of the outcome of innovation. Thus, in these two situations, a regulatory policy can only impact the investment decisions provided if it alters the extent to which it is technology forcing. The more the firm stands to save, the more it will invest.
When the firm commits to remove the device if and only if it innovates, both the unavoidable compliance losses and penalty incurred when caught cheating, impact investment. Higher unavoidable compliance losses depress the investment, while a higher penalty stimulates the investment. Indeed, when the unavoidable compliance losses increase or when the penalty decreases, the firm is keener to rely on the device. Therefore, it has less incentive to innovate.

The countervailing forces exerted by the distinct compliance losses lead us to conclude that the relationship between a commitment to cheating and investing is not obvious. To this day, automobile manufacturers have very heterogenous fleets. Most of the American brands rely on petrol engines, while most of the European cars rely on diesel. Therefore, when an emission target is set uniformly, the compliances losses are likely to diverge substantially across manufacturers. We show that manufacturers who decide to rely on a device regardless of the outcome of innovation could also be the ones who invest the most if the losses that are avoidable thanks to innovation are sufficiently large.

The firms' initial decisions consisting in installing a device or not are interdependent when there are competitive gains. Without the possibility to expand market shares, dominant strategy equilibria emerge whereby a firm installs a device provided (i) it plans to rely on it (at least when innovation fails) and (ii) its ability to innovate is low. In equilibrium the sum of the profits is maximized. When the prospect of expanding market shares emerges, more equilibria arise. Some, but not all, are in dominant strategies. The underlying motivation to install a device remain the same. What is more interesting is the fact that competitive pressures can lead the firms to select a suboptimal equilibrium similar to the one occurring in a prisoner's dilemma game: both install the device when both would be better-off not doing so.

Finally, we establish that an increase in the penalty will deter cheating. Better monitoring capabilities will generally deter cheating as well. However, this may not be the case when competitive pressures are such that firms have much to gain when expanding their market share. A firm that has a greater ability to innovate can be less tempted to install a cheating device under weaker monitoring. Indeed, we show that the possibility to increase its market share incentivises the firm to rely on innovation more so than on a cheating device.

These results and our analysis also add to the literature considering the multifaceted strategic decisions that firms can take to manipulate regulators. Considering specifically the automobile industry, Yao (1988) brings to light one possible pitfall that arises when the regulator is not able to commit to future decisions. Using a two-period model with private information, the author shows that manufacturers have an incentive to underinvest in research and development (R&D) to maintain a high compliance cost which, in turn, leads the regulator to select less stringent regulatory rules. Puller (2006) shows that this outcome may not arise in an oligopoly model where firms who innovate face lower costs than its competitors when the new rules become more stringent.

The next section presents the model and some of the assumptions are discussed in section 3. Section 4 characterizes the optimal investments and the decision to keep or remove the device post-innovation. Section 5 provides an analysis of the initial decision consisting in installing the device or not. Section 6 focuses on comparative statics and policy recommendations. Section 7 concludes.

2. The model

We consider a game initiated by a regulatory agency between two heterogeneous car manufacturers (1 and 2). The regulatory agency has the authority to impose some emissions targets that the manufacturers must reach.

To achieve true compliance, the manufacturers face abatement costs and can invest in innovation activities, such as R&D. As argued in the introduction, abatement costs typically lead to losses incurred at the very least in the short and medium term. More specifically, given its fleet and existing technology, we assume that firm i faces some idiosyncratic losses $(c_i + d_i) \geq 0$ to reach true compliance. If, however, firm i manages to improve its technology and/or to alter the fleet it offers, the overall compliance losses are only equal to $c_i \geq 0$. Therefore, the variable c_i reflects the policy's stringency given the manufacturer's existing fleet and technology. The variable d_i reflects the extent to which the policy is technology forcing because it captures the losses that are avoidable upon innovating.[3]

We let $I_i \geq 0$ denote manufacturer i's investment in innovation which may succeed or fail. It is successful when the firm can comply at no further losses than c_i. The probability

[3] Note that d_i could also capture the present value of future taxes that must be paid when a manufacturer's fleet level of emission is above the standard.

of success is captured by a function $P(\theta_i, I_i)$ where θ_i denotes the *type* of manufacturer $i, i \in \{1,2\}$. This variable captures the idiosyncratic features of a manufacturer that influence the probability of success. These could be the quality of its R&D team, the level of its absorptive capacity, its past innovation record.[4] We will refer to θ_i as firm i's innovative capability. The types θ_1 and θ_2 are independent realizations of a random variable distributed over $[0, +\infty)$.

We make the following assumptions concerning the function $P(\theta, I)$:

(i) For any $(\theta, I), P(\theta, I) \in [0,1]$ with $P(0, I) = 0$,
(ii) $P(.)$ is increasing and concave in θ,
(iii) $P(.)$ is increasing and concave with respect to I,
(iv) $P_I > 0$ for all $\theta > 0$ and such that $\lim_{I \to 0} P_I = +\infty$ and $\lim_{I \to +\infty} P_I = 0$.
(v) $P_{\theta I} > 0$ for all $\theta > 0$

Assumption (i) reflects the fact that the function $P(\theta, I)$ is a probability and that success in innovation requires that some innovative capability. Assumption (ii) captures a convention whereby we assume that a higher type means a greater ability to innovate for any given investment level. Assumptions (iii) and (iv) ensure that the optimization problem will be concave in I as the marginal increase in the probability of success decreases with the investment. Assumption (iv) captures the fact that the increase in the probability of success due to a marginal increment in investment is higher for the firm with higher innovative capability.

Cheating is a strategy whereby a manufacturer has the possibility to install a defeat device in some of the cars to signal that the overall fleet is complying with the new regulation when it does not. It offers the possibility to leave the fleet and prices as they are and, therefore, to avoid compliance losses on the condition that one is not caught. Let $\gamma \in]0,1]$ denote the probability with which the device is *not* detected. When caught, the manufacturer must remove the device and incurs compliance losses as well as a penalty which increases losses by $F > 0$ (which can include reputational damages). If the device is discovered and manufacturer i succeeded in innovating, it incurs losses $(c_i + F)$. If it failed to innovate, it incurs losses $(c_i + d_i + F)$

Finally, we consider that the manufacturers who decide to install the device after the policy is announced can, if they wish to, remove it once the uncertainty about innovation has been resolved. Specifically, we consider the sequential game characterised below.

T=0: Nature sets the firms' types (θ_1, θ_2).

T=1: The government sets the regulatory policy which determines the compliance losses, $(c_i, d_i)_{i=1,2}$.

[4] The concept of absorptive capacities refers to a firm's ability to identify, assimilate, transform, and use external knowledge, research and practice.

T=2: The firms, knowing the policy and their innovative ability, decide simultaneously and non-cooperatively to install a cheating device or not.

T=3: The firms decide simultaneously and non-cooperatively how much to invest in innovation and Nature decides whether they succeed or fail.

T=4: Based on whether they succeed or fail the firms decide simultaneously and non-cooperatively whether to remove the cheating device (if installed).

We capture the competitive pressures between firms considering that a firm may lose some market share under specific circumstances. We consider that consumers care about the environment and prefer cars that comply with emission regulations. However, they do not have the means to verify true compliance and believe that a company relying on a cheating device complies with the regulation so long as this manufacturer is not caught. Consumers are also price sensitive. As larger compliance losses are likely to lead to higher prices, we consider that an innovating firm manages to expand its market share when it faces an honest rival that fails to innovate because it can lower its prices more so than its rival. Thus, all in all, firm i is at disadvantage when it does not use a cheating device and fails to innovate while its opponent either innovates or relies on a cheating device and is not caught. We let $\Delta\pi \geq 0$ denote the profits that transfers from firm i to firm j in such circumstances. Higher values of $\Delta\pi$ capture a greater customer's sensitivity either to successful innovation outcomes or to price differentials.

In Appendix 1 we provide a table with all the variables and their definition.

3. Discussion of the model

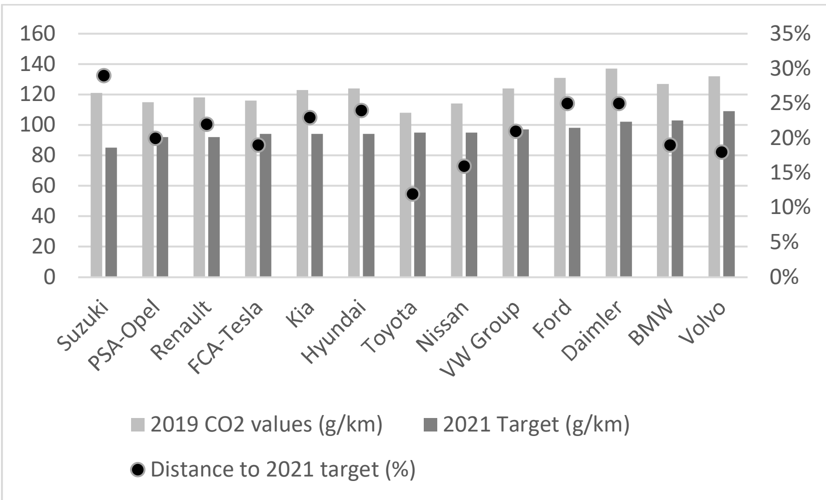
We place ourselves in a world where it is always possible for manufacturers to meet the emissions standards. In this context, the innovation process does not affect a manufacturer's *ability* to reach the standard. Instead, it determines the losses that the firm faces to meet the target. This approach is in line with other papers in the literature such as Yao (1988) and relies on the premises that regulatory agencies are advised by experts informing them about the technological boundaries reflecting what can be achieved.

In practice, the abatement costs and the resulting losses incurred by car companies are typically correlated with some of their fleet's attributes such as its initial average weight and footprint and the proportion of APVs.[5] However, the abatement losses also depend on the policy's *stringency*. The concept of stringency has been captured in various ways in the literature (both empirical and theoretical). One reason is that a regulation is considered stringent either (1) because it requires that manufacturers achieve a substantial reduction in the emission of some toxic substances, or (2) compliance based on the firm's existing technology is costly, or (3) because compliance is dependent on

[5] In Europe, the Volkswagen Group made a case for attribute based policies arguing that it would be at a disadvantage given that, on average, its fleet tends to be heavier.

achieving some form of technological change (see Ashford et al. (1985)). Our approach has the benefit that it captures two possible aspects of a policy's stringency which are shown to have countervailing impacts. Specifically, a regulatory policy will be considered particularly stringent when c_i is high which captures possibility (2) and/or when d_i is high which captures possibility (3).

In order to understand what these compliance losses capture, one must consider more specifically the manufacturers' strategies. In the past years, car manufacturers have devoted much of their resources to supplying better and cheaper electric and hybrid cars for which the demand is increasing. Changing the fleet that is being offered to consumers can lead to substantial unavoidable costs. Firms have also acquired patents working on hydrogen fuelled cars and more radical innovations are taking place with the view of developing fully autonomous vehicles.
The difference in compliance losses is based on their fleet and technology, some manufacturers may be at a disadvantage compared to others if they were submitted to the same, or similar enough, targets. The graph below represents the 2019 CO_2 emissions and the target emissions for different manufacturers in Europe. The dots represent how far each manufacturer is from the target, expressed as a percentage of 2019 emission level. Manufacturers have been ranked (from left to right) according to the target they must reach which, in the European case, is not uniform but correlated to the average weight of the fleet. While emission targets are not too disparate, the distance to target varies greatly from one manufacturer to another. For instance, the emission targets for Hyundai and Toyota are 94g/km and 95g/km respectively, and hence very similar. However, their distances to the targets are quite distinct. Hyundai must reduce its emissions by 24%, while Toyota must reduce these by only 12%. The abatement losses that these two firms will face are therefore likely to be quite distinct.



Source: Tietge et al (2020).[6]

[6] See https://theicct.org/sites/default/files/publications/CO2-EU-update-aug2020.pdf

Finally, our model assumes that the decision to game the system is taken prior to investing in innovation and that it can be revised based on the outcome of innovation. This assumption is motivated considering that innovation is a longer term process which is subject to high uncertainty.

4. Last stage cheating decision and optimal investments

We solve for a subgame perfect equilibrium wherein firms perfectly anticipate their future decisions. Therefore, we start with the last stage. In this section we consider specifically the decision to keep the defeat device should it be installed initially and the investment decision in R&D.

4.1 Decision to keep or remove the device in the last stage

The last stage captures the decision by the firms to keep or remove the device knowing whether innovation was a success or not. There are four possible states of the world. If we let S denote success and F failure, and the vector $O = (O_1, O_2)$ denotes the outcomes reached whereby $O_i \in \{S, F\}$. Specifically, the states of the world are (S, S), (S, F), (F, S), and (F, F). For instance, and to be clear, the state (S, F) refers to a state where firm 1 innovates and firm 2 fails to do so. In each possible state of the world, we find the equilibrium of the non-cooperative game and we reach the following first result.

Lemma 1: *In each state of the world there is a dominant strategy equilibrium that emerges characterized as follows. In states where firm* i *innovates, it removes the device if and only if* $(1-\gamma)F - \gamma c_i \geq 0$. *In states where firm* i *fails to innovate, it removes the device if and only if* $(1-\gamma)F - \gamma(c_i + d_i) - \gamma\Delta\pi \geq 0$. *When the firm is certain that the device can never be found, that is when* $\gamma = 1$, *it systematically keeps it.*

Proof: See Appendix 3.

Firm *i's* decision to keep or remove the device after it has succeeded or failed to innovate is independent of firm *j's* cost of compliance losses because we consider that, at this stage these costs have no further impact in terms of what each firm stands to gain or lose, that is on $\Delta\pi$. When $\gamma < 1$ and there is a chance that the device will be found, and three possible outcomes arise when the penalty fee is sufficiently large $(1-\gamma)F - \gamma\Delta\pi > 0$ while only two possible outcomes arise otherwise as depicted in figures 1 and 2 below.

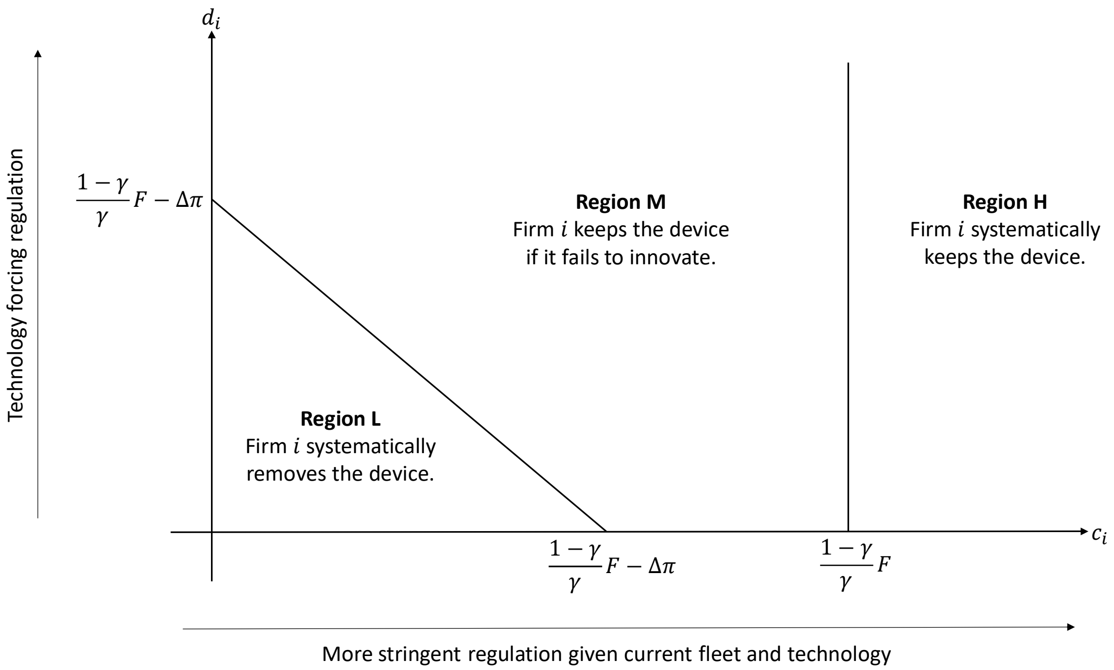


Figure 1: The last stage decision when $(1-\gamma)F - \gamma\Delta\pi > 0$.

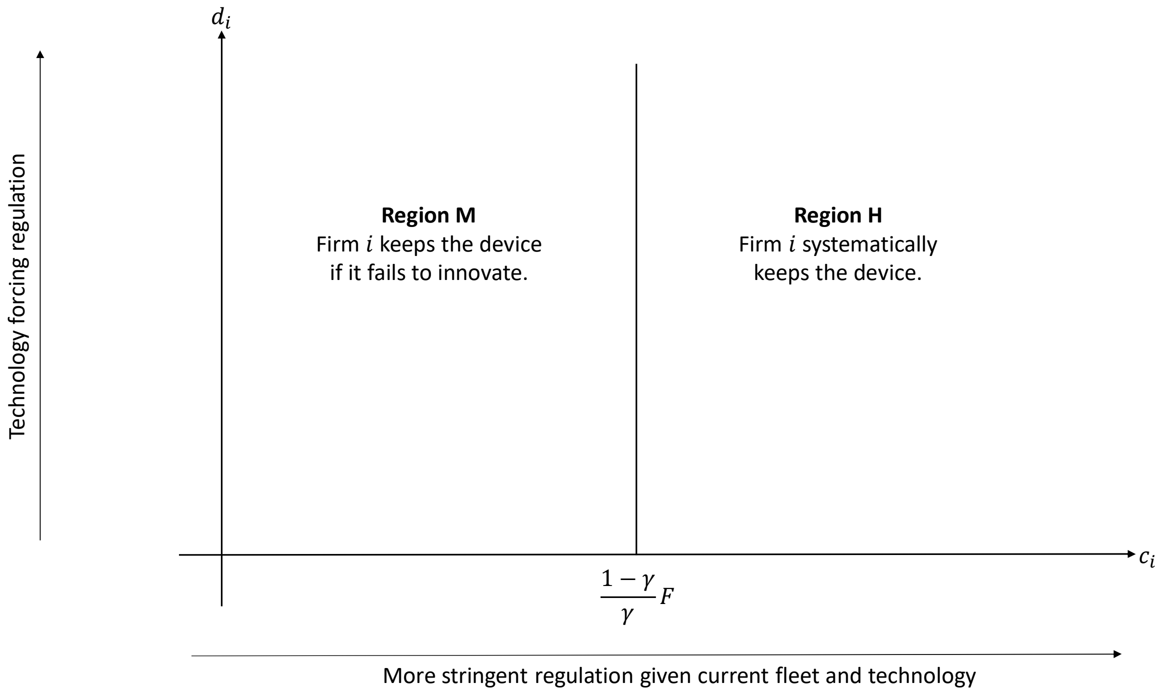


Figure 2: The last stage decision when $(1-\gamma)F - \gamma\Delta\pi \leq 0$.

Region H reflects a situation where the regulation is stringent and, thereby, associated with high, non-avoidable, compliance losses. Region M reflects situations where the regulation is moderately stringent and the non-avoidable compliance losses are capped. However, region M allows for regulations that are technology forcing and, thus, associated with high avoidable losses d_i ($i = 1,2$). Finally, when $(1-\gamma)F - \gamma\Delta\pi > 0$, region L captures cases where the regulation has a low level of stringency and is not technology forcing. It is clear from the figures 1 and 2 that a manufacturer is more likely to remove the cheating device, and therefore truly comply, when the non-avoidable compliance losses are sufficiently low.

As competitive pressures intensify and $\Delta\pi$ increases, region L vanishes meaning that the firm is more inclined to rely on the device. Increments in d_i impact the firm's decision only when, following the increment, the firm's compliance costs shift from region L to region M. Increments in c_i can have more substantial implications. In particular, they can lead a firm to keep the device regardless of the outcome in innovation if, following the increment in c_i, the firm's compliance costs shift from region M to region H.

4.2 Optimal investments

Perfectly anticipating its commitment to keep or remove the device, the manufacturers decide simultaneously and non-cooperatively how much to devote to innovation.

Lemma 2: *Firm i's optimal level of investment only depends on what it intends to do with the device. It does not depend upon the rival's decision in the last stage.*

When the firm intends to keep the device, it invests an amount I_i^H *defined such that*

$$\frac{\partial P}{\partial I_i}[(1-\gamma)(d_i + \Delta\pi)] - 1 = 0. \quad (1)$$

When the firm intends to keep the device only when it fails to innovate, it invests an amount I_i^M *defined such that*

$$\frac{\partial P}{\partial I_i}[(1-\gamma)(d_i + F + \Delta\pi) - \gamma c_i] - 1 = 0. \quad (2)$$

Finally, when the firm intends to remove its device systematically, it invests an amount I_i^L *defined such that*

$$\frac{\partial P}{\partial I_i}(d_i + \Delta\pi) - 1 = 0. \quad (3)$$

Proof: See Appendix 4.

The absence of any strategic dimension is due to the fact that the benefits that accrue to a firm when innovating do not depend on what its rival does with its own device. This outcome arises because we consider that firms are subjected to the same monitoring structure as we consider that the variable γ is not idiosyncratic.

The investment in innovation influences the likelihood of avoiding part of the compliance losses. Without any device or when the firm intends to keep it regardless of the outcome of innovation, the unavoidable compliance losses and penalty incurred when caught cheating, have no impact on the investment. In these cases, the firm either faces these compliance losses or, when it keeps the device, incurs one or the other depending on whether the device is found, irrespectively of the outcome of innovation. When the firm commits to remove the device if and only if it innovates, both the unavoidable compliance losses and penalty incurred when caught cheating, impact investment. The overall comparative statics are described below.

Lemma 3: *The optimal level of investment is continuous with respect to all exogenous variables. It is non-increasing in c_i and γ. It is increasing in θ_i, d_i, F and $\Delta\pi$.*

Proof: See Appendix 5.

It is clear from equations (1),(2) and (3) that under a better monitoring system (meaning that $\gamma \to 0$) and/or under greater competitive pressures, investments in innovation rise.

As argued above, the unavoidable losses, c_i have an adverse impact on the investment only when the firm intends to remove the device if it innovates (region M). Within that region, as the policy becomes more stringent and c_i increases the firm lowers its investment because it prefers to rely on the device to address compliance. Within region M, for any given d_i, investment is at its lowest level when we reach the border with region H. Then, within region H, further increments in stringency have no impact on the level of investment.

By opposition, for any given firm and any given of non-avoidable losses c_i, the level of investment rises as the policy becomes more technology forcing which is very intuitive. Thus, while the two parameters, c_i and d_i measure compliance losses, they exert countervailing forces on the investment decision.

Since the firm is increasingly determined to keep the cheating device as c_i increases, one could argue that a commitment to rely on cheating device and investment strategies are substitutes. This conclusion is somehow flawed.

We illustrate this point considering 3 car manufacturers (T, F, W) and using the specific expression for the probability of successfully innovating $P(\theta, I) = \theta \ln I$.

Assume that the three firms have the same innovative ability $\theta_T = \theta_F = \theta_W = 1$ but that their fleets are very different. Assume that T's fleet relies mostly on hybrid technology, F's fleet relies mostly on petrol engines and, finally, W's fleet relies mainly on diesel engines. Assume that the regulation requires that all firms reduce their Nitrogen Oxide emissions to the same level. Given the disparity in their fleets, their compliances losses are likely to be in different regions as depicted in figure 3 below.

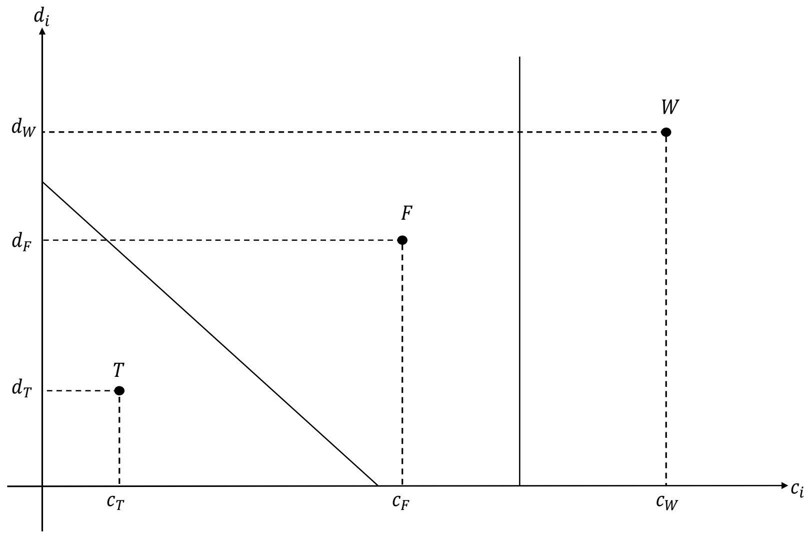


Figure 3: T, F and W's compliance losses following a requirement to reduce NOx emissions.

Using (1), (2) and (3) we can establish that their investments in innovation are given by

$$I_W = (1-\gamma)(d_W + \Delta\pi), I_F = (1-\gamma)(d_F + \Delta\pi + F) - \gamma c_F, I_T = (d_T + \Delta\pi).$$

Assuming that $\gamma = \frac{1}{2}$ and that $\Delta\pi$ is capped so the three regions exist, firm W invests more (not less) than its opponents provided

$$(d_W - d_F) > F - c_F > 0, \text{and } d_W - 2d_T > \Delta\pi.$$

Therefore, compared to a firm in region M, and one in region L, a firm in region H will invest more in innovation provided its avoidable losses are large enough relative to that of its rivals.

- **Policy implications**

In a context where firms have heterogenous fleets, uniform regulatory policies that generate disparate compliance losses among firms, will have an unpredictable impact on the investments that these undertake. The firm for whom the policy is the most stringent could be the one undertaking the largest investment. Attribute based policy, which tend to even out compliance losses, have a more predictable impact whereby the firm for whom the policy is most stringent is more likely to rely on a cheating device and invest less in innovation. If, however, the avoidable and non-avoidable losses c_i and d_i are negatively correlated then a policy that makes compliance based on the firm's existing technology costly (large c_i) will deter investment.

Finally, policies that generate very large non-avoidable losses, pushing all firms further in region H generate an unambiguous loss in welfare as they will not alter any of the firms' decisions.

5. Initial cheating decision

In this section we solve for the sub-game perfect Nash equilibrium focusing on initial decision to install a device. Sub-game perfection allows us to focus on situations where the firms perfectly anticipate the future moves that it will take as well as those of its rival.

We proceed as follows. We start by defining the strategies that the firms can use. Then, since Nash equilibria are such that each firm is on its best-reply to the opponent's strategy, our second step characterises the best-reply strategies. Finally, we solve for the equilibria.

5.1 Characterisation of the strategies.

At this stage of the game, each firm may adopt three strategies which we denote NC, CH and CM.

The first strategy, $s_i = NC$ consists of a decision not to install the device. No matter what compliance losses it will face, when it does not install a device a firm's optimal subsequent investment strategy is given by I_i^L which satisfies (3). Indeed, when it does not install the device, the firm is in a similar situation as the one it faces when it removes it systematically. Therefore, strategy $s_i = NC$ is understood as "*Not cheating and investing I_i^L*", and the level of profits that the firm gathers in this case are given by

$$\Pi_i^{NC}(\theta_i) = \pi - (c_i + d_i) + P(\theta_i, I_i^L)(d_i + \Delta\pi) - P\left(\theta_j, I_j^r\right)\Delta\pi - I_i^L. \tag{4}$$

The strategies CH and CM refer to situations where a cheating device is installed. However, they differ in the subsequent investment decision which are rationally based on their commitment to keep or remove the device.

The strategy $s_i = CH$ is a decision to "*Cheat, invest I_i^H, and keep the device*". In such a case, the profits gathered by the firm are

$$\begin{aligned}\Pi_i^{CH}(\theta_i) = \pi - (1-\gamma)(c_i + d_i + F) + P(\theta_i, I_i^H)(1-\gamma)(\Delta\pi + d_i) \\ -P\left(\theta_j, I_j^r\right)(1-\gamma)\Delta\pi - I_i^H.\end{aligned} \tag{5}$$

The strategy $s_i = CM$ is a decision to "*Cheat, invest I_i^M, and remove the device if innovation is successful*". In such a case, the profits gathered by the firm are

$$\begin{aligned}\Pi_i^{CM}(\theta_i) = \pi - (1-\gamma)(c_i + d_i + F) + P(\theta_i, I_i^M)[(1-\gamma)(d_i + F + \Delta\pi) - \gamma c_i] \\ -P\left(\theta_j, I_j^r\right)(1-\gamma)\Delta\pi - I_i^M.\end{aligned} \tag{6}$$

As we characterize subgame perfect equilibriums, the elimination of non-credible threats enables us to make the following three claims.

- **Claim 1:** A firm with losses in region L perfectly anticipates that it will systematically get rid of the device. Therefore, it does not have any strategic decision to take initially since it has no interest in installing a device. Instead, it relies on strategy NC regardless of its opponent's strategy.
- **Claim 2:** A firm facing a rival with compliance losses in region H anticipates that, initially, the rival will either select strategy NC or strategy CH. Indeed, if it decides to install a device initially, the rival's profit maximizing strategy consists in keeping the device making strategy CM non-credible.
- **Claim 3:** A firm facing a rival with compliance losses in region M anticipates that, initially, the rival will either select strategy NC or strategy CM. Indeed, if it decides to install a device initially, the rival's profit maximizing strategy consists in keeping the device only if it fails to innovate making strategy CH non-credible.

5.2 Characterisation of the best-reply strategies.

The question we answer here is whether a firm who may rely on the device after the innovation process, decides to install one given the strategy of its rival? Following claim 1, we focus on a firm with compliance losses in regions H or M as a firm with compliance losses in region L has no strategic decision to make initially.

To simplify the analysis, we make an additional assumption concerning the probability function $P(\theta, I)$.

Assumption (vi): The function $P(\theta, I)$ is such that $P(0, I) = 0$ and such that the optimal investments satisfy $I_i^r > 0$ for all $\theta > 0$ and $I_i^r \to 0$ at $\theta \to 0$.[7]

Let the variable $P_j \equiv P(\theta_j, I_j^r)$ be the probability of success of firm j given its type and investment strategy. Proposition 1, below, shows that the decision to install a cheating device depends on θ_i.

Proposition 1: *Consider any possible strategy that firm j may adopt, $s_j \in \{NC, CH, CM\}$. Firm i's best-reply strategies are described as follow.*

- *When its compliance losses are in region H and it plans to keep the defeat device there exists threshold values $\theta_{iH}^*(\theta_j, s_j)$ such that firm i installs a defeat device if and only if $\theta_i < \theta_{iH}^*(\theta_j, s_j)$.*
- *When its compliance losses are in region M and it plans to remove the device subject to innovating, and when compliance costs are low enough so that*
$$\frac{(1-\gamma)}{\gamma}F - \Delta\pi \leq (c_i + d_i) \leq \frac{(1-\gamma)}{\gamma}F - P_j\Delta\pi,$$
then firm i does not install the device whatever its type.
- *When its compliance losses are in region M and it plans to remove the device subject to innovating, and when compliance costs are sufficiently large so that*

[7] Note that this assumption is satisfied when considering a functional form $P(\theta, I) = \theta h(I)$ where the function $h(I)$ is increasing and concave and such that the remaining assumptions stated in the model are satisfied.

$$\frac{(1-\gamma)}{\gamma}F - P_j\Delta\pi \leq (c_i + d_i) \text{ and } c_i < \frac{(1-\gamma)}{\gamma}F,$$

there exists threshold values $\theta_{iM}^*(\theta_j, s_j)$ such that firm i installs a defeat device if and only if $\theta_i < \theta_{iM}^*(\theta_j, s_j)$.

Proof: See Appendix 6**.** Note that, given the assumption (vi), the level of profits when the firm has a type equal to zero, and therefore does not invest in innovation, are given by

$$\Pi_i^{NC}(0) = \pi - (c_i + d_i) - P_j\Delta\pi, \tag{7}$$

$$\Pi_i^{CM}(0) = \pi - (1-\gamma)(c_i + d_i + F) - P_j(1-\gamma)\Delta\pi, \tag{8}$$

Therefore

$$\Pi_i^{CM}(0) \geq \Pi_i^{NC}(0) \Leftrightarrow \frac{(1-\gamma)}{\gamma}F - P_j\Delta\pi \leq (c_i + d_i). \tag{9}$$

Broadly speaking, a firm installs a cheating device when it has a low type meaning that it fears it will not be able to innovate. What is interesting is the fact that the decision to behave honestly extends slightly beyond region L. For compliance losses in region M but close to the border separating M from L the firm will behave honestly even if it has a zero chance of innovating.

Figure 4, below, provides a visual representation of the best-reply strategies depicted in Proposition 1.

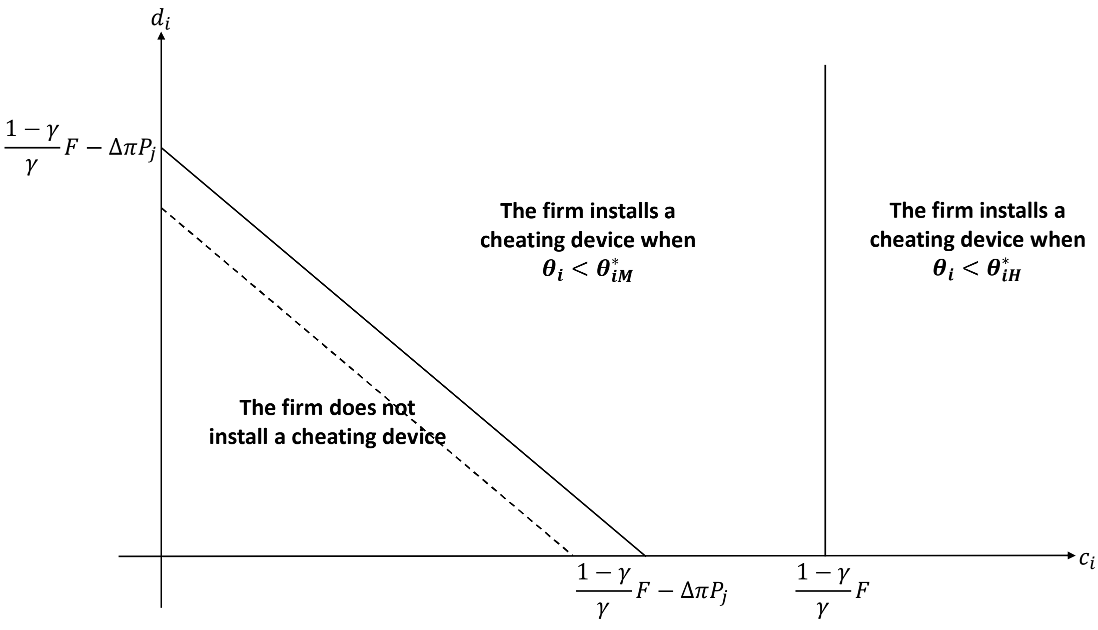


Figure 4: Representation of firm i's best-reply based on its compliance losses. The dotted line represents the limitation of region L.

The width of the area, within region M, within which the firm is behaving honestly is equal to $\Delta\pi\left(1-P_j\right)$. It is wider as firm j is more likely not to innovate and/or when $\Delta\pi$ is large. This suggests that a firm gives more weight to investing as opposed to cheating, when it believes its rival is unlikely to innovate and when it has much to gain by increasing its market share. More importantly, it shows that the decision not to install a device can also be understood as a commitment to invest a larger amount in innovation.

Using the implicit function theorem one can show that the functions $\theta_{iH}^*\left(\theta_j,s_j\right)$ and $\theta_{iM}^*\left(\theta_j,s_j\right)$ are increasing in θ_j as, for any $r\in\{L,M,H\}$, we have

$$\frac{d\theta_{iH}^*\left(\theta_j,s_j\right)}{d\theta_j}=\frac{\gamma\Delta\pi P_\theta\left(\theta_j,I_j^r\right)}{(d_i+\Delta\pi)[P_\theta(\theta_{iH}^*,I_i^L)-(1-\gamma)P_\theta(\theta_{iH}^*,I_i^H)]}\geq 0, \tag{10}$$

$$\frac{d\theta_{iM}^*\left(\theta_j,s_j\right)}{d\theta_j}=\frac{\gamma\Delta\pi P_\theta\left(\theta_j,I_j^r\right)}{(d_i+\Delta\pi)P_\theta(\theta_{iM}^*,I_i^L)-[(1-\gamma)(d_i+F+\Delta\pi)-\gamma c_i]P_\theta(\theta_{iM}^*,I_i^M)}\geq 0. \tag{11}$$

When a firm faces a competitor that is very skilled at innovating, it dampens its incentive to be honest. It is important to note that this is conditional on $\Delta\pi>0$, meaning that the extent to which this initial decision is interdependent and strategic depends on the presence of competitive pressures.

5.3 Representation of the best-reply strategies.

Without any loss in generalities, let us focus on firm 1 with compliance losses in region $r\in\{H,M\}$. Firm 1's best-reply depends on how θ_1 compares to the threshold $\theta_{1r}^*(\theta_2,NC)$ when $s_2=NC$ and on how θ_1 compares to $\theta_{1r}^*(\theta_2,Cr')$ when $s_2=Cr'$ and firm 2 has compliance losses in region $r'\in\{M,H\}$. The threshold values differ based on the region in which (c_1,d_1) belongs to and on the strategy adopted by the rival firm which only accounts for credible investment strategies. Thus, all in all, we have six different thresholds but firm 1's best reply is based on comparing at most two of these thresholds.

In Appendix 6, we show that the threshold value that prevails when firm 1 has compliance losses in region H, that is $\theta_{1H}^*(\theta_2,s_2)$ is the value for θ_1 which solves the following identity

$$\begin{aligned}(1-\gamma)F-\gamma(c_1+d_1)+(d_1+\Delta\pi)[P(\theta_1,I_1^L)-(1-\gamma)P(\theta_1,I_1^H)]\\ +I_1^H-I_1^L\equiv\gamma\Delta\pi P(\theta_2,s_2).\end{aligned} \tag{12}$$

In that same Appendix we show that threshold value that prevails when firm 1 has compliance losses in region M, that is $\theta_{1M}^*(\theta_2,s_2)$ is the value for θ_1 which solves the following identity

$$\begin{aligned}(1-\gamma)F-\gamma(c_1+d_1)+(d_1+\Delta\pi)P(\theta_1,I_1^L)\\ -[(1-\gamma)(d_1+F+\Delta\pi)-\gamma c_1]P(\theta_1,I_1^M)\\ +I_i^M-I_i^L\equiv\gamma\Delta\pi P(\theta_2,s_2).\end{aligned} \tag{13}$$

Table 1, below, indicates the strategies that the firms can adopt and which of the six thresholds each must consider in all possible scenarios as we ignore non-credible threats.

	$(\boldsymbol{c_2}, \boldsymbol{d_2}) \in \boldsymbol{L}$	$(\boldsymbol{c_2}, \boldsymbol{d_2}) \in \boldsymbol{M}$	$(\boldsymbol{c_2}, \boldsymbol{d_2}) \in \boldsymbol{H}$
$(\boldsymbol{c_1}, \boldsymbol{d_1}) \in \boldsymbol{L}$	$s_1 = s_2 = NC$	$s_1 = NC$ $s_2 \in \{NC, CM\}$ based on $\theta^*_{2M}(\theta_1, NC)$	$s_1 = NC$ $s_2 \in \{NC, CH\}$ based on $\theta^*_{2H}(\theta_1, NC)$
$(\boldsymbol{c_1}, \boldsymbol{d_1}) \in \boldsymbol{M}$	$s_2 = NC$ $s_1 \in \{NC, CM\}$ based on $\theta^*_{1M}(\theta_1, NC)$	For $i = 1{,}2$, $s_i \in \{NC, CM\}$ based on $\theta^*_{iM}(\theta_j, NC)$ and on $\theta^*_{iM}(\theta_j, CM)$	$s_1 \in \{NC, CM\}$ based on $\theta^*_{1M}(\theta_2, NC)$ and on $\theta^*_{1M}(\theta_2, CH)$ $s_2 \in \{NC, CH\}$ based on $\theta^*_{2H}(\theta_1, NC)$ and on $\theta^*_{2H}(\theta_1, CM)$
$(\boldsymbol{c_1}, \boldsymbol{d_1}) \in \boldsymbol{H}$	$s_2 = NC$ $s_1 \in \{NC, CM\}$ based on $\theta^*_{1H}(\theta_1, NC)$	$s_1 \in \{NC, CH\}$ based on $\theta^*_{1H}(\theta_2, NC)$ and on $\theta^*_{1H}(\theta_2, CM)$ $s_2 \in \{NC, CM\}$ based on $\theta^*_{2M}(\theta_1, NC)$ and on $\theta^*_{2M}(\theta_1, CH)$	For $i = 1{,}2$, $s_i \in \{NC, CH\}$ based on $\theta^*_{iH}(\theta_j, NC)$ and on $\theta^*_{iH}(\theta_j, CH)$

Table 1: *Relevant strategies in all possible scenarios*

Considering (12) and (13), notice that when $\theta_2 = 0$, and firm 2 has no ability to innovate $P(0, s_2) = 0$, the threshold guiding firm 1's decision is the same, regardless of its rival strategy so that $\theta^*_{1r}(0, CH) = \theta^*_{1r}(0, CM) = \theta^*_{1r}(0, NC), r \in \{H, M\}$.

Notice furthermore that, at $\theta_2 = 0$, we necessarily have $\theta^*_{1r}(0, s_2) > 0$. Indeed, identities (12) and (13) can be reduced to $(1 - \gamma)F - \gamma(c_1 + d_1)$ when $\theta_2 = \theta_1 = 0$. This expression is negative when firm 1 has compliance losses in region *H* or *M.* This means that firm 1 is better-off installing a defeat device when $\theta_1 = \theta_2 = 0$. As the left-hand side of either identity is increasing in θ_1, firm 1 becomes indifferent between installing the device or not doing so when $\theta_2 = 0$ provided it has a strictly positive type .

Using (10) and (11) we can analyse how the thresholds compare to each other as θ_2 increases. For any given compliance losses that it may face, when firm 2 installs a device, it invests less subsequently.[8] Thus, said differently, we have $I_2^H \leq I_2^L$ and $I_2^M \leq I_2^L$. Since

[8] This assertion is correct as we are comparing investments for any fixed given values of d_2 and c_2.

$P_I > 0$ and $P_{\theta I} > 0$, we have, for any given θ_2, $P_\theta\left(\theta_2, I_2^{r'}\right) \leq P_\theta(\theta_2, I_2^L)$. Therefore, for any $r' \in \{M, H\}$ expressions (10) and (11) are such that we have

$$\frac{d\theta_{1Cr}^*(\theta_2, NC)}{d\theta_2} > \frac{d\theta_{1C}^* \ (\theta_2, Cr')}{d\theta_2}.$$

This analysis gives rise to the best replies which are represented in figure 5 below.

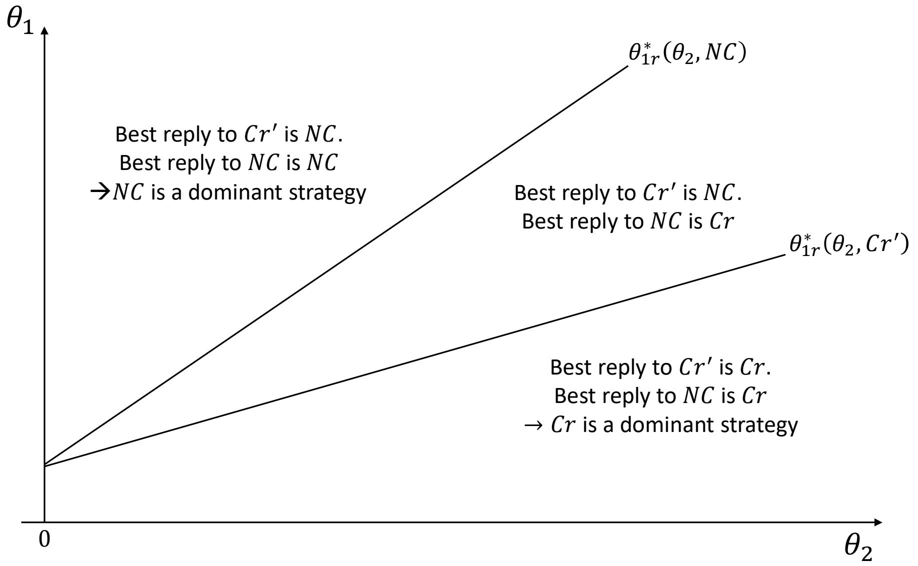


Figure 5: Firm 1's best-reply strategies to firm 2 based on its type.

5.4 Characterisation of the equilibrium.

Given the best reply-functions, we can now describe the equilibriums. We consider separately the cases where $\Delta\pi = 0$ and where $\Delta\pi > 0$.

- **Characterization of the equilibrium when $\boldsymbol{\Delta\pi} = 0$.**

Considering (12) and (13), notice that when $\Delta\pi = 0$, firm 1's threshold values are not dependent on θ_2. More generally, as per (10) and (11), we have

$$\frac{d\theta_{iH}^*\left(\theta_j, s_j\right)}{d\theta_j} = \frac{d\theta_{iM}^*\left(\theta_j, s_j\right)}{d\theta_j} = 0.$$

Therefore, when $\Delta\pi = 0$, the functions $\theta_{ir}^*\left(\theta_j, NC\right)$ and $\theta_{ir}^*\left(\theta_j, Cr'\right)$ in figure 5 become flat lines and each firm has a dominant strategy which consists in installing the device when its type is low.

In that situation, the number of thresholds is reduced to four. Let $\theta_{ir}^* \in \{\theta_{1H}^*, \theta_{1M}^*, \theta_{2H}^*, \theta_{2M}^*\}$ denote the unique threshold that firm i must take into consideration to decide whether to respond to its rival by installing a defeat device or not.

Proposition 2 below fully characterizes the equilibriums that emerge in this case.

Proposition 2: *When there are no competitive pressures to be made ($\Delta\pi = 0$) there are several equilibria characterizing the initial cheating decision, all are in dominant strategies.*

1. *When both firms have low compliance losses located in region L, they do not install a cheating device, and this forms the unique equilibrium.*
2. *When firm i has compliance losses (c_i, d_i) is in region L while firm j has larger compliance losses (c_j, d_j) is in region M or H, there are two dominant strategies equilibriums. In each of these firm i does not install a device and firm j installs one if and only if $\theta_j < \theta_{jr}^*$ $(r = M, H)$.*
3. *Finally, when neither of the firms has compliance losses in region L, four dominant strategy equilibriums arise depending on their ability to innovate as depicted in the graph below.*

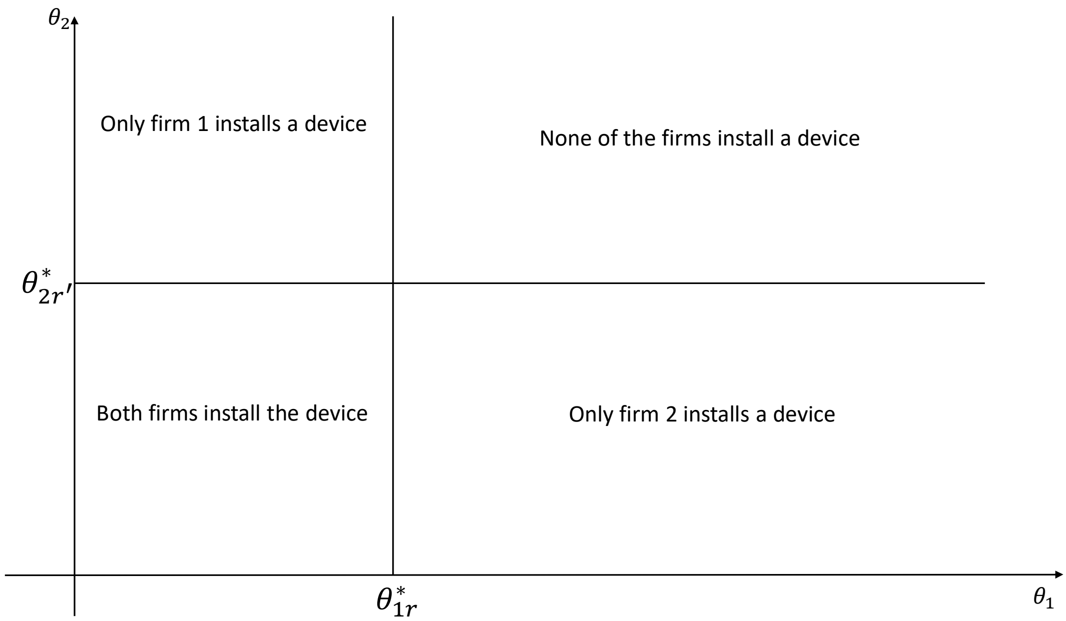


Figure 6: Depicts the Nash equilibriums when $\Delta\pi = 0$, $(c_i, d_i) \in r$, $(c_j, d_j) \in r'$ and r and $r' \in \{H, M\}$.

Proof: Point 1 is obvious. Point 2 results from the fact that firm i has no interest in installing a device when its losses are in region L while firm j opts for its best-reply strategy which depends on whether its type is above or below θ_{ir}^* , $r = H, M$. Finally, both firms use their dominant strategy indicated in figure 6 when neither of the firms has losses in region L which consists in cheating when their type is below θ_{iCr}^* , $r = H, M$.■

In terms of welfare, the equilibriums reached when $\Delta\pi = 0$ share an important characteristic.

Lemma 4: *In equilibrium the sum of profits is maximised.*

Proof: In our model $\Delta\pi$ is a transfer from one manufacturer to the other and it cancels out when considering total profits. Moreover, and as mentioned above, the equilibriums reached when $\Delta\pi = 0$ are in dominant strategies, hence total profits are maximised in equilibrium since each manufacturer is selecting what is best regardless of the strategy used by its opponent.

- **Characterization of the equilibrium when $\boldsymbol{\Delta\pi > 0}$.**

For obvious reasons, it is still the case that both firms behave honestly when they have compliance losses in region L. This forms the unique equilibrium.

When firm i has compliance losses in region L while the other faces larger compliance losses (so (c_i, d_i) is in region L and (c_j, d_j) is in region M or H), two dominant strategies equilibriums emerge. In each of these firm i does not install a device and firm j does so provided $\theta_j < \theta^*_{jr}(\theta_i, NC)$ $(r = M, H)$.

Let us now focus on the situation where neither of the firms have compliance losses in region L. As argued above, when $\Delta\pi > 0$, the slopes of the threshold values are non-zero as we have $\frac{d\theta^*_{ir}(\theta_j, s_j)}{d\theta_j} > 0$. Therefore, the best reply functions are now dependent on the rival's type and the decision to install a device becomes strategic.

Proposition 3: *Several equilibriums emerge when considering the initial decision to install a device when firm 1 when it has compliance losses in region $r \in \{H, M\}$ and firm 2 has compliance losses in region $r' \in \{H, M\}$.*

- *When $\theta_1 \leq \theta^*_{1r}(\theta_2, Cr')$ and $\theta_2 \leq \theta^*_{2r}(\theta_1, Cr)$, installing the cheating device forms a dominant strategy equilibrium (region A in the graph).*
- *When $\theta_1 \geq \theta^*_{1r}(\theta_2, NC)$ and $\theta_2 \geq \theta^*_{2r}(\theta_1, NC)$, acting honestly forms a dominant strategy equilibrium (region C in the graph).*
- *When θ_2 is large relative to θ_1 (dark grey region in the graph) only firm 1 installs a cheating device.*
- *When θ_1 is large relative to θ_2 (light grey region in the graph) only firm 2 installs a cheating device.*
- *Finally, there exists a region (B in the graph) where two Nash equilibria co-exist wherein firms do not coordinate, and one acts honestly while the other installs a device.*

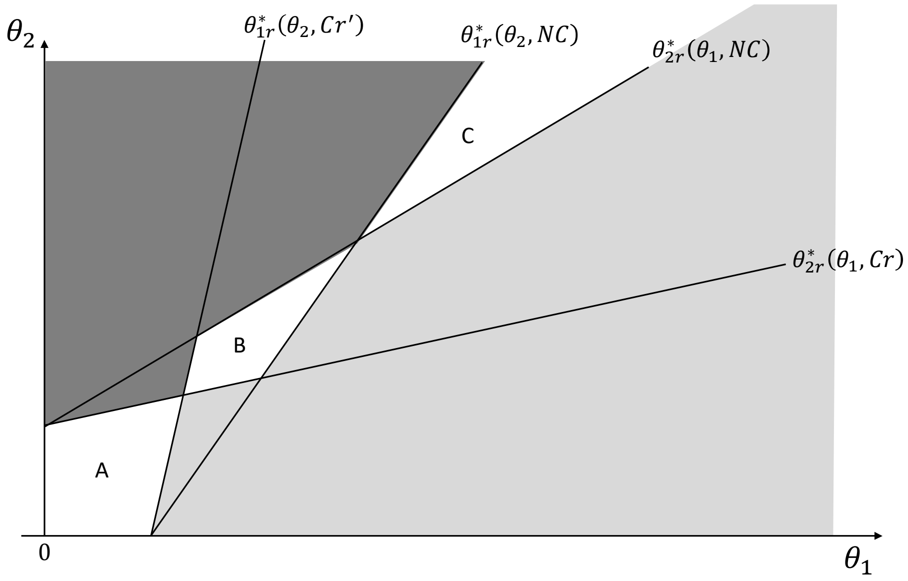


Figure 7: The initial cheating decision.

Proof: The above is done bringing together the best reply functions

In the presence of competitive pressures, the region where both firms are acting honestly shrinks and more cheating occurs. The regions where only one of the firms is honest expand as well. Thus, all in all, competitive pressures lead to more cheating. More importantly, within the region highlighted in figure 7 below, the dominant strategy equilibrium leads firms to cheat when $\Delta\pi > 0$, while being honest would generate higher profits overall. Said differently, in such a case, cheating forms a dominant strategy equilibrium that is similar to the one arising in the "prisoner's dilemma" whereby firms end up in a sub-optimal situation.

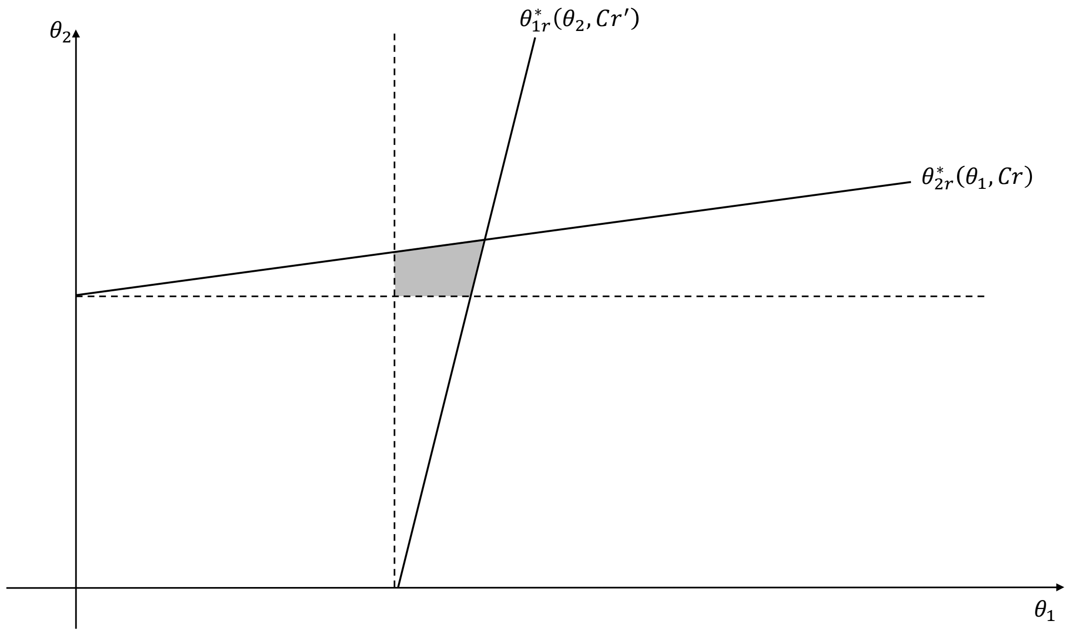


Figure 7: In the grey area cheating forms a dominant strategy equilibrium when both firms would be better-off being honest.

6. Comparative statics and policy implications

In this section we conduct some comparative statics for the threshold values $\theta^*_{iCH}(\theta_j, s_j)$ and $\theta^*_{iCM}(\theta_j, s_j)$ in order to understand how the decision to install a device is influenced by firm's losses (c_i and d_i), the probability of not being caught (γ), and the penalty (F). The exact expressions for the derivatives can be found in Appendix 7. It is important to keep in mind that an increase in the threshold values means that cheating occurs for a wider range of the parameter θ. In what follows recall that $P_j \equiv P(\theta_j, I_j^{r'})$ where r' is the region in which firm j' compliance losses are located.

We discussed in Section 5 the role played by the competitive pressure. We focus here on the other parameters.

- **Policy implications concerning the variables F and γ.**

The thresholds decrease with respect to the penalty F incurred when the firm is caught cheating:

$$\frac{d\theta^*_{ir}(\theta_j, s_j)}{dF} < 0, r = H, M.$$

On figure 7 the area labelled C, where the decision not to install a device forms a dominant strategy, becomes wider as F increases. Thus, and as one would expect, a higher penalty discourages cheating.

Perhaps surprisingly, it is less straightforward to conclude whether a higher probability of not being caught encourages or discourages cheating. The impact of γ depends on the sign of following expressions:

$$\text{sign of } \frac{d\theta_{iH}^*(\theta_j, s_j)}{d\gamma} = \text{sign of}\left[\, c_i + F + d_i\left(1 - P_i(\theta_{iH}^*, I_i^H)\right) + \Delta\pi\left(P_j - P_i(\theta_{iH}^*, I_i^H)\right)\right] \quad (14)$$

and

$$\text{sign of } \frac{d\theta_{iM}^*(\theta_j, s_j)}{d\gamma} = \text{sign of}\left[\, (c_i + d_i + F)\left(1 - P_i(\theta_{iM}^*, I_i^M)\right) + \Delta\pi\left(P_j - P_i(\theta_{iM}^*, I_i^M)\right)\right]. \quad (15)$$

The right-hand side of (14) and that of (15) captures the device's value added subject to not being found. Thanks to the device, the firm avoids facing losses d_i that it incurs when it fails to innovate. The extent to which it avoids facing the losses $(c_i + F)$ depends on whether it relies on the device post-innovation or not. To these benefits one must add $\Delta\pi$ which the firm could lose to its rival if neither firm installs a device, and the latter is more likely to innovate. When the overall added value is non-negative, an increase in γ will promote cheating.

However, the expressions above highlight an interesting phenomenon that occurs when $\Delta\pi\left(P_j - P_i(\theta_{ir}^*, I_i^r)\right)$ is large and negative. As the likelihood of being caught vanishes, the firms forgo the possibility to increase their market shares if they both install a defeat device. Indeed, in the extreme case where $\gamma = 1$, all firms appear to be compliant and market shares become static. Therefore, when $\Delta\pi$ is large an incentive to behave honestly emerges for the firm that is more likely to innovate. The decision not to install a device is guided by a desire to focus on innovation in the hope to expand market share and grab the large gains that we label $\Delta\pi$. By selecting strategy NC, the firm also commits to investing a higher amount. Hence a laxer monitoring policy may lead a firm to refrain from cheating and focus on innovation. If, however, a firm knows that its rival is more likely to innovate, the benefit of installing the device is increased and the incentive to do so is strengthen.

Policy implication 1: *An increase in the penalty will deter cheating. Better monitoring capabilities will generally deter cheating as well. However, when competitive pressures are such that $\Delta\pi$ is large, a firm that has a greater ability to innovate can be less tempted to install a device under weaker monitoring. The possibility to increase its market share incentivises the firm to rely on innovation more so than a cheating device.*

- **Policy implications concerning compliance losses.**

Keeping all the other parameters constant, we find that the threshold values are increasing with the compliance costs c_i:

$$\frac{d\theta_{ir}^{*}(\theta_j, s_j)}{dc_i} > 0, r = H, M.$$

A more stringent policy, associated with higher non-avoidable compliance losses, encourages the firms to install a cheating device prior to investing in innovation.

By opposition, an increase in the opponent's non-avoidable compliance losses c_j will either have no impact (when the firm's rival has losses in region H) or it will deter cheating by depressing the rival's investment decision.

Policy implication 2: *When a regulatory rule increases firm i's non-avoidable compliance losses, while all other parameters remain constant, it incentivises firm i to cheat and deters firm j from doing so when the latter anticipates that firm i will reduce its investment in innovation.*

Keeping all the other parameters constant, we show that the impact of the variable d_i is not obvious:

$$\text{sign of } \frac{d\theta_{iH}^{*}(\theta_j, s_j)}{dd_i} = \text{sign of}\left[\gamma\left(1 - P_i(\theta_{iCH}^{*}, I_i^H)\right) + P_i(\theta_{iCH}^{*}, I_i^H) - P_i(\theta_{iCH}^{*}, I_i^L)\right] \quad (16)$$

and

$$\text{sign of } \frac{d\theta_{iM}^{*}(\theta_j, s_j)}{dd_i} = \text{sign of}\left[\gamma\left(1 - P_i(\theta_{iCM}^{*}, I_i^M)\right) - P_i(\theta_{iCM}^{*}, I_i^L)\right] \quad (17)$$

Once again, the right-hand sides of expressions (16) and (17) capture the value added of a defeat device following a marginal increase in d_i. The first term of the expressions on the right-hand side, namely the expression $\gamma\left(1 - P_i(\theta_{iCr}^{*}, I_i^r)\right)$ represents the marginal gains that arise when the firm fails to innovate and relies on the device to avoid losing the increment in d_i. These only materialize when the firm is not caught cheating. When the firm commits to keep the device post innovation these gains also arise when it innovates and, in this case, they are not dependent on being caught or not. The last term captures the more subtle losses that arise. When the firm installs a device it will lower its investment, thereby reducing the probability of avoiding the increment in d_i.

When γ is small enough, meaning that the firms operate under high scrutiny, a more policy that leads to higher avoidable losses will lead to greater honesty because the firms must rely on innovation to avoid facing the losses d_i. (Indeed, both derivatives are negative at $\gamma = 0$.)

As γ increases and converges to 1, the value added of a defeat device increases. Expression (16) is positive at $\gamma = 1$ meaning that a firm with compliance losses in region H is more tempted to cheat when each of the compliance losses increase. The sign of expression (17) is not clear. This is because cheating devices have a lesser value when the firm plans to remove it post-innovation. Therefore, the firm could be more tempted to avoid these and rely more on innovation as d_i increases.

Finally, an increase in d_j promotes cheating as it increases the value of the threshold via a stimulation of the rival's investment.

Policy implication 3: *When a regulatory rule increases firm i's avoidable compliance losses, while all other parameters remain constant, it incentivises its rival to cheat as the latter anticipates that firm i will increase its investment in innovation. Firm i will, by opposition, refrain from cheating when it operates under strict monitoring rules. When monitoring rules become laxer, firm i may be incentivised to cheat especially if it faces large non-avoidable compliance losses.*

7. Conclusion

This paper considers automobile manufacturers who must comply with emission standards. True compliance is associated with some idiosyncratic losses which also depend on the extent to which the regulation is stringent and the extent to which it is technology forcing. Manufacturers invest in innovation to address compliance, but they can also install a defeat device signaling compliance without incurring any losses. Importantly, we assume that the firms have the option to remove the device once the uncertainty about innovation is resolved. We have explored how these decisions depend on the policy's stringency, the firm's ability to innovate and the sector's competitiveness.

In general, the initial decision to install a device is taken by firms who are not confident that they will successfully innovate. The decision to keep it and rely on it post innovation is taken when non-avoidable compliance losses are sufficiently large relative to the penalty incurred when caught.

In terms of policy recommendations, we make several points. We have shown that compliance losses generate countervailing forces based on whether they are avoidable or not. Broadly speaking, everything else being equal, large non-avoidable losses will lead the firms to rely on a cheating device, more so than on innovation to address compliance. The opposite occurs when considering specifically the impact of losses that are avoidable upon innovating, while taking as given any other variable. That said, and as a result of these countervailing forces, the implementation of uniform policies targeted at firms that are substantially heterogeneous, can lead to a situation where the firm that is the most committed to rely on a device is also the one that will invest the most.

We have established that policies associated with very large non-avoidable losses generate an unambiguous loss in welfare as these will not alter any of the firms' decisions. Indeed, a firm committed to keep a cheating device will not alter its investment strategy when the penalty for cheating and/or the non-avoidable compliance losses increase. Instead, the optimal level of investment is solely (and positively) impacted by the size of the losses that it can save upon innovating and the competitive gains that it can gather when innovating.

We show that, in equilibrium, competitive pressures encourage the initial installation of a cheating devices and the decision to rely on it. It may even lead the firms to an inefficient equilibrium where both install a device while each would be better-off not installing a device.

As pointed in the literature, we would support the view that the design of regulations that stimulate innovation and deter cheating requires that the government understand existing technologies and their potential, the firms' innovation process and incentives (see Banks and Heaton (1995), Anex (2000) and Kemp (2000)). In many situations, there are significant asymmetries of information that prevent government authorities from accessing such information which complicates the design of technology forcing policies.

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APPENDIX

Appendix 1: A list of the exogenous variables

Variable	Definition
$c_i > 0$	Compliance losses that manufacturer i incurs unless he relies on a cheating device and is not caught. Captures the regulation's stringency.
$d_i > 0$	Compliance losses that manufacturer i incurs unless he relies on a cheating device and is not caught or he innovates. Captures the extent to which the policy is technology forcing..
$\theta_i > 0$	Captures manufacturer i's type which reflect his ability to innovate. A higher type means a greater probability of successfully innovating for a given investment.
$I_i > 0$	Manufacturer i's investment in innovation.
$P(\theta_i, I_i) \in [0,1]$	The probability of a successful innovation.
$\gamma \in]0,1]$	The probability of not being caught
$F > 0$	Losses, incurred in addition to compliance losses, associated with getting caught cheating.
$\Delta\pi$	Loss in profits suffered by a firm when it does not cheat and does not innovate while its rival either innovates or cheats and is not caught.

Appendix 2: Profits in all possible states

There are 9 possibilities all together. In 3 of these, both firms have losses (c_i, d_i) in the same region. In the remaining 6, (c_i, d_i) is in a different region than (c_j, d_j).

Case 1: Profits when compliance losses are in the same region.

- (c_1, d_1) and (c_2, d_2) are in region H: the firms always keep the device.

State of the world	Firm 1's profits	Firm 2's profits
(S, S)	$\pi - (1-\gamma)(c_1 + F)$	$\pi - (1-\gamma)(c_2 + F)$
(S, F)	$\pi - (1-\gamma)(c_1 + F - \Delta\pi)$	$\pi - (1-\gamma)(c_2 + d_2 + F + \Delta\pi)$
(F, S)	$\pi - (1-\gamma)(c_1 + d_1 + F + \Delta\pi)$	$\pi - (1-\gamma)(c_2 + F - \Delta\pi)$
(F, F)	$\pi - (1-\gamma)(c_1 + d_1 + F)$	$\pi - (1-\gamma)(c_2 + d_2 + F)$

- (c_1, d_1) and (c_2, d_2) are in region M: each firm keeps the device when it fails to innovate.

State of the world	Firm 1's profits	Firm 2's profits
(S, S)	$\pi - c_1$	$\pi - c_2$
(S, F)	$\pi + (1-\gamma)\Delta\pi - c_1$	$\pi - (1-\gamma)(c_2 + d_2 + F + \Delta\pi)$
(F, S)	$\pi - (1-\gamma)(c_1 + d_1 + F + \Delta\pi)$	$\pi + (1-\gamma)\Delta\pi - c_H$
(F, F)	$\pi - (1-\gamma)(c_1 + d_1 + F)$	$\pi - (1-\gamma)(c_2 + d_2 + F)$

- (c_1, d_1) and (c_2, d_2) are in region L: the firms systematically remove the device.

State of the world	Firm 1's profits	Firm 2's profits
(S,S)	$\pi - c_1$	$\pi - c_2$
(S,F)	$\pi + \Delta\pi - c_1$	$\pi - \Delta\pi - (c_2 + d_2)$
(F,S)	$\pi - \Delta\pi - (c_1 + d_1)$	$\pi + \Delta\pi - c_2$
(F,F)	$\pi - (c_1 + d_1)$	$\pi - (c_2 + d_2)$

Case 2: Profits when compliance losses are in the different regions.

- (c_i, d_i) is in region M and (c_j, d_j) is in region H: firm j always keeps the device but firm i only keeps it when it fails to innovate.

State of the world	Firm i's profits	Firm j's profits
(S,S)	$\pi - c_i$	$\pi - (1-\gamma)(c_j + F)$
(S,F)	$\pi + (1-\gamma)\Delta\pi - c_i$	$\pi - (1-\gamma)(c_j + d_j + F + \Delta\pi)$
(F,S)	$\pi - (1-\gamma)(c_i + d_i + F + \Delta\pi)$	$\pi - (1-\gamma)(c_j + F - \Delta\pi)$
(F,F)	$\pi - (1-\gamma)(c_i + d_i + F)$	$\pi - (1-\gamma)(c_j + d_j + F)$

- (c_i, d_i) is in region L and (c_j, d_j) is in region H: firm i always removes its device and firm j always keeps it.

State of the world	Firm i's profits	Firm j's profits
(S,S)	$\pi - c_i$	$\pi - (1-\gamma)(c_j + F)$
(S,F)	$\pi + \Delta\pi(1-\gamma) - c_i$	$\pi - (1-\gamma)(c_j + d_j + F + \Delta\pi)$
(F,S)	$\pi - \Delta\pi - (c_i + d_i)$	$\pi + \Delta\pi - (1-\gamma)(c_j + F)$
(F,F)	$\pi - \gamma\Delta\pi - (c_i + d_i)$	$\pi + \gamma\Delta\pi - (1-\gamma)(c_j + d_j + F)$

- (c_i, d_i) is in region L and (c_j, d_j) is in region M: firm i always removes its device and firm j keeps the device when it fails to innovate.

State of the world	Firm i's profits	Firm j's profits
(S,S)	$\pi - c_i$	$\pi - c_j$
(S,F)	$\pi + \Delta\pi(1-\gamma) - c_i$	$\pi - (1-\gamma)(c_j + d_j + F + \Delta\pi)$
(F,S)	$\pi - \Delta\pi - (c_i + d_i)$	$\pi + \Delta\pi - c_j$
(F,F)	$\pi - \gamma\Delta\pi - (c_i + d_i)$	$\pi + \gamma\Delta\pi - (1-\gamma)(c_j + d_j + F)$

Appendix 3: Proof of Lemma 1

In each state of the world, each firm has two strategies: keep or remove the device. Let R refer to the strategy "remove" and K refer to the strategy "keep".

- **Firm i innovates successfully.**

Consider the state of the world where both firms innovate (S,S). The profits firm i gathers for each possible strategy that the firms can select are given below

Strategy (s_i, s_j)	Profits
(R, R)	$\pi - c_i$
(K, R)	$\pi - (1-\gamma)(c_i + F)$
(R, K)	$\pi - c_i$
(K, K)	$\pi - (1-\gamma)(c_i + F)$

Clearly, no matter what firm j does, it is best for firm i to remove the device provided

$$\pi - c_i \geq \pi - (1-\gamma)(c_i + F) \Leftrightarrow (1-\gamma)F - \gamma c_i \geq 0.$$

Consider the state of the world where only firm i innovates.[9] If its opponent does not install a device, or when the latter is detected, firm i gains $\Delta\pi > 0$. The profits firm i gathers are then given in the following table

Strategy (s_i, s_j)	Profits
(R, R)	$\pi + \Delta\pi - c_i$
(K, R)	$\pi + \Delta\pi - (1-\gamma)(c_i + F)$
(R, K)	$\pi + \Delta\pi(1-\gamma) - c_i$
(K, K)	$\pi + \Delta\pi(1-\gamma) - (1-\gamma)(c_i + F)$

Given that firm j removes the device, it is best for firm i to remove the device provided

$$\pi + \Delta\pi - c_i \geq \pi + \Delta\pi - (1-\gamma)(c_i + F) \Leftrightarrow (1-\gamma)F - \gamma c_i \geq 0.$$

Given that firm j keeps the device, it is best for firm i to remove the device provided

$$\pi - c_i + \Delta\pi(1-\gamma) \geq \pi - (1-\gamma)(c_i + F - \Delta\pi) \Leftrightarrow (1-\gamma)F - \gamma c_i \geq 0.$$

Hence, when firm i innovates, it is a dominant strategy to remove the device when $(1-\gamma)F - \gamma c_i \geq 0$.

- **Firm i fails to innovate.**

Consider the state of the world where both firms fail to innovate (F, F). In this case, installing a device may give firm i a competitive advantage provided it does not get caught and its opponent does not rely on the same strategy or, if it does, gets caught. The profits firm i gathers are given in the following table.

Strategy (s_i, s_j)	Profits
(R, R)	$\pi - (c_i + d_i)$
(K, R)	$\pi + \gamma\Delta\pi - (1-\gamma)(c_i + d_i + F)$
(R, K)	$\pi - \gamma\Delta\pi - (c_i + d_i)$
(K, K)	$\pi - (1-\gamma)(c_i + d_i + F)$

Given that firm j removes the device, it is best for firm i to remove the device provided

$$\pi - (c_i + d_i) \geq \pi + \gamma\Delta\pi - (1-\gamma)(c_i + d_i + F) \Leftrightarrow (1-\gamma)F - \gamma(c_i + d_i) - \gamma\Delta\pi \geq 0.$$

Given that firm j keeps the device, it is best for firm i to remove the device provided

[9] Given our convention on how states of the worlds are defined, this is the state of the world (S, F) for firm L and (F, S) for firm H.

$$\pi - \gamma\Delta\pi - (c_i + d_i) \geq \pi - (1-\gamma)(c_i + d_i + F) \Leftrightarrow (1-\gamma)F - \gamma(c_i + d_i) - \gamma\Delta\pi \geq 0.$$

Clearly, it is a dominant strategy to remove the device provided

$$(1-\gamma)F - \gamma(c_i + d_i) - \gamma\Delta\pi \geq 0.$$

Consider lastly the state of the world where only firm i fails to innovate.[10] If it does not install a device firm i has a systematic competitive disadvantage and loses $\Delta\pi > 0$. The profits firm i gathers are given in the following table

Strategy (s_i, s_j)	Profits
(R, R)	$\pi - \Delta\pi - (c_i + d_i)$
(K, R)	$\pi - (1-\gamma)\Delta\pi - (1-\gamma)(c_i + d_i + F)$
(R, K)	$\pi - \Delta\pi - (c_i + d_i)$
(K, K)	$\pi - (1-\gamma)\Delta\pi - (1-\gamma)(c_i + d_i + F)$

Whatever firm j does, it is best for firm i to remove the device provided

$$\pi - \Delta\pi - (c_i + d_i) \geq \pi - (1-\gamma)\Delta\pi - (1-\gamma)(c_i + d_i + F) \Leftrightarrow (1-\gamma)F - \gamma(c_i + d_i) - \gamma\Delta\pi \geq 0.$$

Hence, whenever firm i fails to innovates, it is a dominant strategy to remove the device when $(1-\gamma)F - \gamma(c_i + d_i) - \gamma\Delta\pi \geq 0$.

Appendix 4: Proof of Lemma 2

Recall that, by convention, states of the world are written as $(O_1, O_2), O_i \in \{S, F\}$. Given the investment level of its opponent, firm 1 selects an investment level solving

$$\max_{I_1} P_1[P_2\pi_1(S,S) + (1-P_2)\pi_1(S,F)] + (1-P_1)[P_2\pi_1(F,S) + (1-P_2)\pi_1(F,F)] - I_1,$$

and, given I_1, firm 2 selects an investment level solving

$$\max_{I_2} P_2[P_1\pi_2(S,S) + (1-P_1)\pi_2(F,S)] + (1-P_2)[P_1\pi_2(S,F) + (1-P_1)\pi_2(F,F)] - I_2,$$

where $P_t \equiv P(\theta_t, I_t)$ and where the values for the profits depend on which region (c_1, d_1) and (c_2, d_2) belong to as this reflects what the firms do once they know whether innovation is successful or not. Appendix 2 gives the profits that each firm gathers for all possible values of the compliance losses (c_1, d_1) and (c_2, d_2).

The first order conditions that hold at any interior solution require that

$$\frac{\partial P}{\partial I_1}\left[P_2\big(\pi_1(S,S) - \pi_1(F,S)\big) + (1-P_2)\big(\pi_1(S,F) - \pi_1(F,F)\big)\right] - 1 = 0,$$

and

$$\frac{\partial P}{\partial I_2}\left[P_1\big(\pi_2(S,S) - \pi_2(S,F)\big) + (1-P_1)\big(\pi_2(F,S) - \pi_2(F,F)\big)\right] - 1 = 0.$$

[10] Given our convention on how states of the worlds are labelled, this is the state of the world (F, S) for firm L and (S, F) for firm H.

Although it is slightly tedious, one can verify using Appendix 2 that the marginal benefits from innovating only depend on the region in which a firm's own losses belong to:

$$\pi_1(S,S) - \pi_1(F,S) = \pi_1(S,F) - \pi_1(F,F) = \begin{cases} \Delta\pi + d_1 \text{ when } r = L, \\ (1-\gamma)(F + \Delta\pi + d_1) - \gamma c_1 \text{ when } r = M, \\ (1-\gamma)(\Delta\pi + d_1) \text{ when } r = H. \end{cases}$$

and

$$\pi_2(S,S) - \pi_2(S,F) = \pi_2(F,S) - \pi_2(F,F) = \begin{cases} \Delta\pi + d_2 \text{ when } r = L, \\ (1-\gamma)(F + \Delta\pi + d_2) - \gamma c_2 \text{ when } r = M. \\ (1-\gamma)(\Delta\pi + d_2) \text{ when } r = H. \end{cases}$$

Equations (1), (2) and (3), in the text, characterize the first order condition based on which region the firm's losses belong to. In each case it is trivial to see that the second order condition holds based on the hypothesis that the function P_i $(i = 1,2)$ is concave in I.

Appendix 5: Proof of Lemma 3

Consider any exogenous variable $x \in \{c_i, d_i, F, \gamma, \Delta\pi\}$. The first order condition that applies in region $r \in \{L, M, H\}$ can be written as

$$\frac{\partial P}{\partial I_i}\Gamma^r(c_i, d_i, F, \gamma, \Delta\pi) - 1 = 0,$$

where

$$\Gamma^H(d_i, \gamma, \Delta\pi) = (1-\gamma)(d_i + \Delta\pi),$$

$$\Gamma^M(c_i, d_i, F, \gamma, \Delta\pi) = (1-\gamma)(d_i + F + \Delta\pi) - \gamma c_i$$

$$\Gamma^L(d_i, \gamma, \Delta\pi) = (d_i + \Delta\pi).$$

Using the envelope theorem (and the fact that the second order condition holds) we have

$$\text{sign of } \frac{dI_i^r}{dx} = \text{sign of } \frac{d\Gamma^r}{dx},$$

and

$$\frac{dI_i^r}{d\theta_i} = -\left.\frac{P_{I\theta}\Gamma^r(.)}{P_{II}}\right|_{I_i^r} \geq 0$$

because $\Gamma^r(c_i, d_i, F, \gamma, \Delta\pi) \geq 0$ for each r.

Finally, the level of investment is continuous in c_i since the following holds

as $\gamma c_i \to (1-\gamma)F$, we have $(1-\gamma)(d_i + F + \Delta\pi) - \gamma c_i \to (1-\gamma)(d_i + \Delta\pi)$,

as $\gamma c_i \to (1-\gamma)F - \gamma\Delta\pi - \gamma d_i$, we have $(1-\gamma)(d_i + F + \Delta\pi) - \gamma c_i \to (d_i + \Delta\pi)$.■

Appendix 6: Proof of Proposition 1

- Case 1: firm i has compliance losses in region H.

When it does not install a device, it will invest I_i^L and gather profits $\Pi_i^{NC}(\theta_i)$ given by (4) in the text. If it does install a device, it should anticipate that, given its compliance losses, it is profit maximizing to keep it post innovation and invest I_i^H. Therefore, when it installs the device, it gets profits $\Pi_i^{CH}(\theta_i)$ given by (5) in the text.

Comparing the profits at the boundary value $\theta_i = 0$ using (7) and (8), we have

$$\Pi_i^{CH}(0) - \Pi_i^{NC}(0) = \gamma(c_i + d_i) - (1-\gamma)F + \gamma\Delta\pi P_j.$$

Since $\gamma c_i \geq (1-\gamma)F$ we have $\Pi_i^{CH}(0) - \Pi_i^{NC}(0) > 0$ meaning that cheating is always better for a firm with the lowest type. As the type increases, the profits increase, and we have

$$\frac{d\Pi^{NC}}{d\theta_i} = (d_i + \Delta\pi)P_\theta|_{I=I_i^L},$$

and

$$\frac{d\Pi^{CH}}{d\theta_i} = (1-\gamma)(d_i + \Delta\pi)P_\theta|_{I=I_i^H},$$

Considering the first order conditions (1) and (3) characterizing the optimal investments I_i^H and I_i^L, it is clear that we have $I_i^H \leq I_i^L$.[11] Given assumption (iv) stating that $P_{\theta I} > 0$, there is no ambiguity, and we have, for any firm with losses in region 1.

$$\frac{d\Pi^{NC}}{d\theta_i} \geq \frac{d\Pi^{CH}}{d\theta_i}.$$

The profits gathered when being honest are increasing at a faster rate with θ_i meaning that, as the firm's ability to innovate improves, it is more inclined to being honest.

Since $\Pi_i^{CH}(0) - \Pi_i^{NL}(0) > 0$ and $\frac{d\Pi^{NC}}{d\theta} > \frac{d\Pi^{CH}}{d\theta} > 0$, there exists a unique threshold value θ_{iH}^* such that $\Pi_i^{NC}(\theta_{iH}^*) = \Pi_i^{CH}(\theta_{iH}^*)$ and such that firm i will behave honestly and invest I_i^L provided

$$(1-\gamma)F - \gamma(c_i + d_i) + (d_i + \Delta\pi)\left[P\left(\theta_i, I_i^L\right) - (1-\gamma)P\left(\theta_i, I_i^H\right)\right] + I_i^H - I_i^L \geq \gamma\Delta\pi P_j.$$

The left hand side of the above inequality can easily be shown to be increasing in θ_i and therefore, for any given θ_j, there exists a unique $\theta_{iH}^*\left(\theta_j, s_j\right)$ such that firm i is honest if and only if $\theta_i \geq \theta_{iH}^*\left(\theta_j, s_j\right)$. The derivative of $\theta_{iH}^*\left(\theta_j, s_j\right)$ with respect to θ_j, given in the text, is calculated using the implicit function theorem.

- Case 2: firm i has compliance losses in region M.

Recall that this firm has losses such that

$$\gamma(c_i + d_i + \Delta\pi) - (1-\gamma)F \geq 0 \quad \text{and} \quad \gamma c_i < (1-\gamma)F.$$

When it does not install a device, it will invest I_i^L and gather profits $\Pi_i^{NC}(\theta_i)$ given by (4) in the text. If it does install a device, it should anticipate that, given its compliance losses, it is profit maximizing to keep the device only when innovation fails and invest I_i^M. Therefore, when it installs the device, it gets profits $\Pi_i^{CM}(\theta_i)$ given by (6) in the text.

Comparing the profits at the boundary value $\theta_i = 0$ using (7) and (9), we have

[11] The comparison of investments is done for a given firm and thus for a given type.

$$\Pi_i^{CM}(0) - \Pi_i^{NC}(0) = \gamma(c_i + d_i) - (1-\gamma)F + \gamma\Delta\pi P_j.$$

When $\gamma c_i \to (1-\gamma)F$ (so that we are moving towards the border separating regions H and M), we obviously have $\Pi_i^{CM}(0) - \Pi_i^{NC}(0) > 0$. However, when we converge towards the border separating regions M and L, and $\gamma(c_i + d_i) - (1-\gamma)F \to -\gamma\Delta\pi$ we have $\Pi_i^{CM}(0) - \Pi_i^{NC}(0) \to -\gamma\Delta\pi\left(1 - P_j\right) < 0$.

In words, firm i is better-off being honest when (c_i, d_i) is close to the border separating regions M and L (i.e., for less stringent and less technology forcing policy).

The rates at which the profits increase are given by

$$\frac{d\Pi^{NC}}{d\theta_i} = (d_i + \Delta\pi)P_\theta|_{I=I_i^L},$$

and

$$\frac{d\Pi^{CM}}{d\theta_i} = \left((1-\gamma)(d_i + F + \Delta\pi) - \gamma c_i\right)P_\theta|_{I=I_i^M}.$$

Considering the first order conditions (2) and (3) characterizing the optimal investments I_i^M and I_i^L, it is clear that we have $I_i^M \leq I_i^L$.[12] Thus, for any firm with losses in region M

$$\frac{d\Pi^{NC}}{d\theta_i} \geq \frac{d\Pi^{CM}}{d\theta_i}.$$

In conclusion, two possibilities emerge:

Possibility 1: When $\Pi_i^{CM}(0) - \Pi_i^{NC}(0) < 0$ the firm refrains from installing a device whatever its type.

Possibility 2: When $\Pi_i^{CM}(0) - \Pi_i^{NC}(0) > 0$, there exists a unique threshold value θ_{iM}^* such that $\Pi_i^{NC}(\theta_{iM}^*) = \Pi_i^{CM}(\theta_{iM}^*)$ and firm i will behave honestly and invest I_i^L provided

$$(1-\gamma)F - \gamma(c_i + d_i) + (d_i + \Delta\pi)P\left(\theta_i, I_i^L\right) - [(1-\gamma)(d_i + F + \Delta\pi) - \gamma c_i]P\left(\theta_i, I_i^M\right) + I_i^M - I_i^L \geq \gamma\Delta\pi P_j.$$

The left hand side of the above inequality can easily be shown to be increasing in θ_i and therefore, for any given θ_j, there exists a unique $\theta_{iM}^*\left(\theta_j, s_j\right)$ such that firm i is honest if and only if $\theta_i \geq \theta_{iM}^*\left(\theta_j, s_j\right)$. The derivative of $\theta_{iM}^*\left(\theta_j, s_j\right)$ with respect to θ_j is calculated using the implicit function theorem.■

Appendix 7: Derivatives for the comparative statics

Recall that $P_j \equiv P\left(\theta_j, I_j^{r'}\right)$, where r' reflects the region to which firm j' compliance losses belong. The threshold value θ_{iH}^* solves

$$(1-\gamma)F - \gamma(c_i + d_i) + (d_i + \Delta\pi)\left[P\left(\theta_i, I_i^L\right) - (1-\gamma)P\left(\theta_i, I_i^H\right)\right] + I_i^H - I_i^L \equiv \gamma\Delta\pi P_j.$$

[12] The comparison of investments is done for a given firm and thus for a given type.

The threshold value θ_{iM}^* solves

$$(1-\gamma)F - \gamma(c_i + d_i) + (d_i + \Delta\pi)P\left(\theta_i, I_i^L\right) - [(1-\gamma)(d_i + F + \Delta\pi) - \gamma c_i]P\left(\theta_i, I_i^M\right) + I_i^M - I_i^L \equiv \gamma\Delta\pi P_j.$$

Using the implicit function theorem one can establish the following results.

- **Comparative statics with respect to $\boldsymbol{F}$ and $\boldsymbol{\gamma}$**

$$\frac{d\theta_{iH}^*(\theta_j, s_j)}{dF} = \frac{-(1-\gamma)}{(d_i + \Delta\pi)\left[P_\theta\left(\theta_{iH}^*, I_i^L\right) - (1-\gamma)P_\theta\left(\theta_{iH}^*, I_i^H\right)\right]} < 0,$$

$$\frac{d\theta_{iM}^*(\theta_j, s_j)}{dF} = \frac{-(1-\gamma)\left[1 - P_i\left(\theta_{iM}^*, I_i^M\right)\right]}{(d_i + \Delta\pi)P_\theta\left(\theta_{iM}^*, I_i^L\right) - [(1-\gamma)(d_i + F + \Delta\pi) - \gamma c_i]P_\theta\left(\theta_{iM}^*, I_i^M\right)} < 0$$

$$\frac{d\theta_{iH}^*(\theta_j, s_j)}{d\gamma} = \frac{c_i + F + d_i\left(1 - P_i\left(\theta_{iH}^*, I_i^H\right)\right) - \Delta\pi\left[P_i\left(\theta_{iH}^*, I_i^H\right) - P_j\right]}{(d_i + \Delta\pi)\left[P_\theta\left(\theta_{iH}^*, I_i^L\right) - (1-\gamma)P_\theta\left(\theta_{iH}^*, I_i^H\right)\right]},$$

$$\frac{d\theta_{iM}^*(\theta_j, s_j)}{d\gamma} = \frac{(c_i + d_i + F)\left[1 - P_i\left(\theta_{iM}^*, I_i^M\right)\right] + \Delta\pi\left[P_j - P_i\left(\theta_{iM}^*, I_i^M\right)\right]}{(d_i + \Delta\pi)P_\theta\left(\theta_{iM}^*, I_i^L\right) - [(1-\gamma)(d_i + F + \Delta\pi) - \gamma c_i]P_\theta\left(\theta_{iM}^*, I_i^M\right)}.$$

- **Comparative statics with respect to compliance losses**

$$\frac{d\theta_{iH}^*(\theta_j, s_j)}{dc_i} = \frac{\gamma}{(d_i + \Delta\pi)\left[P_\theta\left(\theta_{iH}^*, I_i^L\right) - (1-\gamma)P_\theta\left(\theta_{iH}^*, I_i^H\right)\right]} > 0,$$

$$\frac{d\theta_{iM}^*(\theta_j, s_j)}{dc_i} = \frac{\gamma\left(1 - P_i\left(\theta_{iM}^*, I_i^M\right)\right)}{(d_i + \Delta\pi)P_\theta\left(\theta_{iM}^*, I_i^L\right) - [(1-\gamma)(d_i + F + \Delta\pi) - \gamma c_i]P_\theta\left(\theta_{iM}^*, I_i^M\right)} > 0,$$

$$\frac{d\theta_{iH}^*(\theta_j, s_j)}{dd_i} = \frac{\gamma + \left[P_i\left(\theta_{iH}^*, I_i^H\right)(1-\gamma) - P_i\left(\theta_{iH}^*, I_i^L\right)\right]}{(d_i + \Delta\pi)\left[P_\theta\left(\theta_{iH}^*, I_i^L\right) - (1-\gamma)P_\theta\left(\theta_{iH}^*, I_i^H\right)\right]},$$

$$\frac{d\theta_{iM}^*(\theta_j, s_j)}{dd_i} = \frac{\gamma\left[1 - P_i\left(\theta_{iM}^*, I_i^M\right)\right] - P_i\left(\theta_{iM}^*, I_i^L\right)}{(d_i + \Delta\pi)P_\theta\left(\theta_{iM}^*, I_i^L\right) - [(1-\gamma)(d_i + F + \Delta\pi) - \gamma c_i]P_\theta\left(\theta_{iM}^*, I_i^M\right)}.$$

Changes in d_j and c_j are easier to assess since the threshold variables are always defined such that

$$H(\theta_{ir}^*) \equiv \gamma\Delta\pi P\left(\theta_j, I_j^{r'}\right),$$

where $H(.)$ is an increasing function of θ_i and where $r' = L$ when $s_j = NC$, $r' = H$ when $s_j = CH$ and $r' = M$ when $s_j = CM$. Thus, changes in d_j and c_j affect the thresholds through their impact on the investment strategy of the rival. The variable c_j only has an impact when firm j's losses are in region M.