Uncertain regulatory timing and market dynamics

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A B S T R A C T

Using a dynamic model of capacity accumulation, I examine the relationship between uncertainty about the timing of a new Pigouvian tax and oligopolistic competition. I find that for some market structures uncertainty about the timing of the regulatory change leads firms to increase investment. These results stem from the nature of the uncertainty and its interaction with firms' strategic incentive to engage in capacity races. They dramatize the importance of accounting for initial conditions when forecasting firms' reactions to anticipated regulatory changes. In addition, I find that more protracted uncertainty leads to greater welfare costs.

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1. Introduction

Besides obvious influences like the level of demand, firms' investment decisions depend on their regulatory context. All things equal, we expect – and observe – lower levels of investment in areas with more stringent regulatory regimes (see, e.g., Gray and Shadbegian (1998), Kahn and Mansur (2010)) as such regimes impose greater costs on firms. Thus, when investments are durable and regulation is variable, firms' investment strategies must incorporate expectations about the future regulatory environment.

Regulatory uncertainty differs from other types of uncertainty in several important ways. While demand and certain cost factors might be thought to evolve continuously over time, the regulatory state often changes in a large, discrete fashion. Moreover, while there can sometimes be uncertainty about the nature of a regulatory change (e.g. a focus on price vs. quantities), the broad outline of a regulatory change is often clear well before uncertainty about its adoption period is resolved. For example, in line with the anecdote about Granger Morgan presented above, the Intrade Prediction Markets show that the market believes that though unlikely in the immediate future, cap and trade legislation is likely in the long-run.1 Similarly, the Clean Air Act Amendments were debated for a decade before their eventual adoption. While some elements were uncertain throughout the process, the focus on reducing the level of certain pollutants like sulfur dioxide was clear throughout (Lee and Alm (2004), p. 436).

Prior to the passage of legislation making clear when the regulatory state will change, firms must invest knowing that their expenditures may not be recouped if the regulatory change occurs more rapidly than they had anticipated. In monopolistic settings, the impact of uncertainty about the regulatory future can be modeled using approaches developed in the investment and uncertainty

1 As of November 9, 2010 (i.e. after the November 2nd elections), Intrade offered contracts about the likelihood that cap and trade legislation would be adopted by the Congress by the end of calendar year 2010, 2011, 2012, and 2013. Consistent with the quote about Granger Morgan’s research presented above, the ask prices steadily mounted to a price of 45 (for a contract that pays off 100) on the 2013 contract.
literature and usually applied to demand uncertainty. If the market is oligopolistic, however, the question of how uncertainty affects investment becomes more difficult to answer. This is because an oligopolist’s optimal strategy depends on its competitors’ behavior, and the durability of investments can create incentives for oligopolists to engage in preemption races (see, e.g., Spence (1977)). Thus, there are two different forces on oligopolists facing exogenous uncertainty: 1) consider how the current state of the world conveys information about the future profitability of capacity investment, and 2) invest quickly in an effort to improve their position within the market.

In this article, I examine the tension between these forces and their impact on overall welfare by extending the Besanko and Doraszelski (2004) infinite horizon, discrete time model of dynamic capacity accumulation to allow for a one-time regulatory change. In my model, uncertainty about the regulatory future is restricted to the timing – not the magnitude – of a Pigouvian (i.e. pollution) tax designed to cause firms to internalize an externality in their production process. Before the policy change, firms compete in the product market and make decisions about how much to invest in expanding their productive capacity knowing that in the long-run there will be a discrete jump in their marginal costs.6

Contrasting firms’ numerically calculated Markov Perfect Nash equilibrium policy functions reveals uncertainty does not have a clear comparative static in this setting. Whether or not uncertainty has a positive or negative impact depends on market structure and the level of uncertainty about the arrival time of the Pigouvian tax. Two factors combine to explain the pattern in these results.

First, unlike the settings from which the real options literature originated (e.g., Dixit and Pindyck (1994)), it is inappropriate to think of delay as constituting a financial option in this context. This is not because I focus on a discrete change in the profitability of capacity, but rather because the uncertainty is about the timing of a known change.7 With greater knowledge about the transition period, firms can more precisely calibrate how much to invest depending on the capacity they already have. Thus, if a firm already has a large capacity stock, knowing with certainty when the change will occur allows it to cut investment more dramatically. Conversely, if a firm only has a small amount of capacity but knows with certainty that the transition is still some way off, then it can relatively increase its investment because it knows that it will pay off.

Second, uncertainty about the timing of the regulatory change affects firms’ strategic incentives to varying degrees depending on the market structure. Besanko and Doraszelski (2004) showed that capacity-constrained Bertrand competition creates a capacity race dynamic to determine which firm will be dominant. Uncertainty about a Pigouvian tax’s timing amplifies or attenuates this dynamic depending on market structure because having the largest capacity stock at the time of the regulatory change dramatically increases the likelihood of being the long-run monopolist. When the change is likely to occur soon, firms in markets with small, symmetric structures invest more if they know when the change will take place than if the change’s timing is uncertain. This occurs because the firms realize that they must achieve dominance quickly or be compelled to exit the market, earning negligible profits in the long-run. Conversely, market structures where both firms have large capacity stocks exhibit markedly less investment if the regulatory change is known to occur soon than if its timing is uncertain. Firms behave in this manner because they know that the capacity will not be needed; furthermore, if both firms enter the regulated state with large capacity stocks, it will result in a protracted period of fierce, profitless competition.

After determining how regulatory uncertainty affects firms’ investments, I analyze how their value functions vary as a function of regulatory uncertainty and market structure. I find that uncertainty does not have an unequivocal impact. When the market structure is quite asymmetric and the expected regulatory change near, the smaller firm is better off when the regulatory trajectory is uncertain. This is because a small firm has a larger chance of succeeding in inverting the market structure when the timing of the change is not fixed, and there are lopsided benefits to doing so.6 Alternatively, if both firms have large capacity stocks, they are likely to be better off if the timing is uncertain but anticipated to occur in the near future. This is because their large capacity stocks are likely to lead to a long period of intense, profitless competition if the change occurs soon. Therefore, firms “prefer” uncertainty since there is a higher likelihood that the change would not take place until a leader had emerged.

After analyzing the relationship between uncertain regulatory timing and firm values, I use tools from stochastic process theory to examine regulatory uncertainty’s impact on social welfare. Focusing on mature industries, I find that – on average – total welfare is highest when the timing of the regulatory change is certain. Furthermore, larger expected periods of uncertainty are linked to higher welfare costs. These findings imply that welfare can be improved – on average – if policy-makers can reach agreement at an earlier time. This implies, as in Bloom (2009), that settling for a regulatory change that is less than ideal can sometimes dominate fighting for a first-best outcome. Given the commonality of proposals for new regulations of industries ranging from finance to manufacturing, my results about the varying firm-level impacts of uncertainty and its negative aggregate effect should be of interest to a variety of policy-makers. This article contributes to a number of literatures. First, it adds to the growing number of papers formally incorporating exogenous shocks or uncertainty into models of strategic interaction.6 Within this literature, papers have found that in strategic situations, uncertainty can spur or inhibit firms’ investment (e.g. Weeds (2002) and Abbring and Campbell (2010) find that uncertainty leads to less investment and entry, respectively, while Maggi (1996) and Mason and Weeds (2010) find greater investment in more uncertain markets). The current article introduces a new and relevant type of uncertainty, and shows that in combination with strategic interaction it can lead to either more or less investment. I believe that the finding that uncertainty’s impact is state dependent is a new contribution in this literature.

Second, this article contributes to the small but rapidly growing literature on how uncertainty about regulatory conditions impacts investment and other firm decisions.6 Unlike the current article, the majority of previous work on regulatory uncertainty has abstracted from strategic dynamics and, in general, has supported the real options prediction that uncertainty about the regulatory future leads to lower investment (Pawlina and Kort (2005) is a notable exception). While consistent with the previous literature's finding about the beneficial effects of a good, stable policy environment, this article indicates that uncertainty about the timing of an expected regulatory change can –

6 It should be noted that just because the possibility of a market structure inversion is larger unless the timing of the regulatory change is uncertain, this does not mean that it is likely. This is consistent with business history: “Davids” do sometimes topple “Goliaths” (see, e.g., discussion in Mickelthwait and Adrian, 2005), but it is not common.
8 See, e.g., Hassett and Metcalf (1999), Henisz and Zelner (2001), Ishii and Yan (2004), Lee and Alim (2004), Pawlina and Kort (2005), Reinsel and Smith (2007), Wilson et al. (2011) and Yang et al. (2008). Consistent with the motivating examples presented above, a large amount of the most recent contributions focus on the implications of uncertain climate policy.
especially in conjunction with strategic interaction – elicit a variety of responses.

The remainder of the article proceeds as follows. Section 2 presents the model. In Section 3, I examine how uncertainty about the arrival of a regulatory change impacts firm strategies (and values) conditional on the structure of the market. In Section 4, I show how these differences affect social welfare. Section 5 concludes.

2. Model

I modify Besanko and Doraszelski (2004)’s extension of the Ericson and Pakes (1995) industry evolution framework to allow the state space to vary in ways besides just firms’ capacities. The approach is general enough to accommodate variation in any of the parameters affecting demand, the cost of investment, etc. However, I describe the model as used in this application, where the exogenous variation takes the form of a single change in the marginal cost of production. Also, while the model could straightforwardly be extended to the n-firm case, I describe the duopoly setting employed in this article.

2.1. Setting and timing of events

I consider two infinitely-lived, homogeneous good producers engaged in capacity-constrained price competition in a discrete-time, infinite horizon setting. In any given period, each firm’s possible production capacity \( q^i \) can take on one of \( 0 \leq M - 1 < \infty \) values. For simplicity, I set the interval between the different productive capacities to be the same. The firms have symmetric cost structure which which are determined by the regulatory state \( s = [u, r] \), where \( u \) indicates unregulated and \( r \) indicates regulated.

Fig. 1 shows the timing of events in each period \( t \) of the model. First, both firms observe the state of the world, which is given by \( \{q^1, q^2, s\} \). Second, the firms compete in the product market, with each firm \( i \) earning payoff \( n^i(q^1, q^2, s) \). Third, the firms make their investment decisions, which (along with depreciation) affect the likelihood of different capacity state transitions. Fourth, and finally, the state evolves to \( \{q^1, q^2, s'\} \).

2.2. Product market competition

I specify that firms engage in capacity-constrained price competition (i.e. Bertrand–Edgeworth competition). Demand is linear and given by the inverse demand function:

\[
P = a - bQ,
\]

where \( P \) is the market price, and \( Q \) is aggregate production. Marginal costs \( c_i \) are common to all firms, and, as noted above, are regulatory state dependent. The two firms compete by simultaneously setting their prices \( (p_1, p_2) \) conditional on the regulatory and capacity states, a situation first analyzed by Kreps and Scheinkman (1983) and generalized in Deneckere and Kovenock (1996) and Allen et al. (2000).

I follow Besanko and Doraszelski (2004) in their approach to equilibrium selection. This involves imposing the efficient rationing rule, which implies the following. If \( p_1 > p_2 \), then firm 2 supplies the entire market provided it has the production capacity to do so. If it does not, firm 1 serves the residual demand. Thus, the profit of firm 1 is

\[
p_1 \max \{0, Q(p_1) - q^2\},
\]

and the profit of firm 2 is

\[
p_2 \min \{q^1, Q(p_2)\}.
\]

I specify prices as a function of firm capacities as in Deneckere and Kovenock (1996). This approach leads to the identification of three regions: A, B, and C. Fig. 2 shows a stylized example of how these regions relate to the firms’ capacities. Table 1 summarizes the production and pricing behavior of both firms in each of the three regions.

In region A, neither firm has the capacity to produce at the level that their Cournot best-response function indicates, i.e. \( q^1 < q^2 \) & \( q^2 < q^\ast \). In this judgment, the equilibrium is for both firms to produce at full capacity and charge the market clearing price; thus, \( n^i(q^1 + q^2) \), for \( i = 1, 2 \).

In region B, both firms have the capacity to serve the entire market, i.e. \( q^1 \geq q^2 \) & \( q^2 \geq q^\ast \). In this region, both firms charge their marginal cost and earn zero profits. In order to examine concentration over time, I assume that the firms equally share the market in this region.

Region C contains the remaining capacity states. In this region, it is assumed that the higher capacity firm acts as the high price firm under the efficient rationing rule. Thus, if firm 1 has more capacity, \( n_1 = p_1 \max \{0, Q(p') - q^2\} \). The price charged by the lower firm (i.e. firm 2) is found by considering what the lowest possible price would be for the larger firm to generate the same profit \( n_1 \) if it acted as the low price seller. In other words, it is the smallest root to \( n_1 - p^a Q(p) = 0 \). This price is the one that is used by the lower firm. As noted in Besanko and Doraszelski (2004), in region C, the larger firm earns its Stackelberg follower profit, while the smaller firm earns less than the Stackelberg leader profit. In all cases, profits of the larger firm weakly dominate those of the smaller firm.

2.3. Capacity state dynamics

Like Besanko and Doraszelski (2004) and Chen (2009), I assume that total production capacity changes discretely. Though perhaps not

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9 I have also solved the model assuming that the firms engage in capacity-constrained quantity competition. The key qualitative insight of this article – i.e. that initial conditions matter in how firms respond to regulatory uncertainty, and that uncertainty can produce excessive investment – is robust to this reparameterization. Details are available upon request.
immediately intuitive, discrete changes in total production capacity can be rationalized by thinking of each increase (decrease) coming as the result of the construction (closure) of a plant, which can produce continuously up to some maximum amount.

Two different stochastic forces affect the likelihood of changes in firms' capacity states. First, the amount a firm invests increases the probability that it adds to its total production capacity. Like the bulk of the literature using the Ericson and Pakes (1995) framework, I model the impact of investment on capacity state transitions as in that article. If some firm $i$ chooses to invest $x_i > 0$, the probability that it adds to its capacity is given by $\frac{\alpha x_i}{1 + \alpha x_i}$, where $\alpha$ is a common, exogenously-given measure of investment effectiveness. Thus, firms can only increase their production capacities step-by-step, and investment has a declining marginal impact on the likelihood of increasing the capacity stock. At first, aspects of this modeling approach may seem un-intuitive. However, as noted in Besanko and Doraszelski (2004), many things can disrupt capacity expansions in large-scale productive industries. For example, there may be zoning complications, cost-overruns, and/or delays due to materials or labor shortages. Thus, it is reasonable to assign a certain degree of stochasticity to the results of investment decisions. In addition, in capital intensive industries like electricity it often is unlikely that firms will want, or be able, to simultaneously develop multiple new large production facilities in the same market.

Second, firms’ capacities change as a result of stochastic depreciation shocks. In keeping with the context of physical capacity, this is modeled as an individual-firm process rather than the market-wide phenomenon in Ericson and Pakes (1995). Each period each firm may suffer a depreciation shock with probability $\delta$. Unlike Besanko and Doraszelski (2004) and Chen (2009), I allow depreciation shocks to affect firms with no capacity stocks (although firms can never have less than $q_i^M$). Effectively, this makes it more difficult to “re-enter” the market if a firm did not produce in the previous period.

The overall capacity state transition probabilities for a given firm are found by combining the depreciation and investment probability functions. Thus, if firm $i$ is at some capacity state $q^M_m$ where $m \in \{1, ..., M - 2\}$, the probability of it being in state $q^M_{m+1}$ in the next period is given by:

$$Pr(q^M_{m+1} | q^M_m, x_i) = \begin{cases} \frac{1 - \delta}{1 + \alpha x_i} & \text{if } n = m + 1, \\
\frac{1 - \delta + \alpha x_i}{1 + \alpha x_i} & \text{if } n = m, \\
\frac{\delta}{1 + \alpha x_i} & \text{if } n = m - 1. \end{cases}$$

Since a firm cannot have more than $q^M_{M-1}$, when $m = M - 1$ the transition probabilities are:

$$Pr(q^M_{M-1} | q^M_m, x_i) = \begin{cases} \frac{1 - \delta + \alpha x_i}{1 + \alpha x_i} & \text{if } n = m, \\
\frac{\delta}{1 + \alpha x_i} & \text{if } n = m - 1. \end{cases}$$

Finally, since a firm cannot have less than $q^M_1$, then when $n = 1$, the transition probabilities are:

$$Pr(q^M_1 | q^M_m, x_i) = \begin{cases} \frac{1 - \delta}{1 + \alpha x_i} & \text{if } n = 2, \\
\frac{1 - \delta + \alpha x_i}{1 + \alpha x_i} & \text{if } n = 1. \end{cases}$$

2.4. Regulatory state dynamics

As previously stated, I limit variation in the regulatory state to differences in firms’ marginal costs. The game begins with firms in the unregulated state. In this first period, the firms learn that the market is subject to a cost-increasing regulatory change; they cannot be surprised by a change on that period. The regulatory state subsequently evolves independently of firms’ capacities. The regulatory state’s evolution is modeled in two mutually exclusive ways: with the change occurring at an uncertain point in time or as occurring at a certain point in time. Both evolutionary methods are Markov processes, but they have different transition matrices $P$, where $P_{ij}$ indicates the probability of shifting from regulatory state $i$ to regulatory state $j$ between periods.

If the change occurs at an uncertain point, then conditional on the change not having occurred yet, the probability of moving to the regulated state in the next period is constant and given by $P_{11} = \lambda$. The regulated state is absorbing (i.e., $P_{11} = 1$). Thus, the long-run probability that the industry will be regulated is $1$. This set-up also implies that there are only two states to calculate behavior for: prior to the regulatory change’s implementation (1) and after it has gone into affect (2). The memory-less formulation employed for the uncertainty case also means that the time until the regulatory change is a geometrically distributed random variable with mean $\lambda$ and variance $\frac{1}{\lambda^2}$. Therefore, since firms cannot be in the regulated state in the first period, for a given value of $\lambda$, the expected period of the change $E[R] = \frac{1}{\lambda} + 1$.

Specifying that an uncertain regulatory transition process is this simple is unrealistic insofar as it excludes the possibility that the risk of regulatory change varies over time. However, I believe it captures a large amount of the caprice involved in large regulatory changes, the basics of which may be mooted and largely agreed upon many years before the bill is passed. The delay is often a function of personalities and random events affecting stakeholder beliefs. For example, it took almost 10 years of debate in Congress before the Clean Air Act Amendments of 1990 passed. The likely nature of the future regulatory state was more or less constant; only the timing of the

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13 This separation helps to keep the model analytically tractable and is common in the literature. See Bushnell and Hishi (2007) or Doraszelski and Pakes (2007) for more discussion.

14 For example, Jacobsen et al. (2011) documents the impact of the release of “An Inconvenient Truth” on carbon offsets, and seems likely to have raised the profile of climate change concerns to a point where nationwide legislation is possible in the near term.

15 See Lee and Alen (2004) for details. It should be noted that the specific contents of the Clean Air Act Amendments did vary somewhat over time, though the overall thrust of increasing standards clearly persisted. Similarly, electricity restructuring was gradually adopted in many states and until the California energy crisis was perceived as inevitable (see Hishi and Yan (2004)).
change was uncertain. Overall, I do not believe that adding additional states would lead to substantial qualitative changes to the results.

When the timing of the change is known, a larger number of behavioral states must be calculated. Specifically, for a given \(E(R)\), there are \(E(R)\) distinct behavioral states, even though the number of regulatory regimes remains two. This is because firms will behave differently in each pre-regulatory change period since the incentive to hold capacity differs as the number of periods that will be spent in the different regimes evolves. The final state represents the world once the regulatory change has taken place. The second to last is the preceding period, when \(E(R)\) once the regulatory change has taken place. The second to last is the equivalent period back to state and period 1, which is when the market learns of the regulatory change’s timing. Transition between these states is governed by a deterministic Markov transition matrix. If there are \(g\) states, then \(P_{i,i+1}=1\) for all \(i\neq g\) and \(P_{g,g}=1\).\(^{15}\)

2.5. Optimal investment decision-making

If the market is currently in state \((\tilde{q}, \tilde{q}, s)\), then an incumbent firm \(i\) must solve an intertemporal maximization problem to determine how much it should invest. I focus on firm 1 for simplicity of exposition.

Let \(V^i(\tilde{q}, \tilde{q}, s)\) indicate the expected net present value of all future cashflows to firm 1, conditional on its current capacity, its competitor’s capacity, and the current regulatory state. \(V^i(\cdot)\) is defined recursively as the solution to the Bellman equation:

\[
V^i(\tilde{q}, \tilde{q}, s) = \max_{\tilde{q}'} \left[ \int_0^1 C(q') \, dq' \right] + \beta \int_0^1 E(V^i(\tilde{q}', \tilde{q}, s) | \tilde{q}, \tilde{q}, s, x^i) \, dx^i,
\]

where \(\beta\) is the common discount factor. The expectation operator \(E(\cdot)\) integrates over the probability distribution of all possible states (capacity and regulatory) in the next period. Firm 1’s beliefs about its competitor’s future capacity state and the current regulatory state are captured by the conditional probability distribution functions \(Pr(\tilde{q}' | \tilde{q}, \tilde{q}, s)\) and \(Pr(s'|s)\), respectively. Thus:

\[
E[V^i(\tilde{q}', \tilde{q}, s) | \tilde{q}, \tilde{q}, s, x^i] = \sum_{\tilde{q}'} W(\tilde{q}' | \tilde{q}, \tilde{q}) Pr(\tilde{q}' | x^i).
\]

where

\[
W(\tilde{q}' | \tilde{q}, \tilde{q}) \equiv \sum_s V^i(\tilde{q}', \tilde{q}, s) Pr(\tilde{q}' | \tilde{q}, \tilde{q}, s) Pr(s'|s).
\]

Conditional on beliefs about \(W(\cdot)\), optimal behavior reduces to a single agent optimization problem. As shown in Besanko and Doraszelski (2004), and unchanged by the expansion of the number of states in my model, the first-order condition (FOC) for an interior solution to this investment problem is given by:

\[
-1 + \beta \sum_{m} W(\tilde{q}''_{\infty} | \tilde{q}''_{m}, \tilde{q}) \frac{\partial \Pr(\tilde{q}''_{m} | x^i)}{\partial \tilde{q}''_{m}} = 0.
\]

Since the upper bound of production capacity is chosen to be at or above the lowest capacity where a firm always chooses not to invest, regardless of the states of its competitors, there will not be an interior solution when \(m=1, \ldots, M-2\). Solving the FOC for the optimal investment function gives:

\[
x^i = -1 + \sqrt{\beta \alpha} \left( (1-\delta)(W(\tilde{q}''_{M-1}) - W(\tilde{q}''_{M-2})) + \delta (W(\tilde{q}''_{M}) - W(\tilde{q}''_{M-1})) \right) \frac{\alpha}{\delta}.
\]

The second-order condition (SOC) reduces to:

\[
- (1-\delta)(W(\tilde{q}''_{M-1}) - W(\tilde{q}''_{M-2})) + \delta (W(\tilde{q}''_{M}) - W(\tilde{q}''_{M-1})) < 0.
\]

As a result, the SOC is satisfied provided a solution to the FOC exists. Therefore, the firm’s optimal strategy function will be:

\[
x^i(\tilde{q}, \tilde{q}, s) = \max_{\tilde{q}} \left( 0, -1 + \sqrt{\beta \alpha} \left( (1-\delta)(W(\tilde{q}''_{M-1}) - W(\tilde{q}''_{M-2})) + \delta (W(\tilde{q}''_{M}) - W(\tilde{q}''_{M-1})) \right) \frac{\alpha}{\delta} \right)
\]

when \(\tilde{q}''_{M}\) is not at the highest level.

2.6. Equilibrium and computation

As is common in this literature, I shrink the state space by restricting attention to symmetric equilibria and exploiting the “exchangeability” of firms (see Pakes and McGuire (2001)). The existence of a symmetric pure strategy equilibrium follows according to the arguments laid out in Doraszelski and Satterthwaite (2007), provided an upper bound is placed on production capacity. I follow the majority of the literature drawing on Ericson and Pakes (1995) in solving for the symmetric equilibrium using a variant of the Gaussian algorithm described in Pakes and McGuire (1994) and Pakes et al. (1993).\(^{16}\)

I first solve for firms’ equilibrium strategies when the timing of the regulatory transition is certain, obtaining my starting values by solving for the policy and value functions when \(N=1\). These estimates are used as the initial values in computing the equilibrium for the \(N=2\) case. I solve for the “regulatory certainty” MPE by backwards induction, using the estimates for firms’ behavior once the regulatory change has taken place from the “regulatory uncertainty” model as the behavior and value in the “final period”. I then solve for firms’ value and policy functions in the period prior to the regulatory

\(^{15}\) This is a very similar scenario to that considered in Weintraub et al. (2008).

\(^{16}\) All programs were written and run in Matlab 7.8. Details are available upon request.
change, conditional on those values. This process repeats until I have computed the policy and value functions for all R periods.

As uniqueness of the equilibria is not and cannot be guaranteed, it is necessary to check for multiple equilibria. As is common in this literature, I tested for the presence of multiple equilibria by varying the starting points of my estimation procedure, and consistently converged to the same solutions.17

2.7. Parameterization

As in Besanko and Doraszelski (2004) and Chen (2009), I assume that each discrete capacity element is a plant capable of producing 5 units of the good. The highest capacity M-1 state is 9. Thus, total productive capacity is between 0 and 45. α, the likelihood of receiving a depreciation shock, is set to 0.3, and λ, the parameter in the Ericson–Pakes probability function that affects the likelihood that investment is successful, is set to 0.125. As previously noted, marginal costs in the unregulated state are normalized to 0. I impose that they rise to 1 after the regulatory transition. The intercept of the inverse demand function α is set to 4, while the slope b is set to 0.1. As in Besanko and Doraszelski (2004), I set β equal to 1 / 0.25 18 λ indicates the probability of shifting into the new regulatory state if that has not yet happened. I solve the model for three different values of λ: 0.2 (which translates to E(R) = 6 and αR ≈ 4.5 periods), 0.1 (E(R) = 11 and αR ≈ 0.5 periods), and 0.05 (E(R) = 21 and αR ≈ 19.5 periods).

2.8. Baseline functions

Given the specified demand parameters, the single-period profits are determined according to the equilibrium selection methods discussed above. The first panel of Fig. 3 shows the single-period profits in the “unregulated” state for firm 1 in the market as a function of its own capacity and that of firm 2. Similarly, the second panel shows the single-period profits after the regulatory change has gone into effect. Intuitively, the second panel indicates the same overall patterns observed in the unregulated market only with lower payoffs.

The two panels in Fig. 4 show the equilibrium investment behavior in the unregulated and regulated states, respectively.19 Firms’ investment behavior in the two regulatory regimes is qualitatively similar. However, the level of investment is less in regulated markets, because the higher production costs mean that lower levels of production capacity are required. In both regulatory regimes, there is a capacity race dynamic because of the benefits of being the largest firm. This is revealed by the high levels of investment when firms have close to symmetric levels of production capacity. As in some models of technology races (e.g. Harris and Vickers (1987)), I find that the leading firm (i.e. the one with more capacity) generally invests more than the laggard. This holds true in my results except for when the leader approaches the maximal amount of capacity, at which point they have largely stopped investing.

The graphs in Fig. 5 show the value of being in the unregulated and regulated markets in different market structures. Unsurprisingly, they show that the value of being in the unregulated market is markedly higher for all capacity states. They also dramatize why firms engage in capacity races: the payoffs to being the larger firm are much larger.

Another way of understanding the capacity race dynamics can be found in the long-run steady states of the industries under the different regulatory regimes. I construct this long-run steady state using the calculated equilibrium investment functions, which avoids the possibility of simulation bias. Fig. 6 shows the long-run probability of being in different capacity states under the two regulatory regimes, when strategies are formed in the absence of knowledge of possible regulatory changes. Before the regulatory change, the ergodic distribution is bimodal, and implies that the long-run equilibrium is to have one large firm and one small one. While the limiting distribution is still bimodal after the regulatory change, the equilibrium is now to have a monopolist serve the entire market. Given the increased production costs, it is not cost effective for a smaller firm to make the necessary investments to remain in the market. Thus, firms in the regulated state engage in intense capacity races to see which firm becomes the monopolist and which “exits”.

3. Strategic implications of regulatory uncertainty

3.1. The effect of regulatory uncertainty on investment

In this subsection, I present an analysis of how investment behavior differs depending on whether or not firms know exactly when the regulatory state will change. I do this by focusing on firms’ policy functions in the period they learn that the current regulatory state will eventually change (i.e. period 1). At this time, firms in both certain and uncertain markets have the same expected number of periods in the unregulated state. Thus, variation in their policy and value functions can be attributed to the relative presence of uncertainty. In order to gain insight into how the level of uncertainty affects behavior, I vary E(R). Because the expected value of being in markets with different values of E(R) is not the same, strategies in markets with different values of E(R) cannot be directly compared. Qualitatively, firms’ policy functions when the change’s timing is both certain and uncertain closely resemble those observed above in Fig. 4.20 Moreover, the results for the different E(R)s are intuitive: Because firms expect (know) that they will have more unregulated periods for large values of E(R), they invest more. However, if one looks closely, there are interesting differences between the results for regulatory certainty and

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17 Many articles employing the Ericson and Pakes (1995) framework and Pakes and McGuire (1994) algorithm have not found multiple equilibria (e.g. Besanko and Doraszelski, 2004; Goettler et al., 2005; Chen, 2009; Markovich and Morenius, 2009). However, several recent articles have found them (e.g. Doraszelski and Satterthwaite, 2007; Borkovsky et al., 2009; Besanko et al., 2010). Borkovsky et al. (2009) present evidence that the possibility of entry and exit may increase the likelihood of multiple equilibria. While I consistently converged to the same equilibrium for my baseline parameterization, for robustness checks examining a substantially larger increase in firms’ marginal costs I did find evidence of possible multiple equilibria.

18 As a robustness check, I also solved the model for smaller values of λ. Intuitively, the results were qualitatively similar, but had analogous effects to decreasing λ.

19 Because of the similar parameterizations, the first panel closely resembles panel 4 of Fig. 7 in Besanko and Doraszelski (2004). There are mild differences for very low levels of capacity, because Besanko and Doraszelski (2004) rule out the possibility that depreciation affects firms with 0 current capacity stocks.

20 Depictions of the policy functions for certain and uncertain markets under different E(R)s can be found in Fig. 13 in Appendix A.
uncertainty across the different values of $E(R)$. These are illustrated in Fig. 7, which shows the difference between the investment functions of firms in certain and uncertain markets for each of the $E(R)$s. When the difference is greater than 0, firms invest more in a given capacity state when they know with certainty when the regulatory change will take place than when they do not. In these market structures, uncertainty reduces investment. However, as the Figure shows, I find that in some circumstances the difference is negative, meaning that sometimes uncertainty increases firms’ incentive to invest.

When the regulatory regime is expected (known) to occur soon (i.e. $E(R) = 6$), I find more uncertain than certain investment when firms have large amounts of capacity. When the regulatory transition is expected (known) to occur in the medium-term (i.e. $E(R) = 11$), the same general pattern is true but for higher values of capacity. In no cases do I find greater investment under uncertainty when the regulatory change is expected (known) to occur in the distant future (i.e. $E(R) = 21$).

The finding that when $E(R)$ is small, firms with large capacity stocks respond to uncertainty by increasing investment (relative to the certainty case) while the reverse is true for small firms is predominantly driven by the nature of the uncertainty, which concerns the timing of a negative shock. This is demonstrated by the fact that it occurs even in the monopoly case as can be seen in Fig. 8, which shows the equilibrium policies of a monopolist in certain and uncertain markets for $E(R) = 6$.

As in the duopoly case, a monopolist with a large amount of capacity will invest (slightly) more when it does not know the exact timing of the change than when it does. The reasons for this behavior are intuitive. In the model, the state of the world confers information to the firm about the likely duration of the unregulated state. As seen above in Fig. 3, the profits to being in the market fall markedly after the policy change increases firms’ marginal costs. Before the change, firms must trade off the desire to maintain high capacity stocks during the unregulated period so as to serve relatively high demand with the undesirability of having a large capacity overhang at the time of the regulatory change. Knowing with certainty when the transition will take place allows for more precise calibration of how much to cut investment if a firm has a large existing capacity stock. Conversely, being aware of the transition date means that a firm with a small capacity stock knows that additional investment will not be wasted.

As can be seen in Fig. 7, however, the degree to which a firm invests relatively more or less under uncertainty is also influenced by its competitor’s capacity. This reflects the strategic interaction between firms. As shown in Fig. 6, in the long-run, there is only room in the regulated market for one firm. Before the change, firms adjust their investment patterns depending on whether or not they have already achieved or still can achieve a dominant position.

These adjustments are particularly pronounced when the change is known or expected to be soon (i.e. $E(R) = 6$), and are visible in Fig. 9, which shows the percent increase from regulatory uncertainty (RU) to regulatory certainty (RC) for a monopolist and a duopolist.\textsuperscript{21} For example, the Figure shows that if firm 1 is competing with firm 2, then it continues to invest more under certainty than under uncertainty for much higher levels of capacity than in the monopoly case so long as it has the lead in the capacity race. This is because firm 2 will keep investing since it knows that it has a certain amount of time in the unregulated state even if it cannot achieve a dominant position. Firm 1 wants to ensure that it remains the dominant firm; therefore, it must continue its own (relatively) aggressive investment strategy.

The greatest relative increase in investment by firms in certain markets occurs when firms have low but relatively symmetric stocks of capacity. In this case, the firms have an incentive to race to establish themselves as the dominant firm by the time of the regulatory change so that they earn monopoly profits indefinitely thereafter. Investment by firms in uncertain markets still has a capacity race dynamic in these market structures – as can be seen in Fig. 13 in Appendix A – but it is moderated because the time of the transition could be distant.

Because firms earn the lowest profit when both have very large capacity stocks, the largest relative reductions in certain investment occur when a firm has a lot of capacity but not as much as its competitor and the regulatory change is known (anticipated) to occur fairly soon. In such situations, the smaller firm slows its investments because it realizes

\textsuperscript{21} As noted above in footnote 1, my results generalize to situations where the magnitude of the Pigouvian tax is not sufficient to reduce the industry to a monopoly. However, the cost is sufficient to dramatically reduce the payoffs to being the smaller firm. Thus, the weaker firm will invest less, and there will be more periods where it disappears from the market.
that there is little likelihood that it will become dominant, so it makes more sense to earn profits as a low-capacity firm in the remaining unregulated periods. By contrast, firms in similar capacity states that only have an unbiased estimate of when the regulatory change will occur continue investing comparatively aggressively. They do this as there is a reasonable chance of achieving an inversion in the market structure, and there are lopsided payoffs to achieving it.

It is intuitive that I observe greater investment by certain than uncertain firms for all market structures when the timing of the change is known (anticipated) to be distant. The certain firms know that there is plenty of time for the stochastic depreciation shocks and other elements to ensure that they do not carry too much capacity into the regulated state. In the meantime, firms in all market structures wish to invest in order to ensure that they earn the maximum amount of profit during the unregulated period and position themselves to potentially be the long-run monopolist. By contrast, even though the regulatory change is unlikely to occur in the next period, its possibility mutes uncertain firms’ incentives for carrying high levels of capacity given the much lower profitability of capacity in the regulated state. This helps to explain the fact that there is much higher relative investment by certain firms in the market structures with high levels of capacity.

Overall, the results indicate there is no clean comparative static for the effect of regulatory uncertainty on oligopolists. To predict responses to an anticipated cost shock, it is necessary to understand the initial market structure. Although the setting is very different, we can relate these findings to Hartman (1972) and Abel (1983), where assumptions about the convexity of the marginal product of capital produced the opposite prediction of the real options literature. The combination of strategic incentives and the nature of the regulatory change in this setting sharply increase the marginal product of additional capital in some industry structures, which leads to greater investment under uncertainty in some cases.

My results can also be related to previous work on strategic interaction in declining industries. The model utilized here generates results that contrast with those of Ghemawat and Nalebuff (1985), whose model predicts that in a shrinking market, it is the largest firms that exit first. In large part, the difference in the results can be attributed to their modeling assumption that firms must either fully utilize capacity or exit. By contrast, I allow firms to leave capacity idle; moreover, firms can shrink by ceasing to invest to offset the depreciation results. Instead, my results are similar to those of Whinston (1988), who shows that size conveys an advantage in declining markets to multi-plant firms when plant sizes are symmetric. This article’s results on firms’ equilibrium policies also resemble, in some ways, those of Besanko et al. (2010), who find multiple equilibria in their assessment of demand uncertainty’s impact on investment dynamics. However, in two out of the three equilibria that they uncover, size bestows strategic benefits on firms as seen in this article.

### 3.2. The value of certainty

This subsection considers how firms’ value functions differ according to whether or not the timing of the regulatory change is certain or uncertain. Intuitively, the results show the same general relationship as in Fig. 5.22 As for investment, there are subtle differences based on whether the timing of the change is certain or not. Fig. 10 shows this difference for each possible capacity state for the different values of $E(R)$.

For the most part, the figure is consistent with the comments of industry experts and leaders that firms prefer the regulatory horizon to be clearly defined.23 However, in some instances, the value of firms is higher when the regulatory change’s timing is uncertain. As before, these states occur mainly when $E(R) = 6$. I find that firms with zero capacity stock facing competitors with large capacity stocks are worse off when the change’s timing in certain. This is consistent with the discussion in the previous subsection. In such market structures, it is virtually certain that the smaller firms will not be able to invert the market structure and become the long-run monopolist when the timing of the change is certain. Similarly, if both firms have at least $\gamma$, I find that they have lower values in certain markets, which reflects the fact that they are likely to experience multiple periods of zero

22 Depictions of value functions in the different markets for different $E(R)$s can be found in Fig. 14 in Appendix A.

23 For example, General Electric’s CEO, Jeffrey Immelt, in an editorial about climate change regulation states, “All that we ask for – and this will allow us to grow as a healthy, responsible company – is consistency” (Kosterlitz, 2009).
profits until depreciation and stochastic investment shocks establish a dominant large firm and an eventual exiting small one.

4. Welfare and regulatory uncertainty

Having established that uncertainty about the timing of a regulatory change has a significant impact on oligopolists’ investment and value functions, I now explore the implications these differences have for market structure and social welfare.

4.1. Methodology

I present the average values of a variety of industry performance metrics in different periods below. I determine these values in the following manner.

First, I determine the starting state. This could be any possible combination of capacities $q_1, q_2$ and regulatory regime $s$. However, my baseline initial state is the ergodic distribution of the unregulated regime shown in the first panel of Fig. 6. I make this assumption because most cost-increasing regulatory changes occur to mature industries that evolved for many years without grounds for assuming the likelihood or severity of future regulation.24

Let $E$ be the vectorized matrix of probabilities underpinning Fig. 6 that the industry is in any given capacity state. Similarly, let $X$ be the vectorized matrix of values of some industry metric (e.g. profits, investment, concentration, etc.) conditional on the capacity state.

Fig. 9. Relative difference between RC and RU.

Fig. 10. Difference in value functions between certain and uncertain markets.

24 I have also explored the implications of choosing other initial states. In particular, I focused on the implications for “new” industries, where both firms start out at $q_1 = 0$. Figs. 15 and 16 in Appendix A present the analogs to Figs. 11 and 12, which are discussed in the text. The qualitative differences between certainty and uncertainty remain, though they are now in the context of an intense initial capacity race. Interestingly, I find much larger percentage improvements from removing uncertainty in welfare for the $E(R) = 10$ and $E(R) = 20$ cases than for established industries. However, for $E(R) = 6$, I find that uncertainty has a marginally positive impact on social welfare. This appears to be due to the enormous amount of capacity investment that takes place as firms compete to see which will be dominant. Such investment effectively negates their profits.
Then, the average value of that metric in the first period of the model will be $\bar{x}_1 = E X$. For any subsequent period $t$, the average value will be $\bar{x}_t = E M^{t-1} X$, where $M$ is the Markov transition matrix for all combinations of capacities and regulatory states.

### 4.2. Graphical analysis

I begin by graphically analyzing the differences between regulatory uncertainty (RU) and regulatory certainty (RC) across the values of $E(R)$ for industry concentration, aggregate industry investment, and aggregate profits.

Fig. 11 shows the average value of the Herfindahl–Hirschman Index ($HHI$) for 100 periods for the different modes of regulatory transition. As noted above, the arrival of the Pigouvian tax ultimately leads one firm to leave the market by letting depreciation reduce its capacity stock to 0. Thus, the long-run concentration rate is around 1 — i.e. a monopoly. Fig. 11 indicates that there are not dramatic differences across values of $E(R)$ for each method of transition. As with the investment and value functions examined above, however, there are distinct differences between the uncertainty and certainty cases. Consistent with the fact that regulatory changes begin occurring immediately in the regulatory uncertainty case, these markets begin to converge to the long-run level of concentration in regulated markets first. By contrast, the regulatory certainty case starts converging later. The reason for this is as follows. Fig. 6 shows that there is a strong probability that there will be two firms with significant capacity stocks to begin with. Until one of them establishes itself as dominant, these firms will invest intensively. This causes the markets to become increasingly concentrated, even overshooting the long-run steady state before converging back to it as one firm establishes itself as dominant.

The corollaries to the differences in concentration appear in Fig. 12, which shows the average aggregate industry investment and profits during each period by firms in each type of market. The first column shows average investment patterns in certain and uncertain markets. When the Pigouvian tax’s arrival time is known, average investment is initially higher. This is the period during which firms aggressively invest to achieve a position of dominance. Once this has been established, investment falls below the mean level in the uncertain markets until the period of the regulatory change, at which time it begins to rise back to the long-run level for regulated markets.

The second column of graphs in Fig. 12 shows the variation in cumulative per period profits across the different regimes. When firms know the exact date of the regulatory change, profits spike just before the regulatory state switches. This reflects the “exit” or accommodation of low-capacity firms’ before the switch. If the low capacity firm actually exits as a consequence of reduced investment and the depreciation shocks, the remaining high-capacity firms earn monopoly profits even before the regulatory change. Even if there is no exit, by stratifying into high- and low-capacity firms, both earn significant payoffs. After the regulatory change, however, a brief period of low profits occurs in certain markets. This reflects the fact that some of the certain markets will still contain firms with sufficient capacity that all firms earn zero (or very low) profits. As expected, profits in the regulatory uncertainty markets display no sharp variations, slowly converging to the always-regulated market average.

### 4.3. Net present value estimates

Having established that significant differences exist in how firms respond to the prospect of certain vs. uncertain regulatory change, the question of cumulative impact remains. I assess this question by calculating net present value (NPV) estimates using the average values considered in the previous subsection and the discount factor $\beta$. As in Figs. 11 and 12, I limit consideration to the 100 periods following the discovery that the regulatory state is subject to change. Thus, the NPV of a given welfare statistic $x$ equals $\sum_{i=1}^{100} \beta^{i-1} x_i$.

Using this approach, I consider differences in profits, investment, environmental damages, consumer surplus, and total welfare for each of the three values of $E(R)$ being considered. Total welfare is the sum of industry profits and consumer welfare net of environmental costs and investment expenditures. Consumer welfare is straightforwardly calculated using the linear demand curve, and the equilibrium price functions. To determine the environmental costs, I assume that the Pigouvian tax exactly offsets the externality. Therefore, the net present value of the environmental costs may be calculated as the net present value of all production multiplied by the change in marginal costs. The results are shown in Table 2. As previously noted, I cannot directly compare results when the value of $E(R)$ is not the same. Instead, I emphasize similarities.
Examining the NPV estimates, I find that regulatory certainty always produces higher total welfare. Moreover, the relative benefit of certainty increases in the level of uncertainty about the arrival time of the regulatory shock. When the arrival time is fairly certain, society can be improved, on average, 3.3% by making it definite. However, when the arrival time is quite difficult to predict, total welfare can on average be raised 8.5% by making the timing known. Table 2 indicates that on average the NPV of investment spending is greater under uncertainty than certainty for both \(E(R) = 6\) and \(E(R) = 10\). Consistent with the aforementioned industry anecdotes, the NPV results suggest that firms earn the highest net profits when they know the industrial environment’s trajectory. Consumer surplus is always highest when the regulatory trajectory is certain.

Overall, my results imply that there are real costs to leaving policy uncertain, although the magnitude will vary with the level of regulatory uncertainty. I find that one of the drivers of these costs is that uncertainty about the timing of a regulatory change can lead to inefficiently large amounts of investment spending as firms try to position themselves as the market leader in the smaller post-regulation markets. Though it is implausible to imagine that periods of policy uncertainty can be done away with completely, the model’s results indicate that policy-makers should keep in mind that firms in concentrated industries rationally respond to uncertainty by modifying their investment strategies. As these modifications impact overall welfare, a prolonged debate over comparatively small elements of the ultimate regulatory package may lead to worse outcomes. My results thus support the contention of Bushnell and Ishii (2007) that sometimes accepting a second best solution and removing uncertainty may be better than fighting for an optimal approach.

5. Conclusion

Contributing to a growing literature on how firms cope with both exogenous and strategic uncertainty, this article uses a model based on the Ericson and Pakes (1995) framework to consider how capacity-constrained competitors adjust their investment strategies in response to uncertainty about the timing of a Pigouvian tax. I find that this form of uncertainty has different impacts depending on the level of uncertainty and firms’ relative position within the market. This occurs for two reasons. First, knowing the timing of the change allows firms to calibrate their investment strategies to avoid carrying excess capacity into the regulated world while also ensuring they are able to serve higher demand before the change. This increases investment incentives (relative to uncertain firms) for firms with small capacity stocks, while dampening the relative incentive for large firms. Second, firms’ investment will vary as a function of their strategic incentives, which depend on the market structure and whether or not the timing of the change is known. When it is certain, the weaker firm in some structures has a clearer sense of whether it can (not) invert the market structure, leading to higher (lower) investment than the uncertain case.

In addition to comparing firm strategies in relation to uncertainty, I also use the equilibrium policy functions to calculate the impact on social welfare of the method of regulatory change and whether it varies with the level of uncertainty. The results indicate that total welfare is consistently maximized by fixing the timing of the regulatory change. This suggests that, on average, total welfare can be increased if policymakers settle for the good rather than holding out for the ideal.25

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Net present values.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(E(R) = 6)</td>
</tr>
<tr>
<td>Profits</td>
<td>470.98</td>
</tr>
<tr>
<td>Investment</td>
<td>72.33</td>
</tr>
<tr>
<td>Environmental costs</td>
<td>241.02</td>
</tr>
<tr>
<td>Consumer surplus</td>
<td>266.58</td>
</tr>
<tr>
<td>Total welfare</td>
<td>324.2</td>
</tr>
<tr>
<td>% Gain in total welfare</td>
<td>3.3%</td>
</tr>
<tr>
<td>% Gain in investment</td>
<td>-2.0%</td>
</tr>
</tbody>
</table>

Fig. 12. Comparing investment and profits across regulatory states.
Overall, my results have broad implications insofar as they demonstrate that the presence of uncertainty may not have consistent effects across industries or markets, depending on their level of concentration and the nature of the uncertainty. This indicates the need for careful consideration of initial conditions before making predictions about the implications of changes in the level of uncertainty in concentrated industries. I believe that expanding the model further to incorporate a richer set of strategic choices—such as allowing firms to hold different types of productive assets or invest in “lobbying” efforts that affect the likelihood of the regulatory changes—would allow for interesting insights into the political economy of the policy process (see, e.g., Lyon (2007)).

Appendix A

Fig. 13. Comparing policy functions for certain and uncertain markets.

Fig. 14. Comparing value functions for certain and uncertain markets.
Fig. 15. Concentration across regulatory states for new industries.

Fig. 16. Comparing investment and profits across regulatory states for new industries.

References


