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Patents, imitation and licensing in an asymmetric dynamic R&D race[☆]

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ABSTRACT

R&D is inherently a dynamic process which typically involves different intermediate stages that need to be developed before the completion of the final invention. Firms are not necessarily symmetric in their R&D abilities; some may have an advantage in early stages of the R&D process while others may have advantages in other stages of the process. This paper uses a two-firm asymmetric-ability multistage R&D race model to analyze the effect of patents, imitations and licensing arrangements on the speed of innovation, firm value and consumers' surplus. By using numerical analyses to study the MPE of the R&D race, the paper demonstrates the circumstances under which a weak patent protection regime, that facilitates free imitation of any intermediate technology, may yield a higher consumers' surplus and total surplus than a regime that awards a patent for the final innovation. The advantage of imitation may hold even when we allow for voluntary licensing of intermediate technologies.

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1. Introduction

Patents are designed to provide incentives for innovation. The conventional wisdom is that by protecting innovators from imitation we encourage R&D investment and promote innovation. Recently this rationale has been challenged. There are evidences that the software and computer industries were most innovative in particular during the period of weak patent protection through which these industries experienced rapid innovation (see Bessen and Maskin, forthcoming; Hunt, 2004; Gallini, 2002).[1]

R&D races are inherently dynamic processes that take place over time and may involve several intermediate stages. Firms may adjust their R&D investments over time given their assessments regarding their relative success in the race.[2] The race typically involves the development of different intermediate inventions or complementary technologies that may enable the firms to complete the invention. Furthermore, firms are not necessarily symmetric in their R&D abilities. Some firms may display better abilities in several stages of the R&D race while other firms may exhibit better abilities in other stages of the race. For example, in the pharmaceutical market small startups are typically more efficient in the development of a new drug than the big pharmaceutical companies. In converse, once the drug reaches the preclinical development stage, the large pharmaceutical companies have a clear advantage over small startups.

The distinction between “protection at the end of the race” and “protection during the race” is a central part of our analysis. Some regimes provide strong protection of the final innovation, but no protection for intermediate stages, while others may also protect the intermediate stages. Our main comparison will be between two different types of regimes. In the first, there is strong protection on the final innovation and an effective protection on intermediate discoveries (they cannot be imitated but they are not subject to patent protection). The second regime allows for imitation of any discovery; intermediate or final. Based on these two extreme cases, the paper studies the effect of a weak patent protection regime that facilitates technology imitation in an asymmetric-ability multistage innovation race.

We consider a two-firm multistage R&D race in which one firm has a technological advantage in the early stages of the race while the second firm has a similar advantage in the last stages of the race. The multistage race is a convenient setting that captures the knowledge accumulating process during the race. In these settings, each firm needs to go through several stages of R&D in order to complete the invention (e.g., Fudenberg et al., 1983; Harris and Vickers, 1985, 1987; Grossman and Shapiro, 1987; and Lippman and McCardle, 1987). The paper compares an R&D race with strong patent protection in which a patent is awarded for the final innovation and intermediate technologies cannot be imitated and a race with weak patent protection

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[1] See also the survey in Cohen et al. (2000).

[2] For dynamic R&D models, see for example Reinganum (1981, 1982), Fudenberg et al. (1983), Harris and Vickers (1985, 1987), Grossman and Shapiro (1987), Lippman and McCardle (1987), Malueg and Tsutsui (1997), Judd (2003), Doraszelski (2003) and the survey of Reinganum (1989).

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in which any intermediate technological discovery by one firm can be costlessly imitated by its competitors (hereinafter CTI—Complete Technology Imitation). These are clearly the two extreme cases. In particular, free and costless imitation is not always feasible, thus we view it as a benchmark case. We then introduce the possibility of licensing intermediate technologies and compare the CTI case with an R&D race in which imitation is not possible but instead firms may license their intermediate technologies.

We provide a numerical analysis of these R&D races using a variant of the value function algorithm developed in Pakes and McGuire (1994). We solve for the Markov perfect equilibrium of these races for a wide range of parameters' value and compare the speed of innovation, firms' value, consumers' surplus and investment strategies for each type of race. Our main finding is that in a dynamic asymmetric-abilities R&D race, a weak patent protection regime in the form of CTI may provide higher consumers' surplus and higher value for firms than a strong patent regime.

Our comparison focuses on three key variables that affect the outcome of the race; (i) the degree of ability asymmetry, (ii) the final prize, i.e., the size of the market relative to the cost of innovation and (iii) the intensity of the duopolistic market competition which determines the outcome of a race with imitation or licensing and the market outcome after a patent expired.[3]

Our analysis indicates that the possible advantage of the CTI regime depends on the degree of ability-asymmetry between the firms. If the asymmetry in R&D abilities is sufficiently large, the CTI regime may provide higher consumers' surplus and higher value for firms than regimes that provide patent protection. This advantage, however, disappears when firms have identical or similar R&D abilities.[4] Furthermore, when the product market is small relative to the cost of innovation or when there is an intense duopolistic competition, the CTI regime does not provide sufficient incentives for innovation and the traditional rationale for patent protection holds.

The intuition behind the above results is derived from two conflicting effects. On the one hand, an R&D race with a CTI regime always ends up with a duopoly—implying a lower prize at the end of the race and thus lower incentives to invest. On the other hand, the R&D process itself may be more efficient under the CTI regime. When abilities are identical, the free rider problem reduces the firms' incentives to invest in R&D which implies a slow pace of innovation and consequently low consumers' surplus and a low value for firms. A high degree of ability asymmetry, in converse, induces firms to specialize in developing the technologies they are better at. Thus, one can think of the ability asymmetry as a coordination device that facilitates specialization and alleviates the free riding problem.

The possibility of licensing intermediate technologies may also enable firms to specialize and take advantage of their asymmetric R&D abilities. We, therefore, consider an R&D race in which firms may license their intermediate technologies. Licensing occurs whenever it creates a surplus and we assume that the firms share this surplus equally. We find that in the symmetric-abilities case there is no voluntary licensing. In the asymmetric case, however, the possibility of licensing indeed facilitates specialization resulting in a more efficient R&D process and higher values for firms. We compare the equilibrium performance of the R&D race with licensing to the performance of the race under the CTI regime and demonstrate the conditions under which the CTI regime still yields higher consumers' surplus than the race with licensing.

[3] While both the size of the final prize and the intensity of the duopolistic competition affect the size of the prize, they do not have the same effect. For example, the intensity of the duopolistic competition affects the outcome only whenever we end up with a duopolistic market (and thus has no affect on the E-Pat regime). We discuss the difference between the two effects below.

[4] Symmetry in this context corresponds to firms with identical abilities. It is still possible that the early stages of the innovation are more difficult and more costly for both firms than the other stages of the innovation process.

The possible advantage of weak patent protection was also considered by Bessen and Maskin (forthcoming). Their paper considers a model in which an R&D investment generates a fixed probability of success. Once investment fails, the innovation process stops unless the firm is able to imitate the success of another firm. In such a setup imitation may reduce the firm's current profit but it raises the probability of further innovation and improves the prospect of capturing higher values. Our R&D model is different as we assume a multistage innovation process with a fixed final value rather than sequential innovation. Investment effort is endogenous and failure in one period leads to continuation of effort in the next period. Our main result is that in such R&D processes, imitation is beneficial only in the asymmetric case where firms have different abilities.

Our paper is also related to Judd et al. (2007) that focuses on dynamic multistage innovation races in which patents may be awarded at one of the intermediate stages. Using a numerical analysis, the paper considers the optimal innovation stage at which the patent is awarded and the optimal magnitude of the prize to the winner. Cumulative innovation has also been studied by Scotchmer (1991, 1996) and Scotchmer and Green (1990). In their setup the innovations are not isolated discoveries. Each innovation is built on prior discoveries. In such an environment there can be insufficient incentives for R&D investment if successful firms earn market profits only until competitors develop the next generation of products. These papers consider the solution of transferring some of the profits from the second generation innovators to the initial innovators in order to induce sufficient incentives for R&D investment for the early innovators.[5]

The rest of the paper is organized as follows. Section 2 provides the details of the R&D races. In Section 3 we present the results of the numerical analysis and discuss the role of ability asymmetry and the possibility of imitating intermediate technologies. Section 4 discusses the firms' strategies and descriptive statistics of the asymmetric race. In Section 5 we introduce the possibility of licensing and examine whether licensing may have the advantage of imitation but without reducing the incentives to innovate.

2. Asymmetric R&D races

We start by presenting our benchmark multistage R&D race model in which firms are required to complete the development of several stages prior to the completion of the invention. In the benchmark case, a patent is awarded to the first firm who completes this process and imitation is either not feasible or prohibited.

2.1. Benchmark model: a multistage R&D race with an end patent

Our benchmark model is a two-firm asymmetric-ability n-stage R&D race in which a patent is awarded to the first firm that completes the development of the n intermediate stages. Moving from step l to step $l+1$ is a stochastic process depending on the firm's investment. Letting $x_i \geq 0$ be firm i's investment, we assume that the probability of success, i.e., $p(l+1|x_i,l)$ and denoted by $p(x_i,l)$, is increasing in x_i. If a firm is unsuccessful in moving from step l to $l+1$ in one period, it can try again in the next period.[6]

We assume that the firms are not symmetric in their R&D abilities, and capture this asymmetry by allowing for different cost profiles. Let $c^i=(c_1^i,\ldots, c_n^i)$ be firm i's cost profile, which represents the firm's abilities at different stages of the R&D process. A lower c_l^i implies a greater ability in developing intermediate technology $l+1$. Firm i's cost of investing x_i at stage l is then $c_l^i x_i$.

[5] See also O'Donoghue (1998) which discusses patentability requirements to solve this problem.

[6] An alternative formulation would be to consider a race with learning such that any attempt to move from one stage to the other provides information on the likelihood of having a successful innovation at the end, see Malueg and Tsutsui (1997).

A two-firm R&D race will be defined as $R\equiv\{n, (c^1,c^2),\pi^M\}$ where n is the number of intermediate technologies, (c^1,c^2) are the firms' costs profiles and π^M is the monopolistic profit in the product market—the prize at the end of the race. We assume that the two firms are symmetric in the product market. If a single firm holds the patent, then its reward is the monopolistic profit π^M, while the other firm makes zero profit. When both firms reach the patent stage at the same period, we assume that each firm obtains the patent with probability 0.5. We further assume that firms maximize discounted payoffs and let β be the firms' common discount factor. When we allow for imitation and licensing which may imply that the innovation race ends up with a duopolistic industry, the final prize is the duopolistic profits, π^D; where $\pi^D<\pi^M/2$. While, we do not have a specific model of the duopolistic interaction, we allow for a range of possible outcomes that we specify in Section 3.1.

We consider the Markov Perfect Equilibrium (MPE) of the race. The state of the race is defined as (l,m); i.e., firm 1 is at stage l and firm 2 is at stage m. At every period, firms need to decide simultaneously on their investment level given the state of the race (l,m) and their respective cost profile, regardless of how this state has been reached. Firm i's strategy can be, therefore, denoted by $x_i(l,m)$.

A *Markov Perfect Equilibrium* for a two-firm R&D race $\{n, (c^1,c^2),\pi^M\}$ is defined by

- Investment strategies $x_i^*(l,m)$ for $i=1,2$ and every possible state (l,m).
- Value functions $V_i(l,m)$ for $i=1,2$ and every possible state (l,m).[7]

Such that:

(i) The strategies $x_i^*(l,m)$ are optimal given the value functions $V_i(l,m)$.
(ii) For every state (l,m), the value functions describe the present value of profits realized when both firms play the equilibrium strategies $x_i^*(l,m)$.

In calculating the value functions $V_1(l,m)$ and $V_2(l,m)$, we make repeated use of the following Bellman equation:

$$V_1(l,m)=\begin{cases}\pi^M & l=n, m<n\\ 0.5\pi^M & l=n, m=n\\ \max\limits_{x_1\geq 0}\left\{-c_l^1x_1+\beta\sum\limits_{l',m'}V_1(l',m')p(l'\mid x_1,l)p(m'\mid l,m)\right\} & l<n, m<n\\ 0 & l<n, m=n\end{cases} \tag{1}$$

Where $p(l'|x_1,l)=p(x_1,l)$ if $l'=l+1$; $p(l'|x_1,l)=1-p(x_1,l)$ if $l'=l$; $p(m'|l,m)=p(x_2^*(l,m),m)$ if $m'=m+1$; and $p(m'|l,m)=1-p(x_2^*(l,m),m)$ if $m'=m$.

2.2. Patent policy, imitation and R&D races

In general, the characteristics of an R&D race are governed not only by the patent regime, but also by the realities of each industry. For example, in some industries it is relatively easy to observe the intermediate technologies obtained by rival firms and thus to condition R&D investments on these observations, in other industries only some (or none) of the intermediate technologies are observable. Furthermore, there are industries in which imitation is relatively easy (either of intermediate steps or of the final innovation), while in other industries trade secrets provide a relatively strong protection and imitation is not feasible. Protection is, therefore, a combination of legal environment, which allows one to protect an innovation by patents, and the strength of trade secrets. In considering multistage R&D races one may distinguish between protecting the final innovation and protecting intermediate technologies. Intermediate technologies may be patentable as well. A patent for an intermediate technology may block the race at some intermediate level. In this paper we consider two benchmark cases of strong and weak patent protection. Note, however, that our setup is flexible enough to consider different types of patent regimes.

2.2.1. Strong patent protection

In our analysis we will study two related types of an R&D race with strong patent regime. In the first, the patent is awarded to the first firm that completes all the innovation stages and there is no expiration to this patent. We denote this case as E-Pat and its details are provided in our benchmark model described in Section 2.1. The E-Pat regime, however, may provide a patent protection which is too strong. Thus, we also consider the case in which a patent is awarded for only τ periods. Once the patent expires there is free imitation and the market becomes duopolistic. The length of the patent affects the firms' incentives to innovate but also limits the period in which the firm can exploit its monopolistic power. For each race we calculate the optimal patent length and denote this case as Opt-Pat case.[8] We use consumers' surplus as the criterion for calculating the length of the optimal patent.[9]

Clearly the Opt-Pat regime yields, by definition, better performance than the E-Pat case. However, in our analysis of Opt-Pat regime, the optimal patent length, τ, may vary with the parameters of the R&D race. Consequently, the Opt-Pat regime cannot be implemented as a general patent protection regime but provides a benchmark for comparison with the CTI. We provide the details of the Markov Perfect Equilibrium and the Bellman equation for the Opt-Pat case in Appendix A.

2.2.2. Weak patent protection

We consider a race in which firms may imitate any intermediate technology developed by the other firms. We assume that imitation is without any cost or delay.[10] This may be an extreme assumption but we would like to examine the role of a complete open environment in which every development is imitatable. An alternative interesting case allows only for imitation of the final innovation. In this case the final prize is lower, the standard free riding problem is still present and the firms cannot benefit from a more efficient R&D process which is derived from the possible specialization which characterizes the CTI race. Consequently, we do not consider this case in this paper.

3. Analysis of R&D races

3.1. Details of the numerical analysis

We adopt the algorithm developed in Pakes and McGuire (1994) to calculate the Markov Perfect equilibrium of the different races.[11] For each state, the algorithm calculates the value functions by using the relevant monopolistic and duopolistic profits and the Bellman Eq. (1).

The algorithm is iterative and works as follows: First, the algorithm initiates the value function $V^0(l,m)$ and investment level $x^0(l,m)$ for states (l,m) with $\max\{l,m\}=n$. $V^0(l,m)$ is initiated with the corresponding monopolistic and duopolistic profits based on the patent regime, and $x^0(l,m)$ is set to zero. States (l,m) where $l,m<n$ are initiated with an arbitrary value function $V^0(l,m)$ and investment level $x^0(l,m)$. The algorithm then works iteratively. To move from iteration k to iteration $k+1$, the algorithm takes the value function $V^k(\cdot)$ and policy

[7] For convenience, we suppress dependence of the value function on the firms' cost structures and the different prizes.

[8] For a discussion on optimal patent policy see, for example, Nordhaus (1969), Klemperer (1990), Gilbert and Shapiro (1990) and Denicolo (1999, 2000).

[9] In order to calculate consumers' surplus, we present in the next section a demand function. For every market outcome we calculate consumers' surplus in the standard way. Note that while we choose consumers' surplus as our criterion there are clearly other possible criteria e.g., total welfare.

[10] For simplicity, we focus on the extreme case of free imitation. Clearly, there are cases in which imitation is costly and requires some reverse engineering. This can be captured by a framework that assumes that any success of one firm reduces the cost of innovation (of the same technology) for the other firm.

[11] Another alternative would be to use the backward iteration algorithm presented in Judd et al. (2007). This would obviously give the same results. Given our small state space we were not looking for the fastest algorithm.

function $x^k(\cdot)$ as its input and uses the Bellman Eq. (1) to generate updated values and policy functions, separately for each firm. In each iteration, the algorithm first uses $V_1^k(\cdot)$ and $x_2^k(\cdot)$ from memory and solves Eq. (1) to calculate firm 1's investment strategy, $x_1^{k+1}(\cdot)$. It then takes the calculated $x_1^{k+1}(\cdot)$ and computes firm 1's value function, $x_1^{k+1}(\cdot)$. The same calculations are then done to compute firm 2's values $\{V_2^{k+1}(\cdot), x_2^{k+1}(\cdot)\}$. The algorithm iterates over the value functions and the investment strategies, and stops when $\{V^k(\cdot), V^{k+1}(\cdot)\}$; and $\{x^k(\cdot), x^{k+1}(\cdot)\}$ are very close point-wise between iterations.[12]

The equilibrium investment strategies $(x^*(\cdot))$ are then used to construct the transition probabilities matrix, i.e., the probability distribution over tomorrow's state (l',m') given today's state (l,m). This allows us to use tools from stochastic process theory to analyze the equilibrium Markov process and the appropriate descriptive statistics.

Pakes and McGuire (1994) consider an infinite horizon dynamic game. In such a setup existence and uniqueness is not guaranteed, see Doraszelski and Satterthwaite (2007) for a discussion on the existence and uniqueness of MPE in dynamic games.[13] Our setup is simpler as we study a finite race with known prizes. Given that firms start the race, the race will end (with probability 1) at a finite number of periods. The values at the end of the game are well defined by the rules of the race. One can, therefore, use these values together with the iterative algorithm and backward induction to calculate the value of firms and the equilibrium strategies at other states of the race. Since we have a finite stage race the existence of Markov Perfect Equilibrium is guaranteed for our setting.

3.1.1. Parameter values

We take a period to be a quarter and assume an annual interest rate of 10%. This corresponds to a discount factor of $\beta = 0.97$.[14] Since the paper focuses on asymmetric abilities, we set the length of the race such that it is long enough to capture the effects of the asymmetry; yet small enough to keep our state space small. We, therefore, set the number of innovation steps to $n = 6$.

We look at two types of asymmetry in abilities: (1) firms have different abilities at different stages of the R&D process; (2) firms' relative abilities are different. In order to study the effect of these asymmetries as well as the effect of a multistage race, we look at two cost profiles—(1,1,1,γ,γ,γ) and (γ,γ,γ,1,1,1) where $\gamma \geq 1$. We will compare results where only one type of asymmetry exists, i.e. $c^1 = c^2 = (\gamma,\gamma,\gamma,1,1,1)$, with results where both types of asymmetry are present—$c^1 = (1,1,1,\gamma,\gamma,\gamma)$; $c^2 = (\gamma,\gamma,\gamma,1,1,1)$ and repeat the analysis for different values of γ.[15]

We consider a market in which the demand function is given by $p = 20 - q$. We assume no production cost. The monopolistic payoffs π^M are derived from the demand function; yielding $\pi^M = 100$. The consumers' surplus associated with the same demand function and the monopolistic price is $CS^M = 50$. These expressions refer to the net present value of profits and consumers' surplus. When per-period payoffs are needed, we take them to be $r\pi^M$; where r is the discount rate, such that $\beta = (1+r)^{-1}$.

We do not model the duopolistic market, but rather simply assume that the duopolistic profits are given by $\pi^D = \mu\pi^M$, where $0 \leq \mu \leq 0.5$. We vary μ to capture different intensities of the duopolistic competition (e.g., the collusive duopolistic case would be captured by $\mu = 0.5$ while Bertrand price competition is captured by $\mu = 0$). When we change μ we make the necessary modifications for consumers' surplus $CS^D(\mu)$, i.e.,

$$CS^D(\mu) = 2\left(\frac{20 + \sqrt{20^2 - 2\mu 20^2}}{4}\right).$$

We let the probability of success at every stage of the race be $p(x_i) \equiv 0.1x_i/(1+0.1x_i)$.

We consider the effect of three different variables on the outcome of the race. (i) α—market size (the market prizes are simply set to $\alpha\pi^M$ and $\alpha\pi^D$, and consumers' surplus is adjusted accordingly). (ii) γ—the degree of cost asymmetry. (iii) μ—the intensity of market competition i.e., the portion of the monopolistic payoffs that is captured in a duopolistic competition.[16]

3.2. The performance of the different patent regimes

We start by comparing the performance of the E-Pat, Opt-Pat and the CTI patent regimes without getting into details regarding the firms' investment strategies (see Section 4). We compare consumers' surplus, value for firms, total welfare and the duration of the race. We vary the values of the parameters α, γ and μ to obtain a better understanding of the race characteristics.

3.2.1. The effect of the size of the market

Fig. 1a,b,c,d presents the performance of E-Pat, CTI and Opt-Pat as a function of the market multiplier α; i.e., the prize at the end of the race. We maintain the cost asymmetry at $\gamma = 2$, and the duopolistic competition intensity at $\mu = 0.25$.[17] The figures on the left present the symmetric case in which the cost structure of both firms is $c^1 = c^2 = (\gamma,\gamma,\gamma,1,1,1)$; and on the right side we present the performance of the R&D race with asymmetric cost such that $c^1 = (1,1,1,\gamma,\gamma,\gamma)$; $c^2 = (\gamma,\gamma,\gamma,1,1,1)$.

Fig. 1a illustrates the standard argument justifying the need for patent protection. In the symmetric case, for $1.5 < \alpha < 4.5$ the Opt-Pat and the E-Pat regimes induce positive R&D investment, while the CTI regime does not provide sufficient incentives for the firms to invest. For these parameter values investment in R&D is socially optimal and therefore offering no patent protection results in an inefficient outcome.

Comparing the symmetric and the asymmetric parts of Fig. 1a demonstrates the effect of cost asymmetry in sequential R&D races. Note that for the Opt-Pat and the E-Pat cases there is not much difference between the symmetric and the asymmetric cases. The performance of the CTI case, however, is much better in the asymmetric case. In particular, R&D investment in the CTI case starts at much lower levels of α and for high levels of α the CTI regime yields higher consumers' surplus than the Opt-Pat regime.

The duration of the race is depicted in Fig. 1b. For Opt-Pat we report the time until the first invention as well as the time at which

[12] Our stopping criteria is $\varepsilon = 10^{-6}$.

[13] Our structure is such that the movement of the state space is unidirectional. In addition, we can use the analysis in Doraszelski and Satterthwaite (2007) to argue that our transition function is UIC admissible, and thus that the investment choice is unique. However, this condition does not guarantee that the reaction functions intersect only once (see Doraszelski and Pakes, 2007). Consequently, we cannot rule out multiplicity in our model. While uniqueness cannot be guaranteed in general, our computations always lead to the same value and policy functions irrespective of the starting point and the particulars of the algorithm.

[14] A higher β will only increase the attractiveness of the CTI regime as it will reduce the effect of a delayed innovation.

[15] We have experimented with other cost profiles. Obviously, changing the structure of the cost function changes the outcome of the race and the relative advantage of different patent regimes. One interesting cost asymmetry profile is $c^1 = (1+\gamma, 1+\gamma, 1+\gamma, 1-\gamma, 1-\gamma, 1-\gamma)$; $c^2 = (1-\gamma, 1-\gamma, 1-\gamma, 1+\gamma, 1+\gamma, 1+\gamma)$. While in this cost profile the variation is around a given value, changing γ will change the technology frontier as it would become easier or cheaper to complete the innovation if R&D is allocated among firms (this is particularly important for the CTI case). In our formulation the technology frontier is not affected by γ, which affects only the asymmetry between the firms. Our main results, however, stay qualitatively the same for this cost profile; see our analysis in Appendix B.

[16] Studying the effect of μ on the race allows us to analyze the effect of higher (lower) degree of competition without the need to change the number of firms in the race.

[17] These parameters were chosen to capture the different effects presented in the graphs. We will vary these parameters in the coming subsections.

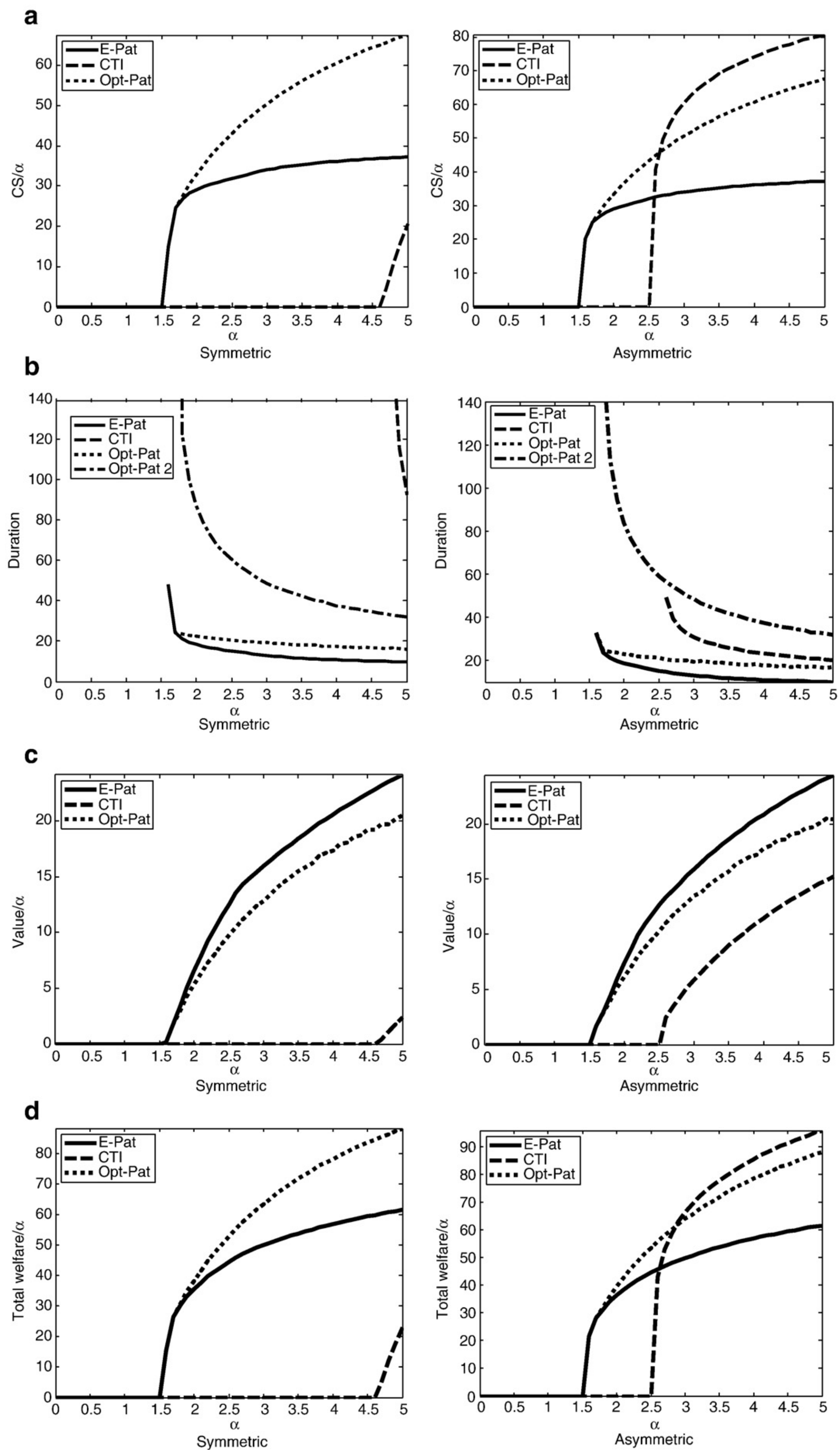

Fig. 1. a: Consumers' surplus. b: Duration. c: Firms' value. d: Total welfare.

the second firm enters; denoted by Opt-Pat 2.[18] In the symmetric case, the CTI regime does not provide sufficient incentives to invest in R&D, therefore, even when firms invest it takes many periods until the invention is completed. In the asymmetric case, in converse, the race with CTI regime is much faster.

Consumers' surplus in R&D races is determined by two factors: the duration of the race and the resultant market game. The outcome of the market game is determined by the number of competitors (in our case monopoly vs. duopoly) and the intensity of competition. The Opt-Pat race ends up with several periods of monopolistic markets and then it switches to a duopolistic market. In the CTI case, in converse, the market is always duopolistic. Consequently, whether the Opt-Pat or CTI regime dominates, in terms of CS, depends on the relative duration of these two races. As the figure shows, for $\alpha > 2.7$ the market structure effect dominates the duration effect and the CTI regime leads to higher consumers' surplus.

Fig. 1c depicts the firms' value. These values are the equilibrium discounted expected profits minus discounted investment. The firms' cost asymmetry implies different equilibrium value for the firms. In Fig. 1c we present only the sum of values and postpone the discussion on the effect of cost asymmetry on the firms' value to Section 4. As the figure indicates, for these parameters' value, the value of firms under the CTI regime is lower than under the E-Pat or the Opt-Pat cases. This is a direct result of the duopolistic market structure that the CTI regime implies.

In order to evaluate the overall performance of the different regimes, Fig. 1d depicts the total welfare for the three regimes. The figure shows that while in the symmetric case the CTI is dominated by the other regimes, for $\alpha > 2.8$ in the asymmetric case, it is the CTI that yields the higher total welfare. We will discuss the intuition behind this result in Section 4.

3.2.2. The effect of market competition

We now turn to discuss the effect of the intensity of the duopolistic competition, μ, on the performance of the weak and strong patent regimes. A low value of μ implies a tougher duopolistic competition, lower duopolistic payoffs but higher consumers' surplus. On the other hand when μ is close to 0.5, the duopolistic firms share the monopolistic profits. In Fig. 2 we present the performance of the three patent regimes as a function of μ fixing the cost asymmetry as before at $\gamma = 2$, and setting α to 3.[19]

The intensity of the duopolistic competition, μ, has a large effect on the incentives to invest in the CTI case, as it always ends up in a duopolistic competition. In contrast, the E-Pat R&D race is not affected by μ since it never ends up with a duopolistic market. In the Opt-Pat case the effect of μ is more complex. The patent is awarded only for a fixed number of periods, followed by a duopolistic market. The level of μ affects the size of the prize of the first innovator, as well as of the follower and therefore affects the incentives of the two firms to invest. Furthermore, in the Opt-Pat case the length of the patent is endogenously calculated such as to maximize consumers' welfare and these calculations are also affected by the intensity of the duopolistic competition μ.

Fig. 2a shows that as before, in the symmetric case the CTI regime is dominated by the E-Pat and the Opt-Pat regimes—both yield higher consumers' surplus. For low levels of μ, the possibility of imitation in the CTI case implies that firms do not have incentives to invest in R&D, and the race does not begin. Higher μ levels induce more R&D investment, but the investment level under the CTI regime is always below the investment levels at the other two regimes (see Fig. 2d). As before, the cost asymmetry has a huge effect on the incentives to invest in the CTI case: While at low levels of μ the CTI case still induces no investment and the Opt-Pat regime dominates the CTI case, when $\mu > 0.225$ it is the CTI regime that yields a higher consumers' surplus. The duration of the race in this range decreases sharply with μ. Decreasing the level of competition increases expected profits, and thus incentives to invest. This in turn speeds up the innovation process. Finally, as μ approaches 0.5 the duration of the race, as well as the consumers' surplus, converges under the three regimes.

The upside down U-shape curve of consumers' surplus in the CTI case illustrates the tension between two effects; duration and market structure. As μ increases, the market structure at the end of the race is less competitive. Consequently, as μ increases, firms invest more in the race; resulting in a much faster innovation process. While the first effect decreases CS, the second effect increases CS. When $0.22 < \mu < 0.3$, the duration effect is large enough to offset the competition effect—CS increases. Once $\mu > 0.4$ the duration does not change much and the competitive effect dominates the duration effect; resulting in a lower CS. When μ approaches 0.5 the duopolistic firms share the monopolistic profits and the duopolistic market structure yields the same consumers' surplus as the monopolistic market. In this case, the consumers' surplus generated by the CTI regime falls sharply. Interestingly, as Fig. 2b indicates, for such μs the length of the optimal patent increases dramatically as maximization of consumers' surplus implies putting more emphasis on the incentives to innovate rather than on the resultant market structure. As a result, investment under Opt-Pat increases considerable, the duration till first invention decreases, and the firms' value decreases.

In the symmetric case, the CTI regime always yields the lowest value for firms (see Fig. 2c). This is, however, not the case in the asymmetric race. Under the CTI regime the firms' value is monotonically increasing with μ. For $\mu > 0.36$ the firms' value under the CTI regime is larger than under the E-Pat or the Opt-Pat regimes. Nevertheless, as Fig. 2b indicates, the duration of the race is similar. The advantage of the CTI regime is derived from a more efficient R&D investment (see Fig. 2d), where firms focus on developing the stages in which they have an advantage.[20] Firms avoid duplication of effort and exploit their relative advantage in the different steps of the race.[21] Consequently, under the CTI regime R&D expenditures are lower but the duration until invention is not much different. We return to this result in Section 4.

3.2.3. The effect of the degree of cost asymmetry

We will now discuss the effect of the degree of cost asymmetry, γ, on the performance of the three patent regimes. A larger γ implies greater R&D costs as well as a greater cost asymmetry. In the symmetric case, a larger γ implies that both firms have higher costs in developing the first three steps of the invention. In the asymmetric case, as γ increases, the advantage of the first firm in the first three steps of the race increases, and similarly the relative advantage of the second firm in the last three steps increases. The effect of γ is depicted in Fig. 3; as before, we fix the values of the other parameters at $\alpha = 3$ and $\mu = 0.25$. As suggested in Figs. 1 and 2, given these parameter values the symmetric case does not provide sufficient incentives to invest in the CTI regime. We, therefore, present only the asymmetric case.

As before, in contrast to the symmetric case, Fig. 3a and d shows that in the asymmetric case it is the CTI regime that yields higher

[18] The time between Opt-Pat and Opt-Pat 2 is τ—the length of the patent. This time period is not constant as it is endogenously determined for every set of parameters and calculated as to maximize consumers' surplus.

[19] Setting α to a small level implies no investment under the CTI regime with symmetric costs. We, therefore, choose a market size that is large enough to induce investment.

[20] The CTI regime yields a higher total surplus than the other two patent protection regimes whenever $\mu > 0.22$. This range includes the Cournot equilibrium which is at $\mu = 0.44$.

[21] This property is also related to the literature on rent dissipation in a multistage R&D race; see Reinganum (1982), Beath et al. (1989) and Doraszelski (2008).

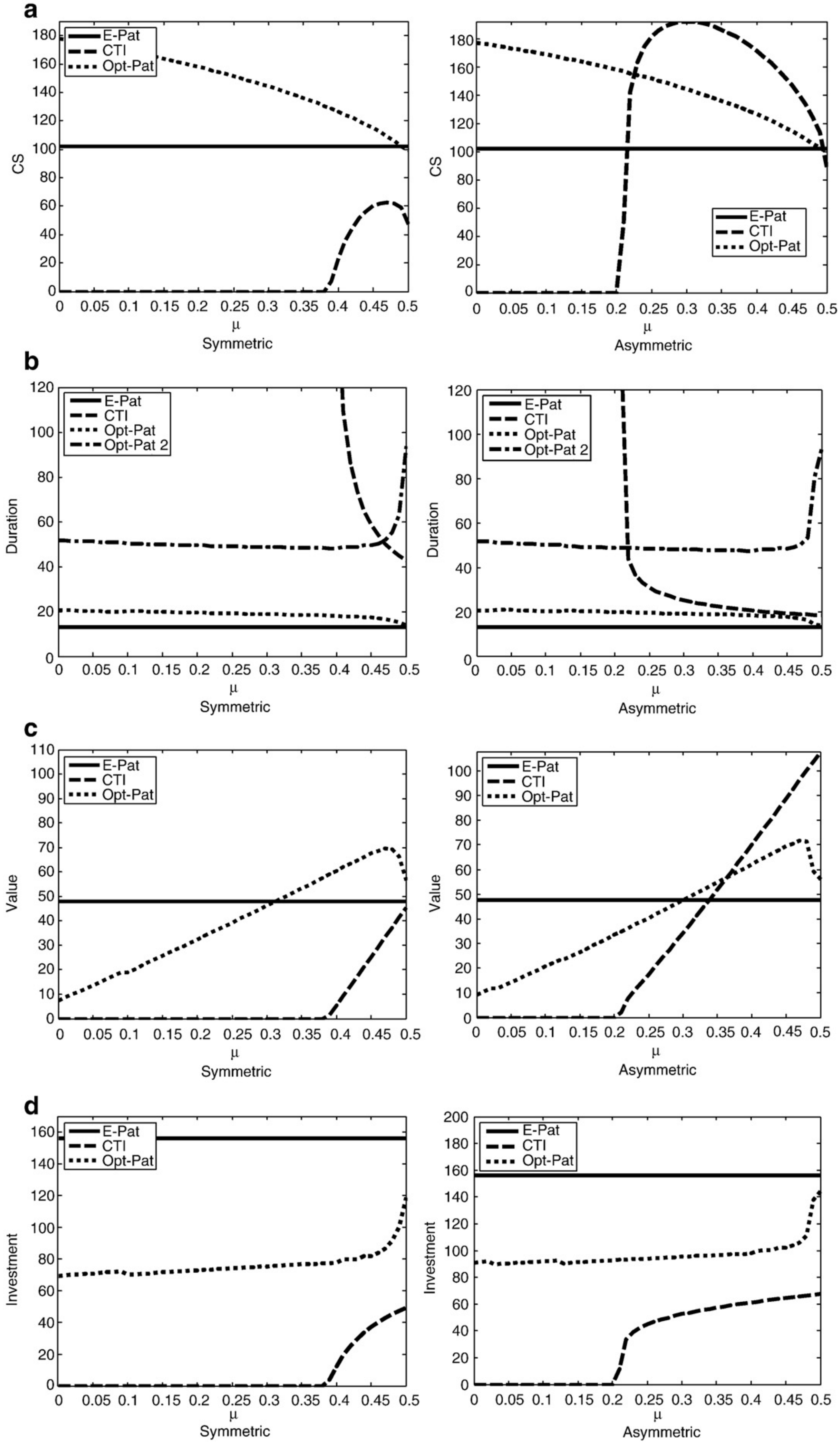

Fig. 2. a: Consumers' surplus. b: Duration. c: Value. d: Investment.

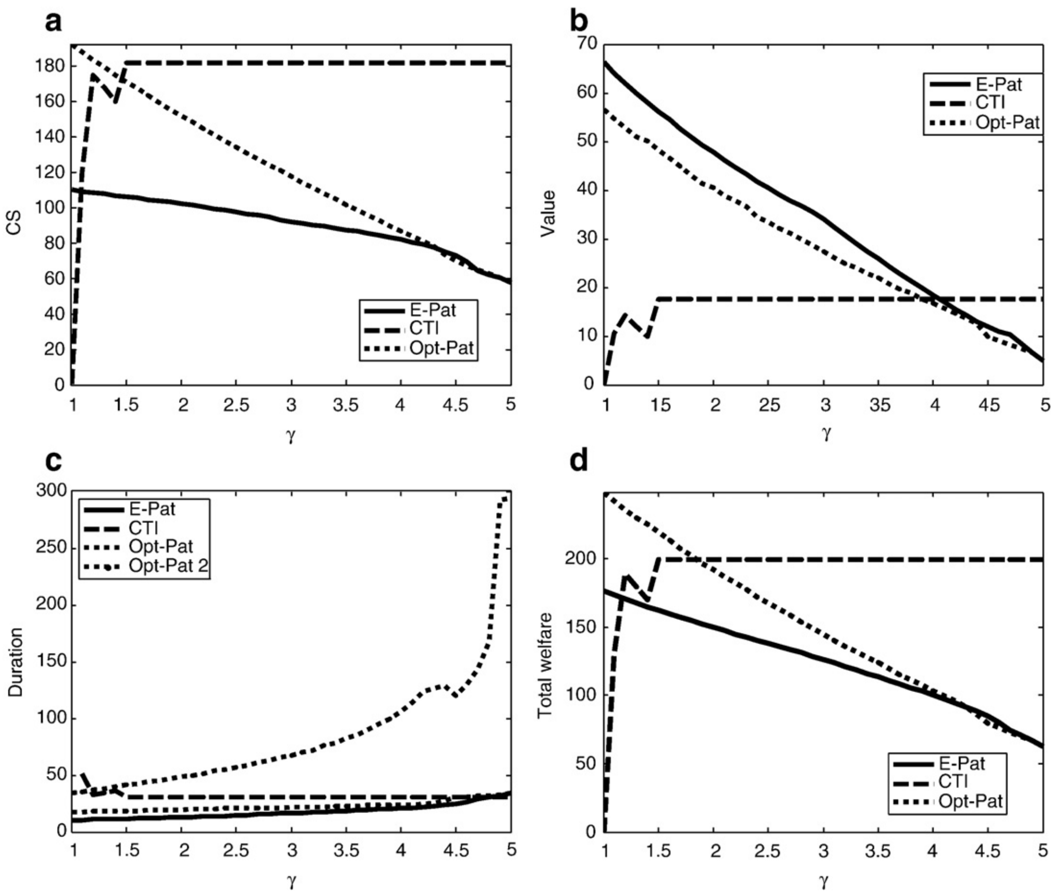

Fig. 3. a: Consumers' surplus. b: Firms' value. c: Duration. d: Total welfare.

consumers' surplus and higher total welfare for most of the relevant range of γ.

An increase in γ implies a higher cost of R&D. In the E-Pat and Opt-Pat cases, the higher costs of investment have a direct effect on firms' values. The lower expected value implies lower incentives to invest and thus longer duration of the innovation process which results in lower consumers' surplus. As Fig. 3c shows, Opt-Pat 2 increases with γ indicating that the length of the optimal patent increases drastically as the overall cost of investment increases. Thus, in the E-Pat and Opt-Pat cases, increasing the cost asymmetry, γ, has a similar effect as decreasing the size of the market. The CTI regime, in contrast, facilitates complete specialization; where each firm invests only in developing the technologies it has an advantage in. This complete specialization eliminates duplicate investment, and thus results in a more efficient race. The non-monotonicity in consumers' surplus and value for firms in the CTI case suggests that as γ increases firms switch from a regime in which the two firms invest in R&D in all stages, to a regime characterized by complete specialization. Once firms reach complete specialization, a further increase of γ has no effect on firms' investment strategies.

4. Strategies and values of the asymmetric R&D race

So far we presented the summary performance of the R&D race under the E-Pat, Opt-Pat and CTI regimes without going into detail regarding the strategic interaction between the firms. In this section we examine the details of the strategic race under a specific set of parameters. We choose parameter values where, in the asymmetric case, the CTI provides higher consumers' surplus than the E-Pat and Opt-Pat regimes. This allows us to explain the superiority of the CTI regime (for these parameter values). We examine two sets of parameter values that differ only in the intensity of the duopolistic competition. Tables 1 and 2 present the summary statistics of the R&D race for the parameters ($\alpha=3$, $\gamma=2$, $\mu=0.25$) and ($\alpha=3$, $\gamma=2$, $\mu=0.45$). Tables 3a, 3b, 4a and 4b then present the investment strategies and value function of the race for the CTI and the E-Pat cases.

In Tables 1 and 2 we let Inv1 and Inv2 be the investment of firm 1 and 2, respectively; TotInv is the firms' total investment. Dur_Prod1 is the average duration of the race prior to first production, while Dur_Race is the number of periods until the race ends and the second firm enters the market. The lines "Value" and "CS" provide the expected discounted total value of the firms and discounted consumers' surplus. Prob_1 and Prob_2 show the probability that firm 1 or 2 is the first firm

Table 1
R&D race, $\alpha=3$, $\gamma=2$, $\mu=0.25$.

	Symmetric			Asymmetric		
	E-Pat	CTI	Opt-Pat	E-Pat	CTI	Opt-Pat
Tot_Inv	156.1	–	95.7	156.5	44.8	94.04
Inv1	78.05	–	47.8	79.04	25.8	56.8
Inv2	78.05	–	47.8	77.45	18.98	37.3
Dur_Prod1	12.93	–	19.5	12.9	30.8	19.4
Dur_Race	–	–	48.5	–	30.8	48.4
Tot_Val	47.93**	–	38.5	47.77**	17.5	40.4
CS	102	–	151.5**	102.1	181.6**	151.8
Prob_1	0.5	–	0.5	0.54	–	0.63
Prob_2	0.5	–	0.5	0.46	–	0.37
V1	23.96	–	19.2	28.2	5.3	21.88
V2	23.96	–	19.2	19.5	12.2	18.55

**—denotes the regime that provides the highest consumers' surplus and total value.

Table 2
R&D race with a less competitive duopolistic market, $\alpha=3$, $\gamma=2$, $\mu=0.45$.

	Symmetric			Asymmetric		
	E-Pat	CTI	Opt-Pat	E-Pat	CTI	Opt-Pat
Tot_Inv	156.1	37.1	105.6	156.5	64.4	102.35
Inv1	78.05	18.54	52.8	79.04	35.7	59.2
Inv2	78.05	18.54	52.8	77.45	28.7	43.1
Dur_Prod1	12.93	58.6	17.3	12.9	19.2	17.56
Dur_Race	–	58.6	49.3	–	19.2	48.56
Tot_Val	47.93	25.2	67.5**	47.77	88.7**	69.3
CS	102	59.9	114.8**	102.1	147.4**	114.8
Prob_1	0.5	–	0.5	0.54	–	0.6
Prob_2	0.5	–	0.5	0.46	–	0.4
V1	23.96	12.6	33.7	28.2	40.9	36.5
V2	23.96	12.6	33.7	19.5	47.8	32.9

**—denotes the regime that provides the highest consumers' surplus and total value.

to complete the invention and (V1,V2) provides the expected initial value of the two firms in the race.

As Tables 1 and 2 indicate, in the symmetric case, the CTI regime is dominated by the E-Pat and the Opt-Pat regimes, both in terms of consumers' surplus and in terms of value for firms. The benefits from the CTI regime come mainly from the specialization and thus materialize only when there is a sufficiently asymmetric cost structure. For example, when ($\alpha=3,\gamma=2,\mu=0.45$), the CTI yields higher consumers' surplus and higher value than the regimes which provide strong patent protection. When the duopolistic interaction is more competitive, as in $\mu=0.25$, the CTI regime yields a lower value for the firms but still a higher consumers' surplus. The higher level of duopolistic competition lowers prices; generating higher consumers' surplus, sufficient to compensate for the slower pace of innovation. Under the CTI regime, there is a much lower level of investment in R&D which is partially due to lower incentives but also derived from a more efficient process that exploits specialization and avoids duplication of effort. The lower investment contributes to the values of firms and for high μs, these savings are sufficient to compensate for the lower profits implied by the duopolistic market structure.

Note that the cost asymmetry has also the role of a coordination device. With cost symmetry, the CTI regime exhibits the standard free riding problem. Each firm wants the other firm to invest since they both share the rewards. As a result, at equilibrium they both reduce their investment. However with a large enough cost asymmetry, the optimal allocation of effort is clear to both firms. They specialize—each develops the intermediate technology it has an advantage in.

Table 3a
Investment, $\alpha=3$, $\gamma=2$, $\mu=0.25$, E-Pat.

Stage	0	1	2	3	4	5	6
0	(11.0,7.2)	(1.4,6.8)	(0,4.8)	(0,7.7)	(0,8.3)	(0,8.9)	(0,0)
1	(9.3,1.0)	(10.9,10.4)	(0.8,6.6)	(0,7.7)	(0,8.3)	(0,8.9)	(0,0)
2	(6.1,0)	(14.8,3.6)	(10.7,13.0)	(0.2,8.5)	(0,8.3)	(0,8.9)	(0,0)
3	(4.8,0)	(4.8,0)	(12.7,6.5)	(8.2,21.3)	(0.6,11.2)	(0,8.9)	(0,0)
4	(5.4,0)	(5.4,0)	(5.4,0)	(15.6,11.3)	(12.8,24.2)	(2.5,17.3)	(0,0)
5	(6.1,0)	(6.1,0)	(6.1,0)	(6.1,0)	(17.4,10)	(18.3,29.1)	(0,0)
6	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)	(0,0)

Table 3b
Value function, $\alpha=3$, $\gamma=2$, $\mu=0.25$, E-Pat.

Stage	0	1	2	3	4	5	6
0	(28.2,19.5)	(0.4,98.9)	(0,151.6)	(0,196.5)	(0,228.8)	(0,263.2)	(0,300)
1	(90.4,0.4)	(22.7,44.5)	(0.1,143.9)	(0,196.5)	(0,228.8)	(0,263.2)	(0,300)
2	(125.6,0)	(93.7,4.4)	(20,77.5)	(0,194.7)	(0,228.8)	(0,263.2)	(0,300)
3	(152.4,0)	(152.4,0)	(96.3,14.9)	(19.8,116.5)	(0.1,221.9)	(0,263.2)	(0,300)
4	(197.5,0)	(197.5,0)	(197.5,0)	(133.7,20.7)	(47.4,116.6)	(1.9,246.4)	(0,300)
5	(246.7,0)	(246.7,0)	(246.7,0)	(246.7,0)	(201.5,15.5)	(89.4,128.7)	(0,300)
6	(300,0)	(300,0)	(300,0)	(300,0)	(300,0)	(300,0)	(150,150)

Table 4
Investment, $\alpha=3$, $\gamma=2$, $\mu=0.25$, CTI.

Stage	(x_1, x_2)	Stage	(V_1, V_2)
0	(1.26, 0)	0	(5.33, 12.2)
1	(2.35, 0)	1	(18.4, 15.5)
2	(3.2, 0)	2	(34.1, 18.1)
3	(0, 2.47)	3	(52.1, 20.4)
4	(0, 3.3)	4	(60.2, 36.4)
5	(0, 4.05)	5	(67.7, 54.7)
6	(0, 0)	6	(75, 75)

Our setup of cost asymmetry implies that firm 1 is more efficient in the early three stages of the technology development, while firm 2 is more efficient in the last three stages of the race. All six stages are necessary for the completion of the invention and besides their order, are totally identical. The question is whether such an asymmetry implies an advantage to one of the firms. Tables 1 and 2 indicate that the answer to this question depends on the patent regime. In the E-Pat and Opt-Pat races, the firm that has better abilities in the first steps of the race has an advantage in the entire race; even though its total level of investment is higher, it has a greater value than the second firm i.e., $V1>V2$. Furthermore, it has a higher probability to be the first to complete the innovation (i.e., Prob_1 > Prob_2). On the other hand in the CTI regime, it is the second firm—the firm with better abilities in the last three stages of the race—which has the higher value. Note that this advantage is derived from lower investment in the R&D process as both firms share the same prize.

The fact that the cost asymmetry across firms affects the race with E-Pat (or Opt-Pat) is somewhat surprising. After all each firm needs to independently develop three intermediate technologies with lower costs and three intermediate technologies with higher costs. Yet, there is a difference between the symmetric case and the asymmetric case. The probability that the firm that has the early advantage will be the one that gets the patent is much larger than the probability that the second firm would win the race. This is a direct result of the first firm's higher level of investment, which in turn also increases its value of the race.

We now turn to present the investment strategies and value functions for the E-Pat and CTI cases. Tables 3a, 3b, 4a and 4b present firms' investment levels and values at different stages of the race for the E-Pat and the CTI cases, respectively. In each cell, the entry on the left represents firm 1's investment (value). The right entry gives firm 2's investment (value).

Comparing Tables 3a, 3b, 4a and 4b provides additional details on the effect of different patent regimes on the R&D race. Under the CTI regime, investment is lower as the reward for success is lower (compare Tables 3b and 4b). On the other hand, the investment process is more efficient since each firm only invests in the technologies in which it has superior abilities. In the E-Pat case there is no specialization; both firms invest heavily in the beginning even in technologies in which they have inferior abilities.

Furthermore, in the CTI case both firms benefit from any success in the innovation process. The value function of both firms increases each time there is a successful innovation, regardless of which firm was responsible (see Table 4b). Thus, while the firms compete at the end in the product market, the possibility of imitation at every stage of the race induces a type of "cooperative" innovation process; though there is no explicit cooperation or coordination between the firms.

5. Licensing and asymmetric R&D race

The CTI regime provides a more efficient innovation process as it facilitates specialization and sharing. One might wonder, then, whether imitation is the only mechanism that allows firms to gain from their complementary advantages. Sharing intermediate technologies may also occur in an environment in which it is possible to license these technologies. Licensing will allow firms to share their discoveries and benefit from specialization. The focus of this section is the effect of licensing of intermediate technologies on the R&D race, and in particular on the comparison of the CTI regime with a race in which firms can license their intermediate technologies.

The possibility of licensing intermediate technologies affects the incentives facing the firms. Firms, for example, may decide to develop only intermediate technology, license it and exit the race. Licensing intermediate technologies may generate "intermediate payoffs", but this also affects the continuation of the race and the probability of winning. One can distinguish between different possible scenarios which depend on the details of the race. For example, if patenting of intermediate technologies is possible, a patent may block the continuation of the race and the race may end before the innovation process is completed. Licensing this patented technology can prolong the race and ultimately shorten the duration of the innovation process. Since our main goal is the comparison with the CTI case, we will focus on the case where patenting the intermediate technology is not possible, however, firms can voluntary license their intermediate technology. Clearly, in the symmetric case the incentives for licensing of intermediate technology are low. However in the asymmetric case, licensing may enable firms to take advantage of their different skills.

5.1. Voluntary technology transfer

Let us begin by examining the possibility of a voluntary transfer of intermediate technologies. In Section 3 we showed that for a wide range of parameter values the CTI yields a higher value for firms than the E-Pat or the Opt-Pat regimes. In these cases, if imitation is not feasible, the firms can adopt a policy of voluntary transmission of intermediate innovation. This policy is equivalent to licensing without compensation. If the firms can commit, at the outset of the race, to reveal all their intermediate and final innovations, the outcome will be indeed equivalent to the CTI regime.

Consider now a race without a commitment to a voluntary transmission of intermediate technologies. Rather, at each stage firms can choose whether to voluntarily reveal their invention.[22] Obviously, in the last stage of the race firms will not share their innovation with rival firms, as such sharing would reduce their value. Given that there is no sharing in the last stage, we may argue that there is no voluntary sharing of technology in the stage before the last one. One can then use backward induction to argue that there would be no voluntary technology transfer at any stage, even though the firms may benefit from such behavior.

5.2. A multistage R&D race with intermediate technology licensing

We consider an R&D race in which a patent is awarded only at the end of the race. Firms may, however, voluntarily license their intermediate technology to their competitors. We assume that licensing takes place only if both firms agree to it. Licensing is a form of technology transfer and it is not exclusive. Once an intermediate technology is licensed, both firms may continue in the race for developing the next step of the innovation.

The time line of this race is as follows. Each period t starts with a state (l,m) which describes the intermediate technologies that had been developed by the two firms prior to period t. Firms then decide whether to sign a licensing agreement which is followed by their investment decision. The outcome of these investments is realized at the beginning of the next period.

For describing this game we need two value functions. We let $\tilde{V}_i(l,m)$ be the value of the game for firm i at the beginning of a period after the realization of the outcome of the R&D investment from the previous period. We let $V_i(l,m)$ be the value of firm i after the licensing decision was made and realized.

Assume that $l>m$ and that firm 1 is ahead of firm 2 in the race. If it licenses its intermediate technology to firm 2, it loses its advantageous position implying a loss of $V_1(l,m)-V_1(l,l)$. On the other hand, the gains to firm 2 from such licensing are $V_2(l,l)-V_2(l,m)$. Since licensing is voluntary, it would occur only when it creates a surplus, that is whenever $V_2(l,l)-V_2(l,m)+V_1(l,l)-V_1(l,m)>0$. We assume that once the surplus is positive, a licensing agreement is concluded and the firms equally share the licensing surplus. Let $T_{1,2}(l,m)$ denote the amount paid by firm 2 to firm 1 for the license of intermediate technology l, such that

$$T_{1,2}(l,m) = 1/2[(V_1(l,m) - V_1(l,l)) + (V_2(l,l) - V_2(l,m))]. \quad (2)$$

Note that licensing is voluntary and that Eq. (2) guarantees that $T_{1,2}(l,m)>V_1(l,m)-V_1(l,l)$. That is, the terms of the licensing agreement are such that licensing would occur only when the licensing firm benefits from it. Let I_L be an indicator function where $I_L(l,m)=1$ if licensing occurred, and $I_L(l,m)=0$, otherwise. The Bellman equation is then:

$$V_1(l,m) = \max_{x_1 \geq 0}\left\{-c_l^1 x_1 + \beta \sum_{l',m'} \tilde{V}_1(l',m')p(l'|x_1,l)p(m'|x_2^*(l,m)\right\} \quad (3)$$

where

$$\tilde{V}_1(l,m) = \begin{cases} V_1(l,m) & \text{if } I_L(l,m) = 0 \\ T_{1,2}(l,m) + V_1(l,l) & \text{if } I_L(l,m) = 1 \end{cases}.$$

The value functions $V_2(l,m)$ and $\tilde{V}_2(l,m)$ are similarly defined for firm 2.

5.3. R&D races with licensing: numerical analysis

We use the same algorithm as before to calculate the Markov Perfect Equilibrium of this game (see details in Section 3.1). For the numerical analysis we maintain the value of the parameters as in our

Table 5
Asymmetric R&D race with licensing ($\alpha=3$, $\mu=0.25$).

	$\gamma=2$			$\gamma=5$		
	E-Pat	CTI	License	E-Pat	CTI	License
TotInv	156.5	44.8	161.5	109.8	44.8	71.4
Inv1	79	25.8	72.6	109.8	25.8	35.1
Inv2	77.5	19	88.9	0	19.0	36.3
DurRace	12.9	30.8	12.1	34	30.8	17.2
Value	47.8	17.5	47.7	4.9	17.5	109.1
CS	102.1	181.6	104.6	57.4	181.6	90.2
Prob_1	0.54	–	0.38	1	–	0
Prob_2	0.46	–	0.62	0	–	1
V1	28.2	5.3	29	4.9	5.3	37
V2	19.5	12.2	18.7	0	12.2	72.1
Relevant License states	–	–	(2,1) (3,2) (4,3) (5,4)	–	–	(3,0)

[22] We solve for the MPE of such a race but provide here only the final conclusion of this study. The details can be obtained from the authors upon request.

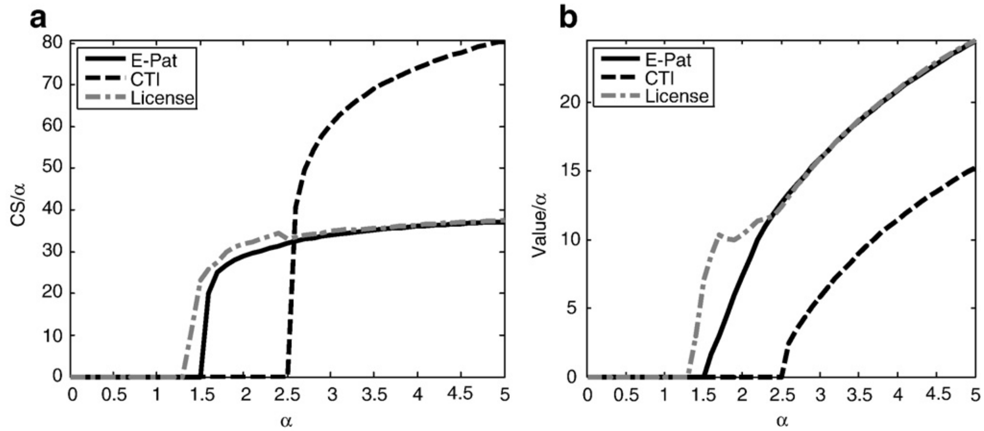

Fig. 4. a: CS ($\gamma=2$, $\mu=0.25$). b: Firms' value ($\gamma=2$, $\mu=0.25$).

benchmark case (i.e., $\alpha=3$, $\mu=0.25$, $\gamma=2$ and 5). Table 5 presents the summary statistics for the R&D race with licensing in comparison to the CTI and the E-Pat regimes.[23] We compare the different regimes for two values of cost asymmetries; $\gamma=2$ and $\gamma=5$. We do not present the symmetric case as there is no intermediate technology licensing in the symmetric cost case. Firms have the same abilities and, therefore, there are no technological or strategic advantages from such licensing.[24] Licensing in our model is, therefore, closely related to the asymmetries across the firms' R&D abilities.

Table 5 shows that the possibility of licensing has an interesting effect on the R&D race. For example, when $\gamma=5$ the E-Pat regime, without the possibility of licensing, results in a long race characterized by large inefficient investment and very low firms' value. Firm 2 does not participate in the race, while firm 1 remains to develop all the intermediate technologies, even those it has a disadvantage in. In contrast, the possibility of licensing facilitates specialization, as in the CTI case, which results in higher firms' values.

Table 5 specifies the states in which licensing will take place. We specify only the relevant states, i.e., those states which are reached with positive probability on the equilibrium path. When $\gamma=5$, the possibility of licensing implies that firms completely specialize in their R&D investment. The first firm develops the first three intermediate technologies; it then licenses these technologies to the second firm and exits the race. Firm 2 completes the R&D process and enjoys a monopolistic market. When $\gamma=2$ (lower level of cost asymmetry), both firms participate in the development of the different stages of the race. Firm 1 has a higher value but this value is the outcome of successful licensing and is not derived from the final market, as the probability that firm 1 will receive the final patent is only 38%.

Interestingly, even when there is a possibility of voluntary licensing at every stage of the race, the CTI regime still provides a higher consumers' surplus than the race with the licensing option. The possibility of licensing enables the firms to adopt a more "cooperative" R&D race and to guarantee themselves higher values than in the CTI case. This creates a fast and efficient development process, yet consumers' are still better off under the CTI regime as the shorter development process does not compensate for the monopolistic market structure.

The degree of cost asymmetry has an interesting effect on the race. Raising γ is a form of a cost increase (for both firms). Yet as Table 5 indicates, when there is licensing, firms are better off in the $\gamma=5$ case than with the lower cost of $\gamma=2$. When $\gamma=2$, the cost asymmetry is not large enough to induce complete specialization in the R&D process. The probability that firm 1 would be the first firm to complete the innovation is 38%, even though this firm has no advantage in the later stages of the R&D process. In converse, when $\gamma=5$, the asymmetry is sufficiently high and "forces" the firms to completely specialize. The first firm develops the first three stages, licenses the technology out to the second firm, which then completes the innovation. This transforms the structure of the race. The firms do not race against each other—but rather "cooperate". An early discovery by one firm benefits both firms. Consequently, even though there are higher R&D costs, the firms invest more efficiently; their investment goes down and their value goes up.

We now turn to discuss the effect of the parameters α and γ on the R&D race and on the comparison between the CTI and the licensing cases.

Fig. 4a and b presents the consumers' surplus and firms' value as a function of the market size, α (holding $\gamma=2$ and $\mu=0.25$). When α is above 2.5 the CTI regime yields higher consumers' surplus than the R&D race with licensing of intermediate technology. On the other hand, since the CTI race is followed by a duopolistic market, it provides lower value for the firms than the race with licensing. In comparison to the E-Pat case, the possibility of licensing enhances both consumers' surplus and firms' value in particular for low values of α. For high levels of α, the prize is sufficiently high, and firms choose not to license at all. The race with licensing then coincides with the E-Pat case.

Fig. 5a and b shows consumers' surplus and firms' value as a function of the degree of cost asymmetry, γ (holding α at $\alpha=3$). As before, for γ close to 1 the CTI regime does not provide sufficient incentives to invest. Nevertheless, for most of the range of γ the CTI regime provides higher consumers' surplus than the race with the licensing option. This is a direct result of the duopolistic market the CTI regime ends up with.

Overall, the possibility of licensing enhances firms' value. For $\gamma<1.5$ there is no licensing and the outcome is identical to the E-Pat regime. When $1.5<\gamma<2.2$, firm 1 licenses to firm 2 (but only when firm 2 is one stage behind it; i.e. close enough to catch-up by itself), and keeps investing in the hope to achieve the patent. Note that when firm 1 achieves the patent, its value is higher than in the E-Pat case as it also includes the licensing fee. When $2.2<\gamma<4.6$, firm 1 licenses the intermediate technology to firm 2 even when firm 2 is a few stages behind. In this case, however, firm 1 does not drop out of the race after the licensing, as long as it is ahead or neck-and-neck with firm 2. Once firm 1 lags even one step behind firm 2, firm 1 drops out of the race. Finally, for $\gamma>4.6$ there is complete specialization in the R&D process. It is this pattern of licensing that explains the increase of the firm's total value as γ increases.

[23] We make a comparison to the E-Pat regime because under our formulation if licensing does not occur, the race is identical to the E-Pat case.

[24] All the equilibria with the symmetric case ended with no licensing. We do not present these results here but they can be obtained upon request from the authors.

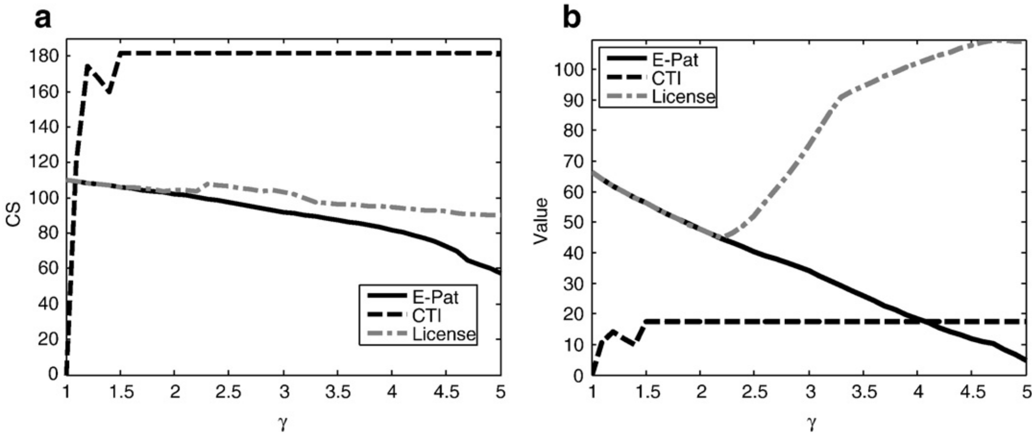

Fig. 5. a: CS. b: Firms value.

6. Concluding remarks

R&D races have many details; the technology may be complex, involving the development of different intermediate technologies and complement parts. There may be different degrees of spillovers, and firms with different abilities, different labs and different personnel. Furthermore, firms may have different evaluations of the final prize. There are R&D races in which firms may receive signals regarding the success and failure of other competitors, while in other races they are totally in the dark without the ability to infer their relative position in the race. The effect of different patent regimes on the race depends mainly on the detailed characteristics of the race. Clearly, one cannot find one regime which dominates all the others for all possible R&D races. Thus, finding the "right" patent regime is a compromise that should take into account the distribution of possible types of R&D races.

A general claim about the appropriate optimal patent policy is beyond the scope of this paper. Our analysis indicates that the optimal patent policy depends on the properties of the R&D process. In particular, it suggests that whenever we have a cumulative R&D race that requires different types of complementary abilities, a weak patent protection may dominate other possible regimes. This conclusion, however, also depends on the available information regarding intermediate stages of the innovation. For example, during the lead-development stages of a new drug, each stage is long and there is not much information on intermediate stages. In these cases, a CTI regime will not be effective.

Appendix A. Bellman equations for the Opt-Pat and the CTI cases

The case of Opt-Pat is analyzed in the following way: We solve the R&D race for the case in which a patent was awarded for τ periods. We then choose the τ that maximizes consumers' surplus. The Bellman equation for the R&D race for which patent is awarded only for τ period is:

$$V_1(l,m,\tau)=\begin{cases} L\left(\pi^{\mathrm{M}},\pi^{\mathrm{D}},\tau\right) & l=n, m<n \\ 0.5L\left(\pi^{\mathrm{M}},\pi^{\mathrm{D}},\tau\right) & l=n, m=n \\ \max\limits_{x_1\geq 0}\left\{-c_l^1x_1+\beta\sum\limits_{l',m'}V_1(l',m',\tau)p(l'|x_1,l)p(m'|l,m)\right\} & l<n, m<n \\ F\left(\pi^{\mathrm{M}},\pi^{\mathrm{D}},\tau\right) & l<n, m=n \end{cases}$$

where $p(l'|x_1,l)=p(x_1,l)$ if $l'=l+1$; $p(l'|x_1,l)=1-p(x_1,l)$ if $l'=l$; $p(m'|l,m)=p(x_2^*(l,m),m)$ if $m'=m+1$; $p(m'|l,m)=1-p(x_2^*(l,m),m)$ if $m'=m$. $L(\pi^{\mathrm{M}},\pi^{\mathrm{D}},\tau)$ is the discounted value of having the monopolistic profits for τ periods and duopolistic profits afterwards and $F(\pi^{\mathrm{M}},\pi^{\mathrm{D}},\tau)$ is the value for the losing firm, i.e., the discounted value of having zero profits for τ periods and duopolistic profits afterwards.

For the CTI case the Bellman equation is ($wlg\ l\geq m$):

$$V_1(l,m,\tau)=\begin{cases} \pi^{\mathrm{D}} & l=n, m\leq n \\ \max\limits_{x_1\geq 0}\left\{-c_l^1x_1+\beta\sum\limits_{l'}V_1(l',l')p(l'|x_1,l)\right\} & l<n, m<n \end{cases}$$

where $l'=l$ with probability $p(l'|x_1,l)=(1-p_1(x_1,l))(1-p_2(x_2^*(l,l))$ and $l'=l+1$ with the complementary probability.

Appendix B. R&D race with a cost profile of $c^1=(1+\gamma,1+\gamma,1+\gamma,1-\gamma,1-\gamma,1-\gamma)$; $c^2=(1-\gamma,1-\gamma,1-\gamma,1+\gamma,1+\gamma,1+\gamma)$

Now we present the properties of the R&D race with an alternative cost profile. Under the above cost profile, the "total" cost remains constant and γ changes only the relative advantage of firms in different parts of the R&D process. The technological frontier, however, improves with γ as it is possible to proceed with the innovation process at each stage at lower costs. In the Figs. A1 and A2 below, we present the effect of market size and cost asymmetry on consumers' surplus, firms' value, the duration of the race and total welfare. We look at the performance of all four patent regimes discussed in the paper: E-Pat, CTI, Opt-Pat and License.

As is evident from Figs. A1 and A2, the main properties that we have presented in the paper remain valid under this specification of the cost functions. In particular, for low values of α, the E-Pat, Opt-Pat and License regimes induce positive R&D investment, while the CTI regime does not provide sufficient incentives for firms to invest. As the size of the market increases, the CTI regime provides higher consumers' surplus than the other three regimes. As before, because of the duopolistic market structure, firms' value is lower under the CTI regime when compared with the E-Pat, Opt-Pat and License regimes.

Fig. A2 demonstrates the effect of changing the technological frontier. Both cost profiles—$c^1=(1,1,1,\gamma,\gamma,\gamma)$; $c^2=(\gamma,\gamma,\gamma,1,1,1)$ and $c^1=(1+\gamma,1+\gamma,1+\gamma,1-\gamma,1-\gamma,1-\gamma)$;$c^2=(1-\gamma,1-\gamma,1-\gamma,\ 1+\gamma,1+\gamma,1+\gamma)$—generate complete specialization when the level of asymmetry is sufficiently large, and thus a more efficient investment process. Furthermore, under both cost profiles, the CTI regime dominates in terms of consumers' surplus. Nevertheless, while in the case

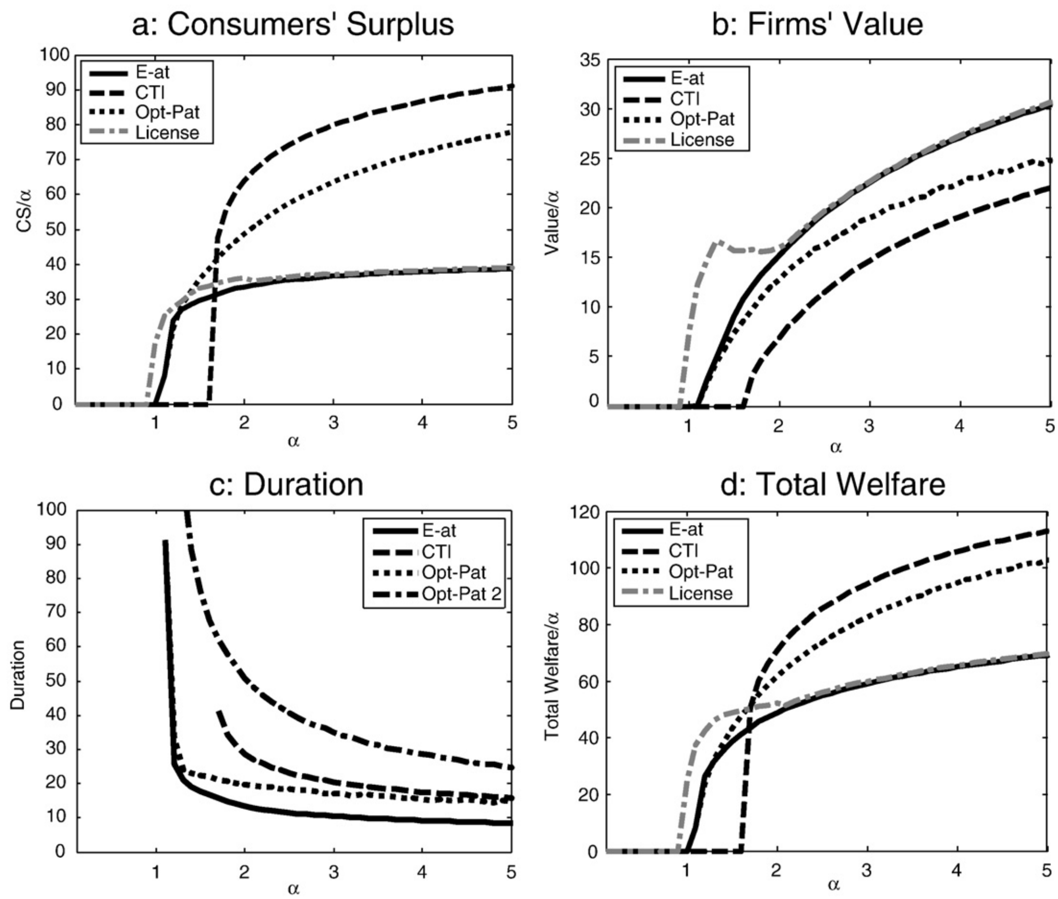

Fig. A1. a: Consumers' Surplus, b: Firms' Value, c: Duration, d: Total Welfare.

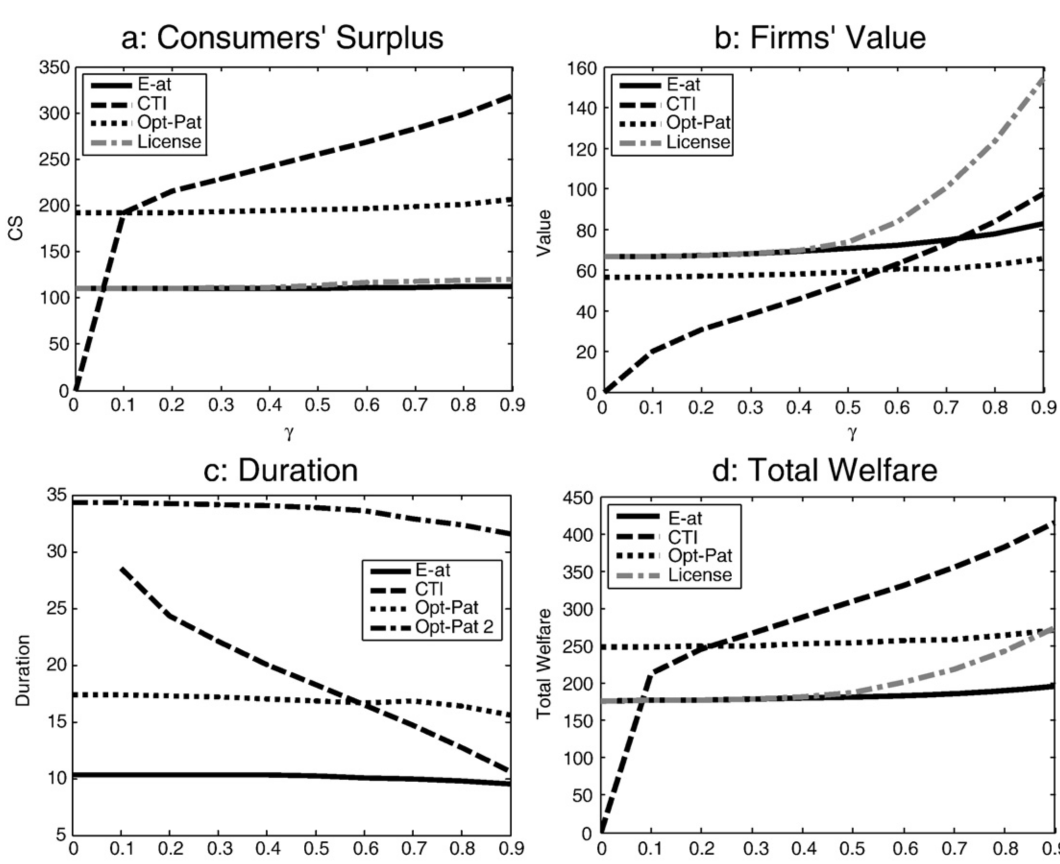

Fig. A2. a: Consumers' Surplus, b: Firms' Value, c: Duration, d: Total Welfare.

where the technology frontier remains unchanged, complete specialization implies a constant level of consumers' surplus (see Fig. 1a); this is not the case when the technology frontier changes. In this case, if firms only develop the stages they have an advantage in, the total costs of completing the innovation decrease. Consequently, consumers' surplus under the CTI regime increases with the level of asymmetry (see Fig. A2a).

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