Technological Progress, Industry Rivalry, and Stock Returns

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Abstract

In this paper we investigate the link between competition in technological innovation and asset prices. We develop a model of an innovation race in which firms are subject to technological as well as market-wide uncertainty and optimally exercise their options to innovate. The model predicts that the race leader has lower systematic risk than its lagging rival, that the follower-leader spread in systematic risk widens as the distance between the firms' technological efficiencies increases, and that the systematic risk of the portfolio of race participants increases with the number of competitors. We test these novel predictions using a comprehensive firm-level panel dataset on patenting activity in the U.S. from 1978 to 2003. Consistent with the model's predictions, we find that: (i) the beta of a portfolio of firms competing in innovation is monotonically increasing in the number of firms in the race, and (ii) within each innovation race, the beta of a firm is lower the closer it is to be the leader. These results have economy-wide implications for the cross-section of expected returns as firms engaged in innovation races account for 40%-50% of the total U.S. market capitalization in our sample period.

JEL Classification Codes: G12, G14

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1 Introduction

A society's rate of technological progress is the key determinant of growth in the economy. Technological progress refers to the perpetual process through which new inventions make existing technologies obsolete (Schumpeter (1934)). A large body of work in industrial organization and on the economics of innovation shows that the competitive structure of the innovation process is the most important driving force for firms' R&D investment decisions. However, surprisingly little is known about the economic mechanism that links competitive interactions among firms to asset prices. If competition affects firms' optimal investment decisions, and if a firm's investment impacts the risk exposure of its cash flows, then competition can affect the firm's cost of capital and, more generally, the cross-section of expected returns.

In this paper, we theoretically show how strategic interactions in the innovation process affect rival firms' systematic risk and offer the first empirical evidence on how the participation in an "innovation race" affects competing firms' betas. In our model, two firms compete for a patent. Investment in innovation is irreversible, which gives rise to an option to innovate. The firms are exposed to two sources of risk: market-wide risk, that originates from the uncertainty of the profits from the commercialization of the patent, and firm-specific risk, that originates from the technological uncertainty of the innovation process. On one hand, irreversibility and the market-wide risk induce firms to delay the investment in innovation. On the other hand, the winner-takes-all nature of the patent and the presence of a rival tend to erode the option value of waiting. An important property of the model is that, because of the technological uncertainty, the firm that invests first is not guaranteed to win the patent race and its opponent may still find it optimal to wait and invest later. We explicitly characterize the equilibrium investment strategies of the competing firms and derive implications for the dynamics of each firm's systematic risk during the innovation race.

We show that, when firms are engaged in the innovation race, the probability with which a firm that invests first (the leader) obtains the patent directly affects the systematic risk of its opponent who is still waiting to invest (the follower). Despite the fact that the outcome of the technological process of innovation is idiosyncratic, this result obtains because the probability of the leader winning the race reduces the option value to invest held by the follower. Consequently, the follower's option becomes effectively more levered and therefore more sensitive to changes in the market-wide risk. There are two types of equilibria that characterize the race: collusive equilibria, in which both firms invest simultaneously and leader-follower equilibria, in which the firm with the highest success rate in the innovation process is the first to invest in innovation. The model predicts that when leader-follower equilibria emerge: (i) the systematic risk of the leader is always smaller than that of the follower, (ii) the difference between the leader's and the follower's level of systematic risk increases in the distance between the innovation efficiencies of the two competing firms and, (iii) the systematic risk of the equally weighted portfolio of the leader and the follower increases in the distance between the innovation efficiencies of the two firms.

We test the predictions of our theory using a comprehensive firm-level panel of patent application filing and patent award events in the U.S. over 1978-2003 which we create by combining information from five sources: (i) the NBER Patent Data Project, (ii) the Worldwide Patent Statistical Database compiled by the European Patent Office, (iii) the CRSP/Compustat Merged Quarterly Database, (iv) the CRSP Daily and Monthly Stock Files, and (v) the TAQ database. The key advantage of the resulting dataset is that it allows us to track innovation activity by both the technology fields of innovation and by individual firms over time on a day-to-day basis. We use these two distinct features to define which firms are active in innovation at any point in time and to empirically identify an innovation race. Our dataset is ideal for testing the theory because firms engaged in innovation races in our data compete for monopoly rents which explicitly derive from patents' exclusive rights granted to inventors, as assumed in the model.

We find a strong support for the model's predictions. As the number of firms that participate in an innovation race increases, i.e., as the number of followers in the race increases, the equity beta of the race increases. Furthermore, the closer a firm is to a leading position in the race, the lower its equity beta is. The effects of the innovation race characteristics on equity betas are statistically and economically significant. For example, the difference between the equity beta of races with ten (thirty) firms and the equity beta of a firm in a non-competitive innovation environment is 0.2 (0.5), which represents one fourth (two thirds) of the standard deviation of the sample distribution of equity betas for firms active in innovation. More broadly, our results have economy-wide implications for the cross-section of expected returns as the firms we identify as active in innovation races account for 40%-50% of the total U.S. market capitalization in our sample period.

This paper bridges the gap between two strands of literature, one in economics and one in finance. Specifically, our model combines the strategic elements studied by the industrial organization literature on patent races,[1] with the concepts of investment irreversibility and risk studied by the real options literature in finance.[2] Our model is closely related to Weeds (2002) who analyzes the case of two identical firms competing in R&D. We generalize Weeds' model to allow for heterogeneity in the innovation success rate between the firms and derive explicit closed-form characterizations of the dynamics of the rival firms' risk. More broadly, our paper follows the seminal work of Berk, Green, and Naik (1999, 2004) in analyzing the effect of optimal investment decisions on asset prices. The closest papers from this literature are Garlappi (2004) and Carlson, Dockner, Fisher, and Giammarino (2009). Garlappi (2004) derives the risk premia dynamics of two firms engaged in a multi-stage R&D game and numerically documents that the risk premium increases as a firm lags behind in the R&D race. Carlson, Dockner, Fisher, and Giammarino (2009) analyze the risk dynamics of firms that compete in a product market and have options to expand and contract production. Unlike Garlappi (2004), we abstract away from the multi-stage nature of R&D investments and are able to derive closed-form solutions for the dynamics of beta in the innovation race. Unlike Carlson, Dockner, Fisher, and Giammarino (2009), we do not model product market competition but focus explicitly on the competitive process in innovation and on the role of technological uncertainty. This allows us to isolate the effect of the leader's success rate in innovation on the beta of the follower. Due to the technological uncertainty, the follower's option to innovate does not expire when the leader invests but, becomes less valuable as its "moneyness" decreases. This "externality" of the leader's investment on the follower does not operate through a product market but through the discount rate the follower uses to evaluate profits from a patent. The leader's innovation success rate acts as a "depreciation rate" that reduces the follower's expected profits from the patent and hence the value of the option to innovate. Finally, in contrast to these papers, we empirically test the predictions of our theory.

Our empirical work relates both to the literature in economics that uses patent data to study firm performance and to the more recent literature in finance that links aggregate technology

[1]A partial list of early work in this area includes Loury (1979); Lee and Wilde (1980); Reinganum (1981b,c); Fudenberg, Gilbert, Stiglitz, and Tirole (1983); Fudenberg and Tirole (1985); Harris and Vickers (1985, 1987); and Grossman and Shapiro (1987).

[2]See, for example, Smets (1991); Grenadier (1996, 1999, 2002); Huisman and Kort (2003, 2004); Thijssen, Huisman, and Kort (2002); Huisman (2001); Boyer, Lasserre, Mariotti, and Moreaux (2004); Lambrecht (2000); Aguerrevere (2003, 2009); Meng (2008); and Pawlina and Kort (2006). See Grenadier (2000) for a survey.

factors to asset prices. The performance literature documents a positive link between stock market valuation and patents (e.g., Pakes (1985, 1986)) and between stock market valuation and patent citations (e.g., Bloom and Van Reenen (2002) or Hall, Jaffe, and Trajtenberg (2005)). With the exeption of Austin (1993), who uses an event-study methodology to estimate the average effect of a patent on rival firms relative to the patent's effect on its recipient, the literature on performance has not addressed the issue of strategic interactions among firms.

A limited set of empirical papers in finance explores the link between industry technological factors and asset returns. Hou and Robinson (2006) show that firms in highly concentrated industries are less risky and thereby command lower expected returns. They argue that this finding is either due to barriers to entry in highly concentrated industries which insulates firms from undiversifiable distress risk, or because firms in highly concentrated industries engage in less innovation. Recently, Hsu (2009) finds that aggregate patent and R&D shocks have predictive power for market returns and premia in the U.S. as well as in other G7 countries. Following this result, Hsu and Huang (2009) construct a technology factor which tracks the changes in technology prospects measured by U.S. patent shocks, and find that this factor helps to explain the cross-sectional variation of Fama and French (1993) portfolios. Unlike these papers, we focus on the link between strategic interactions among firms that compete for new technology and the firms' systematic risk. Our analysis, which is both at the race and at the firm level, and closely follows the predictions of our theory, explicitly uncovers the economic mechanism that rationalizes why the aggregate technology factor of Hsu and Huang (2009) helps to explain the cross-section of returns.

Our paper makes four contributions. First, we formalize the link from the strategic investment decisions to the firms' systematic risk in industry equilibrium. Second, we quantify the effect of competition in innovation on firms' equity betas. To the best of our knowledge, ours is the first study that empirically validates the existence of strategic effects on asset prices. Third, we develop a novel empirical methodology to identify innovation races using patent data. The patent race variables we create are suggested by our structural model and are of an independent interest to other researchers in economics and finance. Fourth, our tests rely on explanatory variables that, by construction, are unconnected to financial market data. We show that the explanatory power of these variables for the cross-section of equity returns is robust and applies to a large part of the U.S. equity market.

The rest of the paper proceeds as follows. In Section 2 we develop a model of an innovation race, construct the equilibria, derive firms' values and betas, and formulate testable predictions. Section 3 describes the data, defines the key variables, explains the empirical methodology, and present the results. Section 4 concludes. Proofs of all propositions are in Apppendix A.

2 Model

In this section, we develop a model of competition in innovation between two firms and characterize the firms' equilibrium investment strategies, values, and risk dynamics.

Two all-equity financed firms, $i = 1, 2$, have an opportunity to invest in innovation. A successful innovation by one firm results in the acquisition of a patent that guarantees the winner monopoly profits and excludes the other firm from any profits. The competing firms are subject to both technological and market-wide uncertainty. The technological uncertainty means that, after a firm invests in innovation, discovery occurs randomly. The market-wide uncertainty refers to the fact that the monopoly profits received upon successful acquisition of the patent evolve stochastically over time.

We denote by $x(t)$ the profit of the new technology for which the firms compete. The process $x(t)$ evolves stochastically over time according to a geometric Brownian motion

$$dx(t) = \mu x(t)dt + \sigma x(t)dW(t), \tag{1}$$

where $dW(t)$ is the increment of a standard Brownian motion under the true probability measure, $\mu > 0$ is the constant drift, and σ is the constant volatility. The process $x(t)$ represents the monopoly profit of the winning firm when it is granted a patent.

Each firm has the opportunity to deploy a fixed amount of capital $K_i > 0$ to set up a research project. Once the capital has been deployed, the discovery happens randomly according to a Poisson distribution with constant hazard rate $h_i > 0$. For simplicity, we assume that the hazard rate h_i is independent of the cost K_i. We set the innovation cost of both firms to $K_i = K$, $i = 1, 2$, and focus our analysis on the degree of asymmetry in the success rates h_i, which measures the efficiency of the innovation effort of each firm. As the investment cost is identical for the two firms, the firm with a higher hazard rate is more efficient in innovation.

We model competition in innovation as a *stopping time game* (see Fudenberg and Tirole (1985)) in which each firm makes a single irreversible investment in innovation. Formally, if firm i invests K at time t, it can make a discovery at all dates $s > t$. Once firm i has invested in innovation it cannot make any other action. The game ends when either firm makes a discovery, i.e., acquires the patent. At each point in time, the state of the game is described by the history of the stochastic process $x(t)$ and by whether firm i has invested in innovation. A strategy is a mapping from the set of histories of the game to the set of actions. At time t, a history is the collection of realizations of the stochastic process $x(s)$, $s \leq t$ and of actions of both firms. Unlike Reinganum (1981a,b,c), the firms in our model do not commit ex ante to a specific investment date. Instead, the firms respond immediately to their rivals' investment decisions, which leads to equilibria of the *closed-loop* type.

We assume that firms follow Markov strategies, i.e., strategies in which actions are functions of the current state $x(t)$ only.[3] As we discuss later, in the case of asymmetry in the innovation success rate between firms, the firm with a higher rate takes the role of the leader. By further assuming that $x(0)$ is sufficiently low, we can focus on Markov equilibria in *pure strategies*. A firm's strategy is a *stopping rule* characterized by a threshold x^* for the state variable $x(t)$ such that the firm invests when $x(t)$ crosses x^* from below for the first time. In contrast, in the case of a stopping time game between symmetric firms, the equilibrium involves mixed strategies whose formulation is complicated by the continuous-time nature of the game (see discussion in Fudenberg and Tirole (1985)).[4] In the case of mixed strategies, the leader and the follower in a race are determined randomly, which makes empirical identification impossible.

2.1 Firm values and investment thresholds

Firms' values are given by the present values of their risky profits. To evaluate profits, we assume the existence of a pricing kernel and, following a standard argument (e.g., Duffie (1996)), construct a risk-neutral probability measure under which the evolution of the process $x(t)$ is

$$dx(t) = (r - \delta)x(t)dt + \sigma x(t)d\widehat{W}(t), \quad r > \delta > 0, \tag{2}$$

[3] In general, one cannot exclude the existence of non-Markovian strategies. However, if one firm follows a Markov strategy, the opponent's best response is also Markov (see Fudenberg and Tirole (1991), Chapter 13, for a formal treatment of Markov equilibria.)

[4] Due to the loss of information that occurs in passing from discrete to continuous time, Fudenberg and Tirole (1985) define mixed strategies by enlarging the strategy space to include both the cumulative probability that a firm has innovated by time t and the "intesity" with which a firm adopts innovation just after t.

where $d\widehat{W}(t)$ is the increment of a standard Brownian motion under the risk-neutral probability measure implied by the pricing kernel, r is the risk-free rate, and δ is the opportunity cost of keeping the ability to invest in innovation alive.[5] From (1) and (2) we infer that the risk-premium associated with the process $x(t)$ is $\lambda \equiv \mu - (r - \delta)$.

To determine the equilibrium of the game we need to first compute: (i) the value of a firm that has not invested given that its opponent has already invested; (ii) the value of a firm that is considering to invest given that its opponent will choose the optimal time to invest in the future; and (iii) the value of a firm when it invests simultaneously with its opponent. We can think of the value in (i) as the best response function of the 'follower' of the value in (ii) as the value of a 'leader' upon investing, and of the value in (iii) as the payoff from 'tacit collusion'. The game is solved backwards, starting with the optimization problem of the follower. Unless needed for clarity, we drop the time argument t when referring to the stochastic process $x(t)$.

2.1.1 Follower

The problem of the follower is to determine the optimal time to invest, given that its opponent has already invested. Let firm i be the follower and firm j be the leader. Denote by x_i^F the follower's investment threshold. The value of firm i is the present value of expected future profits, which in the case of the follower, can be characterized by the solution of the optimal stopping time problem:

$$V_i^F(x) = \max_{\tau_i^F} E_0 \left[e^{-(r+h_j)\tau_i^F} \left(\int_{\tau_i^F}^{\infty} e^{-(r+h_i+h_j)(t-\tau_i^F)} h_i x(t) dt - K \right) \right], \tag{3}$$

where $\tau_i^F = \inf\{t > 0 : x(t) \geq x_i^F\}$ is the stopping time and the expectation is taken under the risk-neutral measure. Notice that the hazard rate of the leader h_j augments the discount rate for the future payoff of the follower. This is because the likelihood of firm j successfully innovating before i reduces the value of the profits from i's discovery. This is common in R&D models involving a constant Poisson arrival process (e.g., Loury (1979)). Furthermore, note that the expected profits $h_i x(t)$ for firm i upon investing are discounted at a rate that includes the hazard rate of both firms, i.e., $r + h_i + h_j$. This is because for $t > \tau_i^F$ both firms have invested in innovation and so the profit of firm i is subject to the hazard rate of both i's and j's innovation

[5]By assuming the existence of a pricing kernel exogenously, we implicitly rule out the possibility that a firm's innovation activity alters the state prices in the economy.

technologies. The following proposition characterizes the solution of the follower's stopping time problem.

Proposition 1. *Conditional on firm j having already invested in innovation, the optimal strategy of firm i is to invest at the threshold*

$$x_i^F = \frac{\phi_j}{\phi_j - 1} \frac{h_i + h_j + \delta}{h_i} K, \quad i \neq j, \tag{4}$$

where

$$\phi_j = \frac{1}{2} - \frac{r-\delta}{\sigma^2} + \sqrt{\left(\frac{1}{2} - \frac{r-\delta}{\sigma^2}\right)^2 + \frac{2(r+h_j)}{\sigma^2}} > 1. \tag{5}$$

The value of firm i acting as a follower is

$$V_i^F(x) = \begin{cases} \left(\frac{x}{x_i^F}\right)^{\phi_j} \left[\frac{h_i x_i^F}{h_i+h_j+\delta} - K\right] & \text{if } x < x_i^F \\ \frac{h_i x}{h_i+h_j+\delta} - K & \text{if } x \geq x_i^F \end{cases}. \tag{6}$$

The quantity $(x/x_i^F)^{\phi_j}$ represents the price of an Arrow-Debreu security that pays one dollar when the process x first hits the threshold x_i^F. This price depends, through the term ϕ_j and x_i^F, on the hazard rate of firm i's opponent, h_j. This innovation technology "externality" is important in determining the follower's cost of capital, as we discuss later.

2.1.2 Leader

We now determine the value of a firm conditional on investing as the leader and anticipating that the follower will respond optimally according to Proposition 1. The value of firm j when it decides to invest K is

$$V_j^L(x) = E_0\left[\int_0^{\tau_i^F} e^{-(r+h_j)t} h_j x(t) dt\right] + E_0\left[e^{-(r+h_j)\tau_i^F} \int_{\tau_i^F}^{\infty} e^{-(r+h_i+h_j)(t-\tau_i^F)} h_j x(t) dt\right] - K, \tag{7}$$

where τ_i^F is the time at which firm i invests in innovation. The first term captures the expected profits that firm j receives before firm i invests, while the second term captures the expected profits received after firm i invests. The next proposition characterizes the value of the leader $V_j^L(x)$.

Proposition 2. *Conditional on firm i investing as a follower at the threshold x_i^F derived in Proposition 1, the value of firm j acting as a leader at the time it invests in innovation is*

$$V_j^L(x) = \begin{cases} \frac{h_j x}{h_j+\delta} - \left(\frac{x}{x_i^F}\right)^{\phi_j} \left[\frac{h_j x_i^F}{h_j+\delta} - \frac{h_j x_i^F}{h_i+h_j+\delta}\right] - K & \text{if } x < x_i^F \\ \frac{h_j x}{h_i+h_j+\delta} - K & \text{if } x \geq x_i^F \end{cases}. \tag{8}$$

When the follower has not invested yet, $x < x_i^F$, the value of the leader in (8) is composed of three parts. The first part is the present value of a perpetuity with expected profits $h_j x$ and discount rate $h_j + \delta$. The second part can be thought of as a short position in $\left[\frac{h_j x_i^F}{h_j+\delta} - \frac{h_j x_i^F}{h_i+h_j+\delta}\right]$ options, each paying one dollar when x first hits x_i^F and each having price of $\left(x/x_i^F\right)^{\phi_j}$. Intuitively, it is as if the leader is shorting these options to the follower who exercises them at the threshold x_i^F. The third part is the fixed investment cost of innovation.

Proposition 2 describes the value of the leader, *at the moment it decides to invest* in innovation. Note that in Proposition 2 the leader is *not* choosing an optimal investment strategy. The function $V_j^L(x)$ represents the value of the leader upon investing, taking into account the follower's optimal investment strategy x_i^F. In contrast, if firm j were a 'designated leader', it would have the option to be the first to invest in innovation, knowing that it cannot be preempted by firm i. The optimal value of a designated leader is obtained by finding the optimal investment threshold, abstracting from strategic considerations. The optimal value of firm j as the designated leader $V_j^D(x)$ would then be to find the optimal entry threshold x_j^D at which to invest in innovation first and become the leader, i.e.,

$$V_j^D(x) = \max_{\tau_j^D} E_0 \left[e^{-r\tau_j^D} V_j^L(x_j^D)\right], \tag{9}$$

where $\tau_j^D = \inf\{t > 0 : x(t) \geq x_j^D\}$. Notice that, because j cannot be preempted, the discount rate in (9) is simply the risk-free rate r. The next proposition solves the problem of the designated leader.

Proposition 3. *Suppose the roles of the firms are preassigned and firm j is the designated leader who cannot be preempted by firm i. The value of firm j is*

$$V_j^D(x) = \begin{cases} \left(\frac{x}{x_j^D}\right)^{\phi_0} V_j^L(x_j^D) & \text{if } x < x_j^D \\ V_j^L(x) & \text{if } x \geq x_j^D \end{cases}, \tag{10}$$

where $V_j^L(x)$ is defined in Proposition 2 and x_j^D is implicitly determined by the smooth pasting condition

$$(\phi_j - \phi_0)\frac{h_j}{h_j + \delta}\frac{h_i x_i^F}{h_i + h_j + \delta}\left(\frac{x_j^D}{x_i^F}\right)^{\phi_j} + (\phi_0 - 1)\frac{h_j x_j^D}{h_j + \delta} - \phi_0 K = 0, \tag{11}$$

with

$$\phi_0 = \frac{1}{2} - \frac{r-\delta}{\sigma^2} + \sqrt{\left(\frac{1}{2} - \frac{r-\delta}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}} > 1, \tag{12}$$

ϕ_j given in equation (5), and x_i^F given in equation (4).

Note that, from the definition of ϕ_0, the value of the Arrow-Debreu security $(x/x_j^D)^{\phi_0}$ does not depend on the hazard rate of any of the two firms. This is because, by construction, the designated leader is shielded from preemption by its rival.

2.1.3 Simultaneous investment

In order to construct the equilibrium of the innovation game, it is necessary to derive the payoffs of both firms when they are constrained to invest at the same threshold. The value of firm i when both firms invest at a pre-specified threshold x^C is

$$V_i(x; x^C) = E_0\left[e^{-r\tau^C}\left(\int_{\tau^C}^{\infty} e^{-(r+h_i+h_j)(t-\tau^C)} h_i x(t) dt - K\right)\right], \quad i = 1, 2, \tag{13}$$

where $\tau^C = \inf\{t > 0 : x(t) \geq x^C\}$. The next proposition characterizes $V_i(x; x^C)$.

Proposition 4. *The value of firm i when both firms invest at a given threshold x^C is*

$$V_i^C(x; x^C) = \begin{cases} \left(\frac{x}{x^C}\right)^{\phi_0}\left[\frac{h_i x^C}{h_i + h_j + \delta} - K\right] & \text{if } x < x^C \\ \frac{h_i x}{h_i + h_j + \delta} - K & \text{if } x \geq x^C \end{cases}, \quad i \neq j, \tag{14}$$

where ϕ_0 is given in equation (12).

The optimal collusive threshold x_i^C from the individual firm's perspective is obtained by maximizing (14) with respect to x^C, yielding

$$x_i^C = \frac{\phi_0}{\phi_0 - 1} \frac{h_i + h_j + \delta}{h_i} K, \quad i, j = 1, 2. \tag{15}$$

Notice that if $h_i \neq h_j$ the two firms disagree on the optimal joint threshold. For example, if $h_1 > h_2$ then, from (15), $x_1^C < x_2^C$. If $x(0)$ is sufficiently small, i.e., $x(0) < x_1^C$, the only sustainable joint investment threshold is x_1^C, because firm 1 has an incentive to deviate from the alternative joint threshold x_2^C that maximizes firm 2's value.

2.2 Types of non-cooperative equilibria

Having defined the leader's and the follower's values, we can now analyze the set of subgame perfect equilibria in which each firm's innovation strategy, conditional on the opponent's strategy, is value maximizing. A set of strategies that satisfies this condition is called a *Markov-perfect equilibrium*.

Without loss of generality, we assume that $h_1 \geq h_2$. When $h_1 > h_2$ the role of the competing firms is uniquely defined: Firm 1 is the leader, unless the two firms invest simultaneously. In this case, there are pure-strategy equilibria. In contrast, when $h_1 = h_2$ the roles of leader and follower cannot be pre-assigned and there are only mixed-strategy equilibria.

The type of equilibrium that emerges depends on how the leader's value $V_i^L(x)$ compares with the value of the simultaneous investment strategy $V_i^C(x; x^C)$. Intuitively, if $V_i^L(x) > V_i^C(x; x^C)$, then only *leader-follower* equilibria are possible; if $V_i^L(x) < V_i^C(x; x^C)$, the equilibrium involves *simultaneous* investment. In the class of leader-follower equilibria, there exist two possible types of equilibria: *preemptive*, in which both firms have an incentive to become the leader, and *sequential*, in which one of the two firms has no incentive to become the leader. To distinguish between preemptive and sequential equilibria, it is useful to define the threshold x_i^P as the lowest realization of the process x at which a firm is indifferent between becoming the leader or being the follower. Formally,

$$x_i^P = \inf \left\{ x : V_i^L(x) = V_i^F(x) \right\}. \tag{16}$$

This condition is the "rent equalization" principle described in Fudenberg and Tirole (1985). At x_i^P, firm i loses the incentive to preempt its rival.

The following proposition describes the regions of the parameter space for which the equilibria of a given type occur.

Proposition 5. *Let $h_1 > h_2$ and let x_2^F, x_1^D, and x_2^P be the thresholds for the process $x(t)$ defined in (4), (11), and (16), respectively. For every h_1 there exist two thresholds for h_2, $J(h_1)$ and $S(h_1)$, such that*

1. *If $h_2 < J(h_1)$ the unique Markov-perfect equilibrium is:*

   (a) *Preemptive, if $h_2 > S(h_1)$, with firm 1 investing in innovation at the threshold $x^P = \min\{x_1^D, x_2^P\}$ and firm 2 investing at the threshold x_2^F, or,*

   (b) *Sequential, if $h_2 < S(h_1)$, with firm 1 investing in innovation at the threshold x_1^D and firm 2 investing at the threshold x_2^F.*

2. *If $J(h_1) < h_2$ there exists a unique Markov-perfect equilibrium that involves simultaneous investment in innovation at the threshold x_1^C.*

Figure 1 depicts the regions of different types of equilibria from Proposition 5 in the (h_1, h_2) plane. The solid line is the threshold $J(h_1)$, the dash-dotted line is the threshold $S(h_1)$, and the dotted line is the 45-degree line. Since we assume $h_1 > h_2$, the relevant region in Figure 1 is the area below the 45-degree line. Simultaneous equilibria occur for values of $h_2 > J(h_1)$, preemptive equilibria occur for values $S(h_1) < h_2 < J(h_1)$, and sequential equilibria occur when $h_2 < S(h_1)$.

Panel A (B) of Figure 1 refers to low (high) level of volatility of the process $x(t)$. The figure shows that simultaneous equilibria are more likely to occur for high levels of volatility. Intuitively, the higher the level of volatility of $x(t)$, the more valuable is the option to wait, and the less incentive the leader has to preempt by investing early. For sufficiently low levels of volatility (Panel A), the threshold $J(h_1)$ is always above the 45-degree line and simultaneous equilibria do not occur. From the threshold $S(h_1)$ we infer that when h_2 is sufficiently smaller than h_1 firm 2 has no interest to become the leader and hence the equilibria are sequential. As h_2 increases and crosses the threshold $S(h_1)$, firm 2 has an incentive to become the leader, and preemptive equilibria ensue. Finally, as discussed in Weeds (2002), note that on the 45-degree line, i.e., when $h_1 = h_2$, there are only preemptive or simultaneous equilibria.

2.3 Firm values and systematic risk in equilibrium

Given the characterization of the equilibria in Proposition 5 , we can now determine the corresponding firm values.

Proposition 6. *Let $V_i^F(x)$ and $V_i^L(x)$, $i = 1, 2$, be given by Propositions 1 and 2, respectively, and let $h_1 > h_2$.*

1. *In a leader-follower equilibrium, the value of the leader (firm 1) and the follower (firm 2) are*

$$V_1^{\mathrm{LF}}(x) = \begin{cases} \left(\frac{x}{x^P}\right)^{\phi_0} V_1^L(x_2^P) & \text{if } x < x^P \\ \frac{h_1 x}{h_1+\delta} - \left(\frac{x}{x_2^F}\right)^{\phi_1} \left[\frac{h_1 x_2^F}{h_1+\delta} - \frac{h_1 x_2^F}{h_1+h_2+\delta}\right] & \text{if } x^P \leq x < x_2^F \\ \frac{h_1 x}{h_1+h_2+\delta} & \text{if } x \geq x_2^F \end{cases}, \tag{17}$$

and

$$V_2^{\mathrm{LF}}(x) = \begin{cases} \left(\frac{x}{x^P}\right)^{\phi_0} V_2^F(x_2^P) & \text{if } x < x^P \\ \left(\frac{x}{x_2^F}\right)^{\phi_1} \left[\frac{h_2 x_2^F}{h_1+h_2+\delta} - K\right] & \text{if } x^P \leq x < x_2^F \\ \frac{h_2 x}{h_1+h_2+\delta} & \text{if } x \geq x_2^F \end{cases}, \tag{18}$$

where, in a preemptive equilibrium $x^P = \min\{x_1^D, x_2^P\}$ and, in a sequential equilibrium $x^P = x_1^D$, with x_1^D and x_2^P given by (11) and (16), respectively.

2. *In a simultaneous equilibrium the value of each firm $V_i^{\mathrm{S}}(x)$ is*

$$V_i^{\mathrm{S}}(x) = \begin{cases} \left(\frac{x}{x_1^C}\right)^{\phi_0} \left[\frac{h_i x_1^C}{h_1+h_2+\delta} - K\right] & \text{if } x < x_1^C \\ \frac{h_i x}{h_1+h_2+\delta} & \text{if } x \geq x_1^C \end{cases}, \quad i = 1, 2, \tag{19}$$

where x_1^C is defined in (15).

The equilibrium firms' values are the present values of the future expected profits from the awarded patent. Note that when investment takes place the values of both firms are discontinuous. This is because the investment cost K is a sunk cost that is financed through influx of new equity capital.[6]

To determine the risk premium demanded by each firm competing in innovation we use the fact that the systematic risk β_i of firm i can be expressed as the elasticity of the firm's value

[6] If, for example, K were financed through debt, the firm values would need to be adjusted to incorporate the present value of the liability cash flows.

with respect to the underlying profit originating from the patent x, i.e.,

$$\beta_i = \frac{dV_i(x)}{dx}\frac{x}{V_i(x)}. \tag{20}$$

Hence, the instantaneous expected return of firm i can be expressed as

$$E\left[R_i\right] = r + \beta_i\lambda, \tag{21}$$

where λ is the risk premium of the process x.

Using the expressions for the firms' values in the different equilibria from Proposition 6, we obtain the following characterization of the firms' systematic risk.

Proposition 7. *Let β_i be the measure of systematic risk of firm i defined in equation (20).*

1. *In a leader-follower equilibrium, the systematic risk of the leader (firm 1) and of the follower (firm 2) are*

$$\beta_1^{\mathrm{LF}}(x) = \begin{cases} \phi_0 & \text{if } x < x^P \\ 1-\omega(x)(\phi_1-1) & \text{if } x^P \leq x < x_2^F \\ 1 & \text{if } x \geq x_2^F \end{cases}, \tag{22}$$

and

$$\beta_2^{\mathrm{LF}}(x) = \begin{cases} \phi_0 & \text{if } x < x^P \\ \phi_1 & \text{if } x^P \leq x < x_2^F \\ 1 & \text{if } x \geq x_2^F \end{cases}, \tag{23}$$

where $\omega(x) = \frac{b(x)}{a(x)-b(x)} > 0$ with $a(x) = \frac{h_1 x}{h_1+\delta}$ and $b(x) = \left(\frac{x}{x_2^F}\right)^{\phi_1}\left[\frac{h_1 x_2^F}{h_1+\delta} - \frac{h_1 x_2^F}{h_1+h_2+\delta}\right]$. In a preemptive equilibrium $x^P = \min\{x_1^D, x_2^P\}$ and, in a sequential equilibrium $x^P = x_1^D$, with x_1^D and x_2^P given by (11) and (16), respectively.

2. *In a simultaneous equilibrium both firms have the same systematic risk*

$$\beta_i^{\mathrm{S}}(x) = \begin{cases} \phi_0 & \text{if } x < x_1^C \\ 1 & \text{if } x \geq x_1^C \end{cases}, \quad i = 1, 2, \tag{24}$$

where x_1^C is defined in (15).

The proposition states that innovation decisions affect the firms' systematic risk. In particular, in the case of either preemptive or sequential equilibria, when the leader invests, its beta drops from $\phi_0 > 1$ to $1 - \omega(x)(\phi_1 - 1) < 1$, while the beta of the follower increases from ϕ_0 to $\phi_1 > \phi_0$.

The drop in the leader's beta is a familiar result: the option to innovate is a levered asset and by exercising it, its riskiness is reduced. In a non-strategic case, the beta would drop from ϕ_0 to the beta of the underlying profit which is equal to 1. In the case of a leader-follower equilibrium, the leader's beta is affected by the follower investing later at a higher threshold x_2^F. Specifically, for the values of the state variable between x^P and x_2^F the leader is in a de facto monopoly position because it can make a discovery while the follower, who has not invested yet, cannot. However, because of the technological uncertainty, the follower is "long" a valuable innovation option which can be though of as being "written" by the leader (see the negative term in equation (17)). This short position in the innovation option lowers the beta of the leader which drops below the beta of the underlying profit. The mechanism is similar to the "hedging channel" documented in Carlson, Dockner, Fisher, and Giammarino (2009) although, in our setting, it does not operate through market clearing in a product market but through the technology channel, captured by the hazard rates h_1 and h_2. Intuitively, by investing first, the leader is "buying insurance" against being preempted by its rival. Such insurance is more valuable when the threat of the opponent is higher, i.e., when the opponent has a similar hazard rate. In other words, the effect on the leader's beta is stronger the smaller is the distance between the two firms' innovation efficiencies.

The increase in the follower's beta reflects the fact that its option to invest in innovation suddenly becomes less valuable and more risky when the competitor has already invested and started the discovery process. This can be seen by analyzing the value of the follower in equation (18). Note that as the process x crosses the threshold x^P at which the leader invests, the follower's value $V_2^{\mathrm{LF}}(x)$ becomes more convex in x (since $\phi_1 > \phi_0$). In other words, the increase in the riskiness of the follower's value comes from an increase in the sensitivity of the option value to changes in the process x. One can describe the consequence of the leader's decision to invest in innovation as imposing an externality on the follower. This externality takes the form of adding extra "leverage" to the follower's option to innovate.

The above results can be extended to the case of N firms.[7] A full theoretical treatment of the equilibrium in a N-firm game has little value in guiding empirical analysis because the solution involves identifying all the possible subsets of firms investing in either simultaneous of leader-follower equilibria. Instead, we can obtain testable predictions by focusing on a sequential leader-follower equilibrium. In the next proposition, we derive firms' betas in a N-firm game under the assumption that a sequential leader-follower equilibrium is being played. This focuses our analysis on the dynamics of risk which is the most relevant for our empirical analysis.

Proposition 8. *Suppose N firms have innovation efficiencies $h_1 > h_2 > \ldots > h_N$ and $x_1 < x_2 < \ldots < x_N$ are the investment thresholds in a sequential leader-follower equilibrium of a N-firm game. Then the equilibrium firm value $V_m^{LF}(x)$ is given by*

$$V_m^{LF}(x) = \begin{cases} \left(\frac{x}{x_1}\right)^{\phi_0} V_m(x_1) & \text{if } x < x_1 \\ \frac{h_m x}{H_m+\delta} - \left(\frac{x}{x_{m+1}}\right)^{\phi_n} h_m \Gamma_m & \text{if } x_n \leq x < x_{n+1},\ m \leq n \text{ (leader)} \\ \left(\frac{x}{x_{n+1}}\right)^{\phi_m} V_m(x_{n+1}) & \text{if } x_n \leq x < x_{n+1},\ m > n \text{ (follower)} \\ \frac{h_m x}{H_N+\delta} & \text{if } x \geq x_N \end{cases} \tag{25}$$

where $\Gamma_m = \sum_{k=m+1}^{N} \left(\frac{x_k}{H_{k-1}+\delta} - \frac{x_k}{H_k+\delta}\right) \prod_{l=1}^{k-2} \left(\frac{x_{l+1}}{x_{l+2}}\right)^{\phi_{l+1}}$, $H_k = \sum_{i=1}^{k} h_i$,

$$\phi_k = \frac{1}{2} - \frac{r-\delta}{\sigma^2}\sqrt{\left(\frac{1}{2} - \frac{r-\delta}{\sigma^2}\right)^2 + \frac{2(r+H_k)}{\sigma^2}} > 1, \tag{26}$$

and $V_m(x)$ is the value of firm m upon investing, given the investment thresholds $x_1 < x_2, \ldots < x_N$, i.e.,

$$V_m(x) = \begin{cases} \frac{h_m x}{H_n+\delta} - K - \left(\frac{x}{x_n}\right)^{\phi_n} h_m \Gamma_n & \text{if } x_n \leq x < x_{n+1},\ n = 1, \ldots, N-1 \\ \frac{h_m x}{H_N+\delta} & \text{if } x \geq x_N \end{cases} \tag{27}$$

[7]For example, Bouis, Huisman, and Kort (2009) characterize equilibria investment thresholds in an oligopoly game without technological uncertainty.

The beta of firms in a leader-follower equilibrium is

$$\beta_m^{LF}(x) = \begin{cases} \phi_0 & \text{if } x < x_1 \\ 1 - \omega_m(x)(\phi_n - 1) & \text{if } x_n \le x < x_{n+1},\ m \le n \text{ (leader)} \\ \phi_m & \text{if } x_n \le x \le x_{n+1},\ m > n \text{ (follower)} \\ 1 & \text{if } x \ge x_N \end{cases} \tag{28}$$

where $\omega_m(x) = \frac{b_m(x)}{a_m(x) - b_m(x)}$ *with* $a_m(x) = \frac{h_m x}{H_m + \delta}$ *and* $b_m(x) = \left(\frac{x}{x_{m+1}}\right)^{\phi_n} h_m \Gamma_m$.

Equation (28) shows that a firm's beta depends on how the firm's innovation efficiency compares to that of its competitors. Specifically, a firm's beta increases as the firm ranks lower: The most efficient firm has the lowest beta while the least efficient one has the highest beta. Equation (28) also shows that the beta of a firm with a given rank depends on the innovation efficiencies of all more efficient firms in the race. These findings are consistent with the two-firm race results in Proposition 7.

In summary, our model of a two-firm race predicts that the systematic risk of the leader is always (weakly) smaller in comparison to the systematic risk of the follower in all equilibria we consider. Importantly, in the leader-follower equilibria, the systematic risk of the leader is strictly smaller for $x \in [x^P, x_2^F]$. Analogous results also obtain for the N-firm race in a sequential leader-follower equilibrium.

2.4 The effect of innovation efficiency on systematic risk

In this subsection, we analyze the effect from a change in the firms' innovation efficiencies on systematic risk. Figure 2 shows the betas for the leader and the follower in leader-follower equilibria, derived in Proposition 7. Panel A analyzes the case of the follower "catching up", i.e., the hazard rate of the leader is set to $h_1 = 1$ and we consider three levels for $h_2 = \{0.5, 0.7, 1\}$. Panel B analyzes the case of the leader "pulling ahead", i.e., the hazard rate of the follower is set to $h_2 = 1$ and we consider three levels for $h_1 = \{1, 1.5, 1.7\}$. In both panels, the left graph plots the beta of the leader (equation (22) in Proposition 7) and the right graph plots the beta of the follower (equation (23) in Proposition 7). The solid line refers to the betas in a symmetric game, i.e., when $h_1 = h_2$. Figure 2 highlights that as h_1 and h_2 change, the investment thresholds also change, which complicates the interpretation of the comparative statics exercise. In particular, it is possible to show that both x^P and x_2^F (i) decrease with h_2 for a given level of h_1, and

(ii) increase with h_1 for a given level of h_2. Moreover, the difference between the investment threshold of the leader and the follower is the narrowest when the firms have the same innovation efficiency, $h_1 = h_2$.

Panel A of Figure 2 shows that, as h_2 increases, the beta of the follower is unaffected, while the leader's beta decreases. To understand the behavior of the leader's beta in the left graph of Panel A for $x \in [x^P, x_2^F]$ note that the leader's value is $V_1^{\mathrm{LF}}(x) = a(x) - b(x) > 0$, where $a(x) = \frac{h_1 x}{h_1+\delta}$ and $b(x) = \left(\frac{x}{x_2^F}\right)^{\phi_1} \left[\frac{h_1 x_2^F}{h_1+\delta} - \frac{h_1 x_2^F}{h_1+h_2+\delta}\right]$ (see equation (17)). Therefore, we can think of the leader's value as a portfolio of two assets: (i) a long position in the patent's expected discounted profits $a(x)$ and (ii) a short position in the option to innovate held by the follower $b(x)$. The weight $\omega(x) = b(x)/(a(x) - b(x)) > 0$ that enters the leader's beta (see equation (22)) is the fraction of the leader's value from the short position in the option. As h_2 increases, the innovation option is more valuable to the follower and $b(x)$ increases, and since $a(x)$ does not depend on h_2, this causes $\omega(x)$ to increase. This reasoning, together with the fact that a change in h_2 does not affect ϕ_1 imply that an increase in h_2 reduces the beta of the leader.

Panel B of Figure 2 shows that, as h_1 increases, the beta of both the leader and the follower increases. From Proposition 7 we know that, in a leader-follower equilibrium, the systematic risk of the follower increases in the innovation efficiency of the leader because this makes the follower's option to innovate more sensitive to the underlying process x, i.e., the convexity of the follower's option increases with the leader's efficiency. This effect can be seen by inspecting the expression for the follower's beta β_2^{LF} in equation (23). From the definition of ϕ_1 in equation (5), it is immediate to see that ϕ_1 increases with the leader's hazard rate h_1 and hence β_2^{LF} increases with h_1 as well. In other words, as the leader becomes more efficient in innovation, all else being equal, the upper bound of the follower's beta increases.

The implications of a change in h_1 on the beta of the leader in the left graph of Panel B are more subtle because a change in h_1 has both a direct and an indirect effect. An increase in h_1, keeping $\omega(x)$ in equation (22) fixed, implies a decline in β_1^{LF} (direct effect). However, as h_1 increases, $\omega(x)$ changes as well. In particular, a higher h_1 reduces the value of the innovation option $b(x)$ and increases the value $a(x)$ of the leader's expected discounted profits from the patent, causing $a(x) - b(x)$ to increase and $\omega(x)$ to decrease. Therefore, a decrease in $\omega(x)$ causes an increase in β_1^{LF} (indirect effect). It is not clear, a priori, which of the two effects prevails. In the left graph of Panel B, the indirect effect is dominating and so, an increase in h_1 causes an increase in the beta of the leader.

2.5 Testable predictions

The comparative static results from the previous subsection provide an intuitive understanding of our model, but do not lead directly to testable predictions as they are conditional on the state variable x. To describe the unconditional "long-run" relationship between fundamental technology characteristics of innovation races and systematic risk and to formulate testable predictions for empirical analysis, we use the results from Subsection 2.3 to simulate the model.

For every pair (h_1, h_2) giving rise to a leader-follower equilibrium, we simulate I paths with T periods each of the process $x(t)$ according to (1). Along each path, we record the betas of the leader and the follower, which we compute using equation (22) and (23), respectively. We then compute the time series average of the betas in each of the I paths and, finally, the mean of the time series averages across the I paths. Such a procedure captures the long-run values of the betas of the leader and the follower, assuming that each patent race we model can be repeated I times with different realizations of x.

Figure 3 plots (i) the spread $\beta_2^{\mathrm{LF}} - \beta_1^{\mathrm{LF}}$ between the leader's and follower's long-run values of the beta and (ii) the long-run beta of the equally weighted portfolio of the leader and the follower $(\beta_1^{\mathrm{LF}} + \beta_2^{\mathrm{LF}})/2$, as either h_1 or h_2 increases.[8] We are interested in the latter quantity because it represents the systematic risk of the race which we can measure empirically. In the top two (Panels A and B) we fix h_1 and vary h_2, while in the bottom two (Panels C and D) we fix h_2 and vary h_1. In Panel A (B) h_1 is fixed at $h_1 = 1$ ($h_1 = 2$) and $h_2 \in [0.5, 1]$ ($h_2 \in [1, 2]$). In both panels, as h_2 increases, firm 2 "catches up" to firm 1. In Panel C (D) h_2 is fixed at $h_2 = 1$ ($h_2 = 2$) and $h_1 \in [1, 2]$ ($h_1 \in [2, 3]$). In both panels, as h_1 increases, firm 1 "pulls ahead" from firm 2.

Figure 3 shows that the spread between the follower's and the leader's long-run values of the beta is *decreasing* in the innovation efficiency of the follower h_2 and *increasing* in the innovation efficiency of the leader h_1. The figure suggests that the effect from increasing h_1 has a bigger

[8]All graphs in Figure 3 are obtained by simulating $I = 100,000$ time series with $T = 240$ observations each, starting from an initial value $x(0) = x^P/2$. To mitigate the effect of the starting value, we drop the first 120 observations in each simulation. The parameters we use are: $r = 3\%$, $\mu = 10\%$, $\sigma = 30\%$, and $K = 1$. The parameters are kept constant in each simulation. Results are robust to different parameterizations.

impact on the spread in comparison to the effect from increasing h_2. In other words, the leader pulling ahead has a stronger pricing impact than the follower catching up. Figure 3 also shows that the long-run beta of the equally weighted portfolio of the leader and the follower *increases* in the innovation efficiency of the leader h_1 and *decreases* in the innovation efficiency of the follower h_2. Therefore, our testable predictions are:

Prediction 1. *The long-run beta of the equally weighted portfolio of the leader and the follower* $(\beta_1^{LF} + \beta_2^{LF})/2$ *increases in the 'distance' between the innovation efficiencies of the two competing firms* $h_1 - h_2$.

Prediction 2. *The spread between the follower's and the leader's long-run values of the beta* $\beta_2^{LF} - \beta_1^{LF}$ *increases in the 'distance' in innovation efficiencies of the two competing firms* $h_1 - h_2$.

The simulation analysis also helps us to understand the relative magnitudes of the comparative static effects from changing h_1 and h_1 in Figure 2. In Panel A of Figure 2, when h_2 increases, the beta of the leader decreases, while the upper bound of the beta of the follower is unaffected. Based on this observation, one would expect that the spread between the leader's and the follower's beta would *increase* as h_2 increases, contrary to the simulation result. However, note that, as h_2 increases, the interval $[x^P, x_2^F]$ shrinks. This means that, in the long run, the probability of drawing a realization of $x(t)$ in this interval is smaller. Therefore, on one hand, as h_2 increases, the spread between the follower's and the leader's beta increases, but, on the other hand, the likelihood of observing a positive spread is smaller. The simulation shows that the second effect dominates the first and the spread decreases as h_2 increases. A similar reasoning can be used to link the results from an increase in h_2, displayed in Panel B of Figure 2, to the simulations in Panel B of Figure 3. Finally, the same intuition also relates the simulation results for the long-run beta of the equally weighted portfolio of the leader and the follower shown in Figure 3 to the results reported in Figure 2.

3 Empirical Analysis

In this section, we empirically verify the predictions of our theory about the relationship between competition in technological innovation and firms' systematic risk. In Subsection 3.1 we describe the five data sources used in the analysis. In Subsection 3.2 we formally identify the empirical counterparts of the two key elements of our theory: The concepts of an innovating firm and of an innovation race. In Subsection 3.3 we describe our empirical methodology. Subsection 3.4 presents summary statistics of characteristics of firms active in innovation races. We present the results in Subsection 3.5 and Subsection 3.6 reports robustness checks.

3.1 Data sources

Our empirical analyses rely on data from five sources: (i) the NBER Patent Data Project (May 2009 version), (ii) the Worldwide Patent Statistical Database (PATSTAT, April 2008) compiled by the European Patent Office, (iii) the CRSP/Compustat Merged Quarterly Database, (iv) the CRSP Daily and Monthly Stock Files, and (v) the Trade and Quote (TAQ) database.

The NBER Patent Data Project provides data about all utility patents[9] awarded by the U.S. Patent and Trademark Office (USPTO) in 1976-2006. Among other variables, the NBER dataset contains, for each patent, a unique patent number, patent assignee names matched to firms in Compustat (a patent number-GVKEY link), and a patent's technology field of innovation defined according to the standards of the International Patent Classification (IPC) system. The original matching of patent assignees, by name, to firms in Compustat comes from Hall, Jaffe, and Trajtenberg (2001). Since then, the matching has been updated using multiple manual and computer generated matches (see Bessen (2009) for details).

The PATSTAT database contains information from patent documents submitted to and issued by the USPTO including, unlike the NBER dataset, the exact day when an application for each patent was filed and the day when each patent was granted. We merge the NBER dataset with the PATSTAT database and create, for each firm, day-by-day time series of patent filing and grant events. We consider all firms matched to Compustat that obtained at least one patent. The resulting dataset contains a GVKEY as the primary firm identifier (7,494 unique GVKEYs), a patent number as the unique identifier of each patent (1,330,115 unique patent numbers), the IPC technology field of innovation of each patent, the day when the patent application was filed for each patent, and the day when each patent was granted. The key advantage of the resulting dataset is that it allows to track innovation activity over time by technology fields of innovation as well as by firms, and we use these two features to define an innovation race and a firm's position in the race.

[9]According to the U.S. Patent Law (35 U.S.C. §101) utility is a necessary requirement for patentability and is used to prevent the patenting of inoperative devices. In our analysis, we do not use plant patents, i.e., patents for new varieties of plants.

Firm-level financial variables come from the CRSP/Compustat Merged Quarterly Database and CRSP Monthly Stock File. We estimate monthly market and Dimson (1979) "sum" betas using the return data available in the CRSP Daily Stock File. Finally, we use the TAQ database to compute realized betas using high frequency returns. We provide details of how different betas are constructed in Subsection 3.3.

3.2 Empirical proxies for firms competing in an innovation race

To test our theory we need to develop proxies for firms that are competing in innovation, which we call 'innovating firms', and for 'innovation races'. To define these two empirical concepts, we use the fact that patent examiners classify each patent according to the standards of the IPC. The IPC provides an internationally uniform hierarchical system for the classification of patent documents according to the different areas of technology to which they pertain.[10] This means that the area of technology in which a firm is claiming and/or being awarded a patent is unequivocally specified. We refer to the third level of the IPC hierarchical system, called the "IPC Subclass Symbols", as to a 'technology class'.[11] Innovating firms and innovation races are defined based on their technology class. Each patent in our data has an IPC Subclass Symbol and this level of the IPC hierarchy corresponds to a well defined body of technical knowledge in which firms compete in innovation.[12]

3.2.1 Innovating firm

We refer to a firm as an 'innovating firm' in technology class k at month t if the firm has been awarded at least one patent in technology class k during the last $\tau = 36$ months (including t), and has filed one or more patent applications in technology class k in at least $\theta = 20$ percent of months over the same τ-months period.[13] Specifically, we create a dummy variable $D_{ikt}^{\text{innovating}}$

[10] The IPC is used as a search tool for the retrieval of patent documents by intellectual property offices and other users and it serves as a basis for investigating the state of the art in a given field of technology by patent officers. A patent examiner assigns a classification to the patent (or patent application) at the most detailed level of the IPC hierarchy which is applicable to its contents.

[11] For example, IPC Subclass Symbol "A61N" stands for "Electro therapy, Magneto therapy, Radiation therapy, and Ultrasound therapy"; "B60T" stands for "Vehicle brake control systems or parts thereof, Brake control systems, or parts thereof, in general"; and "F15C" stands for "Fluid-circuit elements predominantly used for computing or control purposes". The last (eighth) edition of the IPC defines 639 subclasses.

[12] The IPC Subclass Symbol describes, "as precisely as is possible in a small number of words, the main characteristic of a portion of the whole body of knowledge covered by the IPC." See IPC (2009, p. 13) for details (`http://www.wipo.int/export/sites/www/classifications/ipc/en/guide/guide_ipc_2009.pdf`).

[13] We tried alternative definitions by varying: (i) the length of the relevant time period, τ, over which we count patent filings and awards, (ii) the percentage threshold of months, θ, in which a firm needs to file for a

that is equal to 1 if firm i is an innovating firm in technology class k at month t and is equal to 0 otherwise. Let D_{iks}^{patent} be equal to 1 if firm i is awarded one or more patents in technology class k at month s and 0 otherwise. Similarly, let $D_{iks}^{\text{application}}$ be equal to 1 if firm i files one or more patent applications in technology class k at month s and 0 otherwise. Formally, variable $D_{ikt}^{\text{innovating}}$ is defined as follows

$$D_{ikt}^{\text{innovating}} = \begin{cases} 1 & \text{if } \sum_{s=t-\tau+1}^{t} D_{iks}^{\text{patent}} \geq 1 \text{ and } \sum_{s=t-\tau+1}^{t} D_{iks}^{\text{application}} \geq \theta \times \tau \\ 0 & \text{otherwise} \end{cases}. \tag{29}$$

Table 1 provides summary statistics of the characteristics of the sample of innovating firms as well as of the sample of all non-financial firms (i.e., we exclude firms with four-digit SIC codes between 6000 and 6999). The statistics are computed using firm-quarter observations available in the CRSP/Compustat Merged Quarterly Database. For each firm, a quarter is included in the sample of innovating firms if there is at least one month during this quarter in which the firm is innovating in at least one technology class according to definition (29). We use data from January 1978 to December 2003 when NBER patent data are matched to firms in Compustat and we require that firms in our sample have non-missing total assets and positive sales. In the calculation of the reported statistics, we drop observations in the top and bottom 1% of the distribution of each variable to remove outliers.

The mean (median) size of an innovating firm in our sample measured by *Market Capitalization* is \$8,208M (\$1,512M) while the mean (median) size of all firms is \$1,176M (\$76M). The innovating firms are on average more profitable (*Profitability* of 2.9%) than the average of all firms (*Profitability* of 1.9%), have a higher average Tobin's Q (*Tobin's Q* of 2.15 vs. 1.86), and have a lower average book-to-market equity ratio (*Book/Market Equity* of 0.57 vs. 0.74). On the investment side, the innovating firms spend on average more than twice on R&D (*R&D/Sales* of 13.8%) in comparison to all firms which spend 6.1% on average. The innovating firms have on average lower capital expenditures (*Capital Expenditures/Sales* of 10.4%) in comparison to all firms which spend 12.1% on average. R&D expenses as a fraction of total investment (i.e., the sum of R&D expenses and capital expenditures) is on average a lot higher for the innovating firms (*R&D/Total Investment* of 31.0% vs. 14.2%). The average ratio of cash to total assets is

patent during the relevant period. Such alternative definitions lead to similar samples of innovating firms and to analogous results.

16.4% for the innovating firms and 14.2% for all firms. The leverage of the innovating firms is on average 16.0% (*Market Leverage*) and 20.5% (*Book Leverage*), while it is on average 20.7% (*Market Leverage*) and 24.4% (*Book Leverage*) for all firms. In sum, a typical innovating firm in our sample is very big, highly profitable, exhibits high R&D spending, holds more cash, and is less levered.

The number of firm-quarter observations in the sample of innovating firms represents about 6.3% of all firm-quarter observations. To show the economic significance of this sample, Figure 4 plots the quarterly time series of the number (market capitalization) of the innovating firms expressed as the fraction of the total number (market capitalization) of all non-financial firms available in CRSP/Compustat Merged Quarterly Database in 1978-2003. The figure reveals that our sample of innovating firms contains about 6.6% (time-series average) of the total number of firms available in CRSP/Compustat in a given quarter. Importantly, this 6.6% of firms represents about 42.8% (time-series average) of the total market capitalization of all non-financial firms in a given quarter. In 2000, the fraction of market capitalization taken by the innovating firms reaches its maximum value of 54.6%. In summary, only a relatively small number of firms exhibit high-enough patenting intensities to satisfy our definition of being innovating according to definition (29), but, the firms that enter the sample of innovating firms belong to those with the largest market capitalization.

3.2.2 Innovation race

The second step in linking our theory to the data requires the identification of an innovation race. An innovation race in technology class k at month t occurs when there are two or more innovating firms in the same technology class and at the same time. For brevity, we refer to an innovation race in technology class k as 'race k'. We denote by N_{kt} the *number of innovating firms* in race k at month t. To measure the position of firm i in race k at month t we compute the relative amount of patenting output firm i has achieved in race k during the last τ months (including t). Specifically, for firm i in race k at month t we compute the fraction h_{ikt} of the total number of patents that have been awarded in race k during the last τ months to firm i. Formally,

$$h_{ikt} = \frac{\sum_{s=t-\tau+1}^{t} P_{iks}}{\sum_{\{i:D_{ikt}^{\text{innovating}}=1\}} \sum_{s=t-\tau+1}^{t} P_{iks}}, \tag{30}$$

where P_{iks} is the number of patents awarded to firm i in technology class k at month s. To identify the leader and the followers, we order the innovating firms in race k at month t using the fraction h_{ikt} decreasingly $h_{1kt} > h_{2kt} > \ldots > h_{N_{kt}kt}$. We assign rank 1 to the firm with the highest innovation efficiency, $n_{1kt} = 1$, rank 2 to the firm with the second highest innovation efficiency, $n_{2kt} = 2$, and so on until firm N_{kt} (the hindmost follower) is assigned rank $n_{N_{kt}kt} = N_{kt}$.[14] As a result, the *rank* of firm i in race k at month t, $n_{ikt} \in [1, N_{kt}]$, denotes the relative position of firm i in race k at month t based on its recent patenting success.

Table 2 describes how the races evolve over time using the sample of innovating firms. To ease presentation, we separate race-month observations with only one innovating firm, $N_{kt} = 1$, and we aggregate the *number of innovating firms* in a race variable using bins by five firms, $N_{kt} = \{2–5, 6–10, 11–15, \ldots, 56–60, >60\}$. The *rank* of a firm variable is aggregated analogously.

Panel A of Table 2 reports transition probabilities between an innovation race with a given *number of innovating firms* at month t and the *number of innovating firms* this race has at month $t + 1$. The race-months just before the race-months in which we observe one or more innovating firms for the first time are coded as 'Enter'. The race-months immediately after the last race-months in which we observe one or more innovating firms are coded as 'Exit'. Panel A shows that the *number of innovating firms* in a race is stable in between two consecutive months as it can be inferred from the high values on the main diagonal of the transition matrix. For example, a race with 2–5 innovating firms in month t has a 95.1% chance of having the same *number of innovating firms* in the next month, a 2.9% chance of becoming a race of size 1 (monopoly) and a 1.9% chance of becoming a 6–10 firm race. We also observe that the probabilities of an increase/decrease in the *number of innovating firms* in a race are similar and that, as we move towards races with a higher *number of innovating firms*, the probabilities of an increase/decrease in the *number of innovating firms* in a race both increase. The row of the transition matrix labelled 'Enter' shows that only 16.4% of races start with more than one firm. The races reach high values of the *number of innovating firms* gradually over time.[15] The findings about time-series properties of races reported in Panel A of Table 2 suggest that innovating firms in technology class k at month t typically remain active in this technology class

[14] In case two firms have the same h_{ikt}, we refine their ranking using the number of patent applications filed over the same τ months period.

[15] The end of a race is a low probability event in our data. Before a race ends, the *number of innovating firms* in a race decreases and we observe race 'Exit' only when the *number of innovating firms* in the immediately preceding month is 1 (3.4%) or 2–5 (0.1%).

for an extended period of time and are therefore valid proxies for firms that compete for the next patent in race k at month t.

Panel B of Table 2 reports transition probabilities between the *rank* an innovating firm has in race k at month t and the *rank* this firm has in the same race at month $t+1$. The firm-race-month just before the firm-race-month in which we observe the firm as active in innovation in this race for the first time is coded as 'Enter'. The firm-race-month immediately after the last firm-race-month in which we observe the firm as active in innovation in this race is coded as 'Exit'. Panel B shows that the firm's *rank* is fairly stable in between two consecutive months as the values on the diagonal of the transition matrix range from 93.2% for races with 2–5 firms to 68.0% for races with 56–60 firms. Typically, the probability with which an innovating firm improves its *rank* in the race is higher than the probability with which its *rank* worsens. As we move towards races with a higher *number of innovating firms*, the probability of a change in *rank*, both improvement and worsening, goes up.

3.3 Methodology

Our goal is to investigate the effect of innovation race characteristics on the cross-section of systematic risk. Prediction 1 in Subsection 2.5 relates the technology distance between the leader and the follower to the beta of a race. Since firms join races as followers, the technology distance between the leader and a "typical" follower increases when a new firm starts to be active in a race. Therefore, at the race level, we use the *number of innovating firms* as a proxy for the technology distance. This leads to our first hypothesis:

Hypothesis 1. *The equity beta of the portfolio of innovating firms in race k at month t increases in the number of innovating firms N_{kt}.*

To test Hypothesis 1 we estimate regression

$$\beta_{kt} = \lambda_0 + \lambda_1 N_{kt} + \gamma X_{kt} + u_k + v_t + \epsilon_{kt}, \tag{R1}$$

where β_{kt} represents the equity beta of the portfolio of innovating firms in race k at month t, N_{kt} is the *number of innovating firms* in race k at month t, and X_{kt} is the average market capitalization of innovating firms in race k at month t. Race and month fixed-effects are denoted u_k and v_t, respectively.[16]

Prediction 2 in Subsection 2.5 relates the technology distance between the leader and the follower to the spread between the follower's and the leader's beta. We use firm i's *rank* scaled by the *number of innovating firms* in a race as a measure of the technology distance between the leader and firm i. This leads to our second hypothesis:

Hypothesis 2. *The equity beta of an innovating firm i in race k at month t increases in its relative rank $\frac{n_{ikt}}{N_{kt}} \in [\frac{1}{N_{kt}}, 1]$.*

To test Hypothesis 2 we estimate regression

$$\beta_{ikt} = \lambda_0 + \lambda_1 N_{kt} + \lambda_2 \frac{n_{ikt}}{N_{kt}} + \gamma X_{ikt} + u_k + v_t + \epsilon_{ikt}, \tag{R2}$$

where β_{ikt} represents the equity beta of innovating firm i in race k at month t; N_{kt}, as before, is the *number of innovating firms* in race k at month t; $\frac{n_{ikt}}{N_{kt}}$ is the relative *rank* of firm i in race k at month t, i.e., the *rank* n_{ikt}, scaled by the *number of innovating firms* in race k at month t, N_{kt}; and X_{ikt} is the market capitalization of firm i in race k at month t.

We follow three approaches to estimate the equity betas that we use as dependent variables in regressions (R1) and (R2). First, we use standard time-series CAPM regressions $R_{it} = \alpha_i + \beta_i R_{Mt} + \zeta_{it}$, where R_{it} is the excess return on stock of firm i and R_{Mt} is the excess return on the market portfolio. We use daily returns from CRSP Daily Stock File to estimate the equity beta for each firm-month using separate short-window regressions. This approach gives a direct estimate of a conditional equity beta for each firm-month without using any state variables or making any assumption about month-to-month variation in equity beta (see Lewellen and Nagel (2006) for details of this approach). Second, following Dimson (1979), we augment the procedure above by including current, one-period lag, and one-period lead market returns in the regression and estimate the equity beta for each firm-month as the sum of the slopes on all three market returns. In both cases above, our market proxy is either the CRSP equally-weighted or CRSP value-weighted index (all stocks), and we calculate excess returns using the one-month T-bill rate (obtained from Ken French's web page).[17] As a result, we have four different estimates

[16] We use a fixed-effects econometric model as our main regression specification. This approach ensures that we obtain consistent estimates in the presence of omitted variables that can induce unobserved heterogeneity related to both the dependent and independent variables (Wooldridge (2002)).

[17] We set the estimated equity beta to missing in case the estimate is based on less than five observations.

of equity betas to which we refer as *equally-weighted market beta*, *equally-weighted sum beta*, *value-weighted market beta*, and *value-weighted sum beta*.

When estimating monthly equity betas using daily returns, each regression uses a small number of observations and produces noisy estimates. To reduce this noise, our third approach is to use the TAQ database to compute realized equity betas based on high frequency returns.[18] The TAQ database contains, since 1994, intraday transactions data (trades and quotes) for all securities listed on the NYSE, AMEX, and Nasdaq. For each stock we use prices between 9:45am and 4:00pm, sampled every 25 minutes, to compute high frequency returns. We combine these returns with the overnight return, computed between 4:00pm on the previous day and 9:45am on the current day, yielding a total of 16 intra-daily returns. We choose a 25-minute frequency to balance the desire for reduced measurement error with the need to avoid the microstructure biases that arise at the highest frequencies (e.g., Epps (1979), Griffin and Oomen (2010), and Hayashi and Yoshida (2005)). The prices we use are the national best bid and offer (NBBO) prices, computed by examining quote prices from all exchanges offering quotes on a given stock. We use the exchange traded fund tracking the Standard & Poor's Composite Index (SPDR, traded on Amex with ticker SPY, and available on the TAQ database) to measure the market return, as in Todorov and Bollerslev (2007). This fund is very actively traded and, since it can be redeemed for the underlying portfolio of S&P 500 stocks, no arbitrage ensures that the fund's price does not deviate from the fundamental value of the underlying index. We compute monthly equity beta as the ratio of stocks' realized covariance with the fund to the realized variance of the fund over a given month and we refer to it as *high-frequency beta*.[19]

3.4 Characteristics of firms active in innovation races

We start by presenting summary statistics of the characteristics of the sample of innovating firms broken down by the *number of innovating firms* in a race N_{kt} and the *rank* of a firm in a race n_{ikt}. Panel A of Table 3 reports the number of firm-race-month observations based on the number non-missing values of market capitalization available in the CRSP Monthly Stock File.

[18]See Andersen, Bollerslev, Diebold, and Labys (2003) and Barndorff-Nielsen and Shephard (2004) for econometric theory underlying the estimation of volatility and covariance using high frequency data and Bollerslev and Zhang (2003) for an application.

[19]To reduce the impact of outliers, for all our equity beta estimates separately, we set to missing observations that lie outside the 0.5 to 99.5 percentile of the respective equity beta distribution.

Panel B of Table 3 reports the average *equally-weighted market beta* of the innovating firms computed using firm-race-month observations for each combination of the *number of innovating firms* in a race and the *rank* of a firm in a race variables. Panel B shows that the equity beta increases with the firm's *rank* in a race. This pattern is strong and holds consistently across races with different *numbers of innovating firms*. For example, on average, the equity beta of firms in races with 21–25 innovating firms is equal to 1.34 for the firms with *ranks* 2–5, while it is equal to 1.56 for the firms with *ranks* 21–25. The pattern of equity betas is consistent with the statistics in Panel C, where we report the average buy-and-hold one-year return from investing into the innovating firms for each combination of the *number of innovating firms* in a race and the *rank* of a firm in a race variables. The return is computed using monthly returns (available in the CRSP Monthly Stock File) from one-month ahead ($t+1$) to twelve-months ahead ($t+12$) for each firm-race-month observation. The return increases with the firm's *rank* in a race and this is true for races with different *numbers of innovating firms*. These descriptive results suggest the *number of innovating firms* in a race and the *ranks* of firms in a race could play an important role in determining the innovating firms' systematic risk and expected returns, which provides a preliminary support for our hypotheses from the previous subsection.

Panel D of Table 3 reports the average market capitalization (available in the CRSP Monthly Stock File) of the innovating firms computed using firm-race-month observations for each combination of the *number of innovating firms* in a race and the *rank* of a firm in a race variables. The average market capitalization increases the higher the firm is *ranked* in a race, i.e., the race leaders are the biggest firms on average. This relationship holds independently of the *number of innovating firms* in a race and it gets stronger for races with many innovating firms. The results on market capitalization (Panel D) may suggest that the fact that the laggards in races have higher returns (Panel C) is a manifestation of the "size effect". However, the size effect cannot explain why the betas of the laggards are higher, as documented in Panel B. These findings leads us to include market capitalization as a control variable in all regressions. Panel E reports the analogous results for the average *Book/Market Equity*. *Book/Market Equity* tends to decrease with the *rank* of a firm in a race, but the association is not robust.

3.5 Results

In this section, we present the results of our tests of Hypotheses 1 and 2. Table 4 reports the regressions of the equity beta of the portfolio of innovating firms in a race on the *number of innovating firms* in a race and the average (log of) market capitalization of the firms in this portfolio (regression equation (R1)). The sample for regression (R1) consists of all race-month observations with at least one innovating firm in a race-month over the 1978-2003 period. The dependent variable is the equity beta of the portfolio of innovating firms in a given race-month. In columns 1–3, each firm's equity beta is measured using the *equally-weighted market beta*, the *equally-weighted sum beta*, and the *high-frequency beta*, respectively. When computing the equity beta of the portfolio of innovating firms in a race-month we weight each firm's equity beta equally. In columns 4–6, each firm's equity beta is measured using the *value-weighted market beta*, the *value-weighted sum beta*, and the *high-frequency beta*, respectively. When computing the equity beta of the portfolio of innovating firms in a race-month we weight each firm's equity beta by its market capitalization.

In Panel A of Table 4, the *number of innovating firms* in a race is entered as a continuous variable. The coefficient estimates suggest that the *number of innovating firms* in a race increases equity beta. This result is highly statistically significant across all six specifications. In Panel B of Table 4, the *number of innovating firms* in a race variable is entered as a set of dummies for ranges of values of the variable, $\{2\text{–}5, 6\text{–}10, 11\text{–}15, \ldots, 56\text{–}60, >60\}$. For example, dummy variable 2–5 is equal to one for race-month observations with at least two but no more than five innovating firms and is zero otherwise. Dummy variables 6–10, 11–15, etc. are defined analogously. This specification relaxes the assumption that equity beta increases linearly with the *number of innovating firms* in a race. The race-month observations with the *number of innovating firms* equal to one form the base group. The results in Panel B of Table 4 confirm that the *number of innovating firms* in a race increases equity beta. The coefficients obtained using this semi-parametric specification have a simple economic interpretation. Each estimated coefficient shows by how much bigger is the equity beta of the portfolio with a given *number of innovating firms* relative to the equity beta of the portfolio formed using the race-month observations with only one innovating firm. For example, the coefficient 0.538 in front of 31–35 dummy variable in the first column implies that the equity beta of the portfolio formed using race-month observations with at least 31 but no more than 35 innovating firms is by 0.538 larger than the equity beta of the portfolio formed using the race-month observations with only one innovating firm. Standard errors are clustered at race level in all specifications.

Figure 5 plots the coefficients obtained using the semi-parametric regressions analogous to the ones in columns 1–3 in Panel B of Table 4. The only difference to Panel B of Table 4 is that we enter a dummy variable for each value of the N_{kt} variable separately, i.e., we have separate dummies for $N_{kt} = 2, 3, \ldots, 60$, and $N_{kt} > 60$. As in Panel B of Table 4, the race-month observations with only one innovating firm form the base group. Figure 5 documents a monotonic relationship between the equity beta of a race and the *number of innovating firms* in a race and illustrates the economic significance of the estimated effect. For example, the difference between the *equally-weighted market beta* of innovating firms in races with ten (fifty) firms and the same beta of innovating firms in a non-competitive environment is 0.2 (0.8), which represents 25% (100%) of the standard deviation of the sample distribution of the equity betas for innovating firms. The results are similar, although somewhat smaller, if we use the *value-weighted market beta* or the *high-frequency beta* as the dependent variable.

Next, we test Hypothesis 2 that the equity beta of an innovating firm in a race increases in the firm's *rank* in the race. This test, presented in Table 5, is formalized using regression equation (R2) that we estimate using the sample of firm-race-month observations with at least two innovating firms in a race-month over the 1978-2003 period. The dependent variable is the equity beta of an innovating firm in a race-month. In columns 1 and 2, beta is measured using the *equally-weighted market beta* and the *equally-weighted sum beta*, respectively. In columns 3 and 4, beta is measured using the *value-weighted market beta* and the *value-weighted sum beta*, respectively. Finally, in column 5, beta is measured using the *high-frequency beta*.

In Panel A of Table 5, the firm's *rank* in a race is entered as a continuous variable. The coefficient estimates suggest that the firm's *rank* in a race increases equity beta. This result is highly statistically significant across all five specifications. In Panel B of Table 5, the *number of innovating firms* in a race variable is entered as a full set of dummies (denoted *firms in a race*) for ranges of values of the variable. For example, dummy variable 2–10 *firms in a race* is equal to one for the race-month observations with at least two but no more than five innovating firms and is zero otherwise. Dummy variables 11–20 *firms in a race*, etc. are defined analogously. This set of dummy variables fully spans the sample and the constant is excluded from the regression. The firm's *rank* in a race is entered as a continuous variable directly and is also interacted with the *firms in a race* dummies. The interaction with the 51–60 *firms in a race* dummy variable forms the base group. This specification allows for the effect of the firm's rank in a race on the firm's equity beta to differ across races depending on the *number of innovating firms* in a race. The results in Panel B of Table 5 confirm that the firm's *rank* in a race increases equity beta independently of the *number of innovating firms* in a race. The coefficients in front of the firm's *rank* in a race variable range from 0.213 to 0.359 across the five specifications and are always precisely estimated. The coefficients in front of the interaction terms reveal that the slope of the firm's *rank* in a race effect is significantly lower for races with 2–10 innovating firms and lower for races with 11–20 innovating firms. In other words, these results suggest that the slope of the firm's *rank* effect on beta increases with the *number of innovating firms* in a race. Standard errors are clustered race level in all specifications.

Panel A of Table 6 repeats the estimation from Panel A of Table 4 while including the lagged beta of a race as a control variable. The coefficients in front of the *number of innovating firms* in a race variable decrease only slightly in magnitude and remain highly statistically significant in all specifications. Similarly, Panel B of Table 6 repeats the estimation from Panel A of Table 5 while including the lagged beta of an innovating firm as a control variable. The coefficients in front of the firm's *rank* in a race variable decrease by about 25% on average across our five specifications but remain always highly statistically significant.

To summarize, the results presented in Tables 4, 5, and 6 suggest that systematic risk increases with the number of firms in an innovation race and it also depends on a firm's position in the race. These findings support the hypotheses from Subsection 3.3 and suggest that competition in innovation does affect systematic risk through the channel we formalize in our theory.

3.6 Robustness

In this subsection, we develop additional investigations and present robustness checks on our results. First, we explore whether the beta of a race increases in the number of *rank transitions* in a race. The number of *rank transitions* in a race is an alternative dimension one can use to assess the intensity of competition within an innovation race, and, therefore, relates to the broad question that motivates our study.

Specifically, we define a dummy variable *1 rank transition* in a race which is equal to one if there is exactly one change in *ranks* among innovating firms in the race between the current and the immediately preceding month and is zero otherwise. Dummy variables *2 rank transitions* and *≥3 rank transitions* in a race are defined analogously. Table 7 reports results of race-level regressions with *rank transitions* dummies entered as the independent variables. The sample and the dependent variables are identical to those in Panel A of Table 4. The only difference is that we only use race-month observations for which the *number of innovating firms* in a race has not changed relative to the immediately preceding race-month. This approach eliminates mechanical *rank* changes due to an increase/decrease in the *number of innovating firms* in a race. We find that observing two or more *rank transitions* in a race increases the beta of the race which is consistent with the view that competition in innovation leads to a higher systematic risk.

Second, we show robustness to using alternative estimation methods. Panel A of Table 8 reports estimates of regressions (R1) and (R2) obtained using the OLS estimator without race and month fixed effects. Panel B of Table 8 reports estimates of regression (R1) obtained using the random-effects model. In Panels A and B, standard errors are clustered at race level in all specifications. Finally, Panel C of Table 8 reports estimates of regression (R1) obtained using the feasible GLS estimator. In this case, the standard errors are robust to heteroscedasticity across races as well as autocorrelation within races. Specifically, we allow for the autocorrelation coefficient to be race-specific. The results of these alternative tests are for all practical purposes identical to the results reported in our main Tables 4 and 5.

4 Conclusion

This paper explores the link between competition in innovation and asset prices. To do so, we develop a model of an innovation race in which two firms compete for the acquisition of a patent and investment in innovation is irreversible. The firms are exposed to two sources of risk: the technological risk of the innovation process, which is firm-specific, and market-wide risk. The model predicts that when leader-follower equilibria emerge: (i) the systematic risk of the leader is always smaller than that of the follower, (ii) the difference between the leader's and the follower's level of systematic risk increases in the distance between the innovation efficiencies of the two competing firms and, (iii) systematic risk of a race increases in the distance between the innovation efficiencies of the two firms.

We test the predictions of our theory using a comprehensive panel of patent application filing and patent award events in the U.S. in 1978-2003 period which we create by combining information from the NBER Patent Data Project with the Worldwide Patent Statistical Database. We find a strong support for the model's predictions. The equity beta of a portfolio of patent race participants is monotonically increasing in the number of firms in the race. For example, when we compare a two-firm race to a twenty-firm race, the beta of a portfolio increases by about 0.3. We also find that the equity beta of a firm decreases the closer the firm is to a leading position in a race. These results are of an economy-wide importance as innovation races in our sample period account for about 40%-50% of the total U.S. market capitalization.

The fact that innovation race variables have a strong explanatory power for systematic risk in the cross section of firms suggests that modelling industry rivalry is important for understanding the cost of capital of firms in different competitive environments. In particular, the pattern of within-industry heterogeneity of equity betas suggested by our model challenges the commonly followed practice of using industry peer betas to estimate the cost of capital.

Consistent with earlier empirical work, we observe that only the firms with the largest market capitalization are active in innovation. Our model provides a possible answer to this empirical phenomenon. A firm that has just joined a race has the highest cost of capital. This makes joining the race costly and constitutes a *de-facto* barrier to entry. A formal investigation of this issue has potentially important policy implications for the relationship between competition and innovation. To fully address this point, however, one would need to extend the current model to an equilibrium context with entry and exit, a task we leave for future research.

A Appendix: Proofs

The following lemma contains two preliminary results that will be used extensively in the sequel.

Lemma 1. *Let $x(t)$ be the stochastic process in (1) with $\mu < r$ and $\tau = \inf\{t > 0 : x(t) > x^*\}$, $x^* > x(0)$. Then*

$$E_0\left[e^{-r\tau}\right] = \left(\frac{x(0)}{x^*}\right)^{\phi}, \tag{A1}$$

$$E_0\left[\int_0^{\tau} e^{-rt}x(t)dt\right] = \frac{x(0)}{r-\mu}\left[1-\left(\frac{x(0)}{x^*}\right)^{\phi-1}\right], \tag{A2}$$

where $\phi = \frac{1}{2} - \frac{\mu}{\sigma^2} + \sqrt{\left(\frac{1}{2} - \frac{\mu}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}} > 1$.

Proof: The proof is standard and can be found, for example, in Harrison (1985), Chapter 3, or Dixit and Pindyck (1994), pp. 315–316. ∎

Proof of Proposition 1

By the law of iterated expectations, we can express (3) for $x < x_i^F$ as

$$V_i^F(x) = \max_{\tau_i^F} E_0\left[e^{-(r+h_j)\tau_i^F}E_{\tau_i^F}\left[\int_{\tau_i^F}^{\infty} e^{-(r+h_i+h_j)t}h_i x(t)dt - K\right]\right], \quad x(0) = x, \tag{A3}$$

$$= \max_{x_i^F}\left(\frac{x}{x_i^F}\right)^{\phi_j}\left(\frac{h_i x_i^F}{h_i+h_j+\delta} - K\right), \tag{A4}$$

where the last equality follows from (A1) in Lemma 1. Maximizing with respect to x_i^F, yields (4) and (6). ∎

Proof of Proposition 2

From Lemma 1, the leader's value (7) for $x < x_i^F$ can be written as

$$V_j^L(x) = \frac{h_j x}{h_j+\delta}\left[1-\left(\frac{x}{x_i^F}\right)^{\phi_j-1}\right] + \left(\frac{x}{x_i^F}\right)^{\phi_j}\frac{h_j x_i^F}{h_i+h_j+\delta} - K, \tag{A5}$$

from which (8) follows. ∎

Proof of Proposition 3

From Lemma 1, the value of the designated leader (9) for $x < x_i^D$ can be written as

$$V_j^D(x) = \max_{x_i^D} \left[\left(\frac{x}{x_j^D} \right)^{\phi_0} V_j^L(x_j^D) \right]. \tag{A6}$$

Maximizing with respect to $x_i D$ yields (9) where x_i^D is implicitly defined by (11). Because $V_i^L(x)$ is increasing and concave for $x \in [0, x_j^F]$, $x_i^D <_j^F$. ∎

Proof of Proposition 4

The proposition follows immediately from the law of iterated expectations and Lemma 1. ∎

Proof of Proposition 5

Because $h_1 \geq h_2$, $V_1^L(x) \geq V_2^L(x)$, $V_1^C(x; x^C) > V_2^C(x; x^C)$ and $x_1^C \leq x_2^C$. A simultaneous equilibrium can only occur when $V_1^C(x; x_1^C) > V_1^L(x)$ and $V_2^C(x; x_1^C) > V_2^L(x)$ for all x. The only sustainable joint investment threshold is x_1^C, because, given that $x(0) < x_1^C$, firm 1 will have always incentive to deviate from the alternative joint threshold x_2^C that maximizes firm 2's joint value. Because $V_1^L(x)$ is concave in $x \in [0, x_2^F]$ and $V_1^C(x)$ is convex, for every h_1 there exist a pair (x^*, h_2^*) such that $V_1^L(x^*) = V_1^C(x^*; x_1^C)$ and $\frac{\partial V_1^L(x)}{\partial x} = \frac{\partial V_1^C(x; x_1^C)}{\partial x}|_{x=x^*}$ Let $J(h_1) = h_2^*$. For $h_2 > J(h_1)$, $V_1^L(x^*) < V_1^C(x^*; x_1^C)$ and a simultaneous equilibrium is possible. For $h_2 < J(h_1)$, $V_1^L(x^*) > V_1^C(x^*; x_1^C)$ and no simultaneous equilibria are possible. If $J(h_1) > h_1$ then no simultaneous equilibria are possible if $h_1 \geq h_2$.

Similarly, there is for every h_1 there exist a pair (x^{**}, h_2^{**}) such that $V_2^L(x^{**}) = V_2^C(x^{**}; x_1^C)$ and $\frac{\partial V_2^L(x)}{\partial x} = \frac{\partial V_2^C(x; x_1^C)}{\partial x}|_{x=x^{**}}$ Let $\widehat{J}(h_1) = h_2^{**}$. For $h_2 > \widehat{J}(h_1)$, $V_2^L(x^*) > V_2^C(x^*; x_1^C)$ and a simultaneous equilibrium is not possible. For $h_2 < \widehat{J}(h_1)$, $V_2^L(x) < V_2^C(x; x_1^C)$ for all x and simultaneous equilibria are possible. Furthermore, if $J(h_1) < h_1$ then there exist a unique $\tilde{h}_1$ such that $\widehat{J}(h_1) > h_1 > J(h_1)$ for all $h_1 < \tilde{h}_1$ and $J(\tilde{h}_1) = \widehat{J}(\tilde{h}_1) = \tilde{h}_1$. Hence, if $h_1 > h_2$ a simultaneous equilibrium can emerge only if $J(h_1) < h_1$ and $h_1 \leq \tilde{h}_1$.

A sequential equilibrium emerges if $V_1^C(x; x_1^C) < V_1^L(x)$ for some x and $V_2^L(x) < V_2^F(x)$ for all x. Because $V_2^L(x)$ is concave $V_2^F(x)$ is convex in $x \in [0, x_1^F]$, for every h_1 there exists a pair (x', h_2') such that $V_2^L(x') = V_2^F(x')$ and $\frac{\partial V_2^L(x)}{\partial x} = \frac{\partial V_2^F(x)}{\partial x}|_{x=x'}$ Let $S(h_1) = h_2'$. For $h_2 < S(h_1)$,

$V_2^L(x) < V_2^F(x)$ for all x and the equilibrium is of the sequential type. For $h_2 > S(h_1)$, $V_2^L(x') > V_2^F(x')$ and so no sequential equilibrium are possible. In the last case, firm 2 will attempt to preempt firm 1 as long as $V_2^L(x) = V_2^F(x)$. Let $x_2^P = \inf\{x \in [0, x_1^F] : V_2^L(x) = V_2^F(x)\}$. Then, if $h_2 > S(h_1)$,firm 2 will try to preempt firm 1 until $x \geq x_2^P$. Because $V_1^L(x_2^P) > V_1^F(x_2^P)$, the optimal response of firm 1 is to invest at $x^P = \min\{x_2^P - \epsilon, x_1^D\}$, where x_1^D is the optimal investment threshold of firm 1 as a designated leader, defined in (11).

The two thresholds $J(h_1) < h_1$ and $S(h_1) < h_1$ partition the space (h_1, h_2), $h_1 > h_2$, into four separate regions. We now characterize the equilibrium emerging in each region.

1. *Region 1.* $h_2 > J(h_1)$ and $h_2 > S(h_1)$: Simultaneous equilibria. In this region, (i) $V_1^L(x) > V_1^C(x; x_1^C)$, $\forall x$, (ii) $V_2^L(x) < V_2^C(x)$, $\forall x$ and (iii) $V_2^L(x) > V_2^F(x)$ for some x. (ii) and (iii) implies $V_2^C(x) > V_2^L(x)$ $\forall x$. Hence the equilibrium involves simultaneous investment.

2. *Region 2.* $h_2 > J(h_1)$ and $h_2 < S(h_1)$: Simultaneous equilibria. In this region, (i) $V_2^L(x) > V_2^F(x)$, $\forall x$, (ii) $V_1^L(x) < V_1^C(x)$, $\forall x$ and (iii) $V_2^L(x) < V_2^C(x)$, $\forall x$. Because of (ii), firm 1 does not find it optimal to lead, firm 2 cannot be a follower. The only equilibrium involves simultaneous investment.

3. *Region 3.* $h_2 < J(h_1)$ and $h_2 > S(h_1)$. Preemption equilibria. In this region, (i) $V_1^L(x) > V_1^C(x)$, for some x, (ii) $V_2^L(x) > V_2^F(x)$, for some x and (iii) $V_2^L(x) < V_2^C(x)$, $\forall x$. Because of (i), firm 2 will not be able to invest jointly and the only equilibrium involved preemption.

4. *Region 4.* $h_2 < J(h_1)$ and $h_2 < S(h_1)$. Sequential equilibria. In this region, (i) $V_2^L(x) < V_2^F(x)$, $\forall x$ and (ii) $V_1^L(x) > V_1^C(x)$, for some x. Because firm 2 does not find optimal to lead and firm 1 does not find optimal to invest jointly, the equilibrium is of the sequential type. ∎

Proof of Proposition 6

The firms' value in the case of preemptive or sequential equilibrium follow directly from Propositions 1 and 2 while the firms' value in the case of simultaneous equilibria follow from Proposition 4. ∎

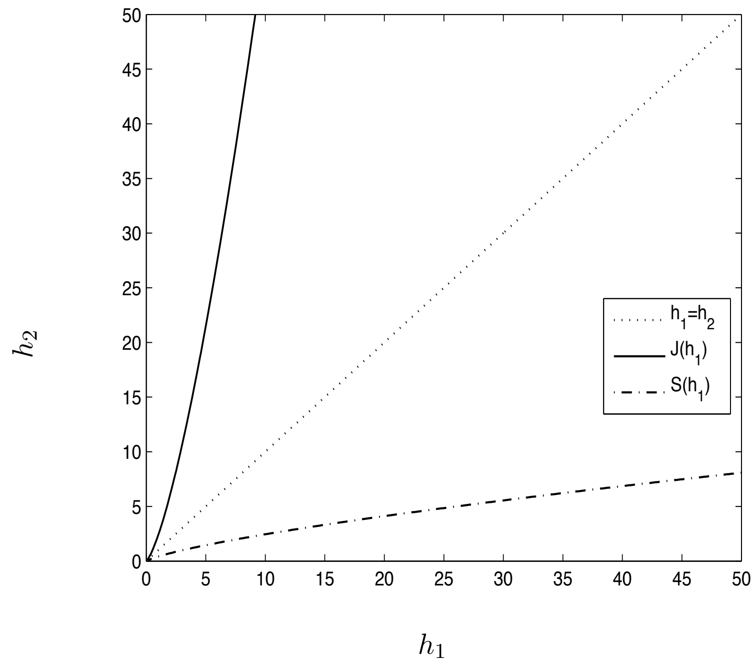
Proof of Proposition 7

Immediate from the definition of beta in (20) and Proposition 6. ∎

Figure 1: Equilibrium regions

The figure reports the thresholds $J(h_1)$ (solid line) and $S(h_1)$ (dash-dotted line) derived in Proposition 5. The dotted line represents the 45-degree line in which $h_1 = h_2$. Parameter values: $r = 3\%$, $\delta = 2\%$, and $K = 1$.

Panel A: Low volatility ($\sigma = 30\%$)



Panel B: High volatility ($\sigma = 75\%$)

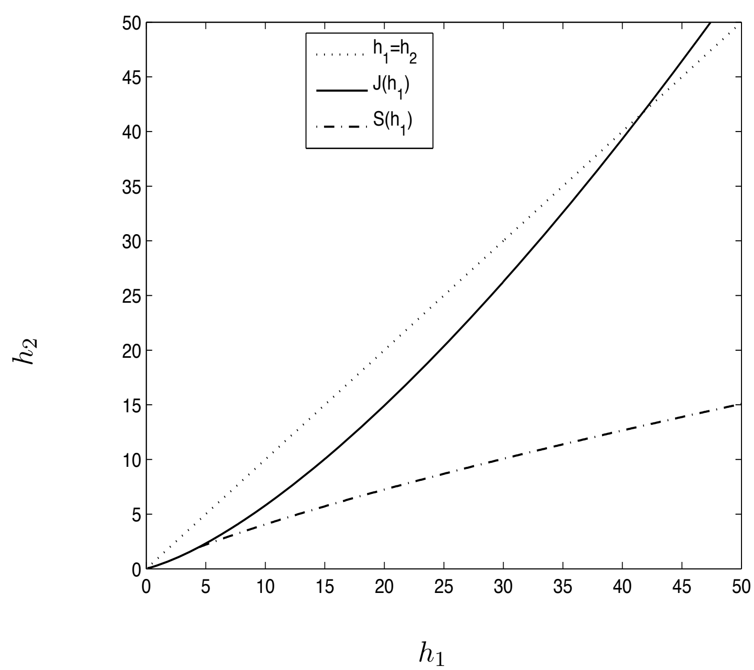
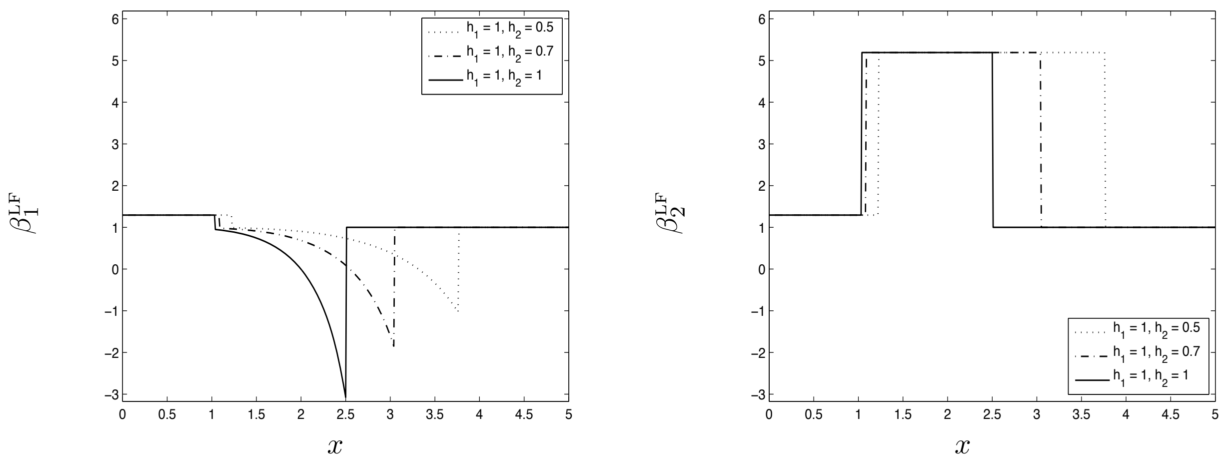


Figure 2: Leader and follower's beta

The figure reports the beta of the leader, $\beta_1^{LF}(x)$, and the follower, $\beta_2^{LF}(x)$, derived in Proposition 7. In Panel A, $h_1 = 1$ and $h_2 = \{0.5, 0.7, 1\}$. In Panel B, $h_2 = 1$ and $h_1 = \{1, 1.5, 1.7\}$. Parameter values: $r = 3\%$, $\delta = 2\%$, and $\sigma = 30\%$.

Panel A: h_2 varies, h_1 fixed



Panel B: h_1 varies, h_2 fixed

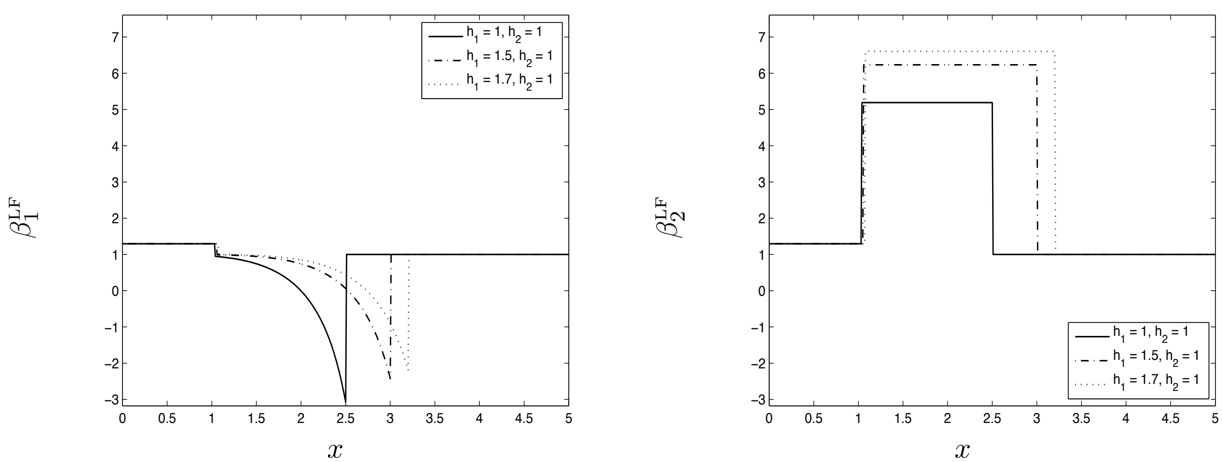


Figure 3: Leader and follower's beta and innovation efficiency

The figure reports the average beta spread $\beta_2^{\mathrm{LF}} - \beta_1^{\mathrm{LF}}$ (solid line) and the equally-weighted portfolio of betas $(\beta_1^{\mathrm{LF}} + \beta_2^{\mathrm{LF}})/2$ (dotted line) across 100,000 time series of 240 periods each. In Panel A, $h_1 = 1$ and $h_2 \in [0.5, 1]$. In Panel B, $h_1 = 2$ and $h_2 \in [1, 2]$. In Panel C, $h_2 = 1$ and $h_1 \in [1, 2]$. In Panel D, $h_2 = 2$ and $h_1 \in [2, 3]$. Parameter values: $r = 3\%$, $\mu = 10\%$, and $\sigma = 30\%$. In each simulation, $x(0) = x_2^F/2$ and the first 120 observations are removed to reduce the effect of the initial condition.

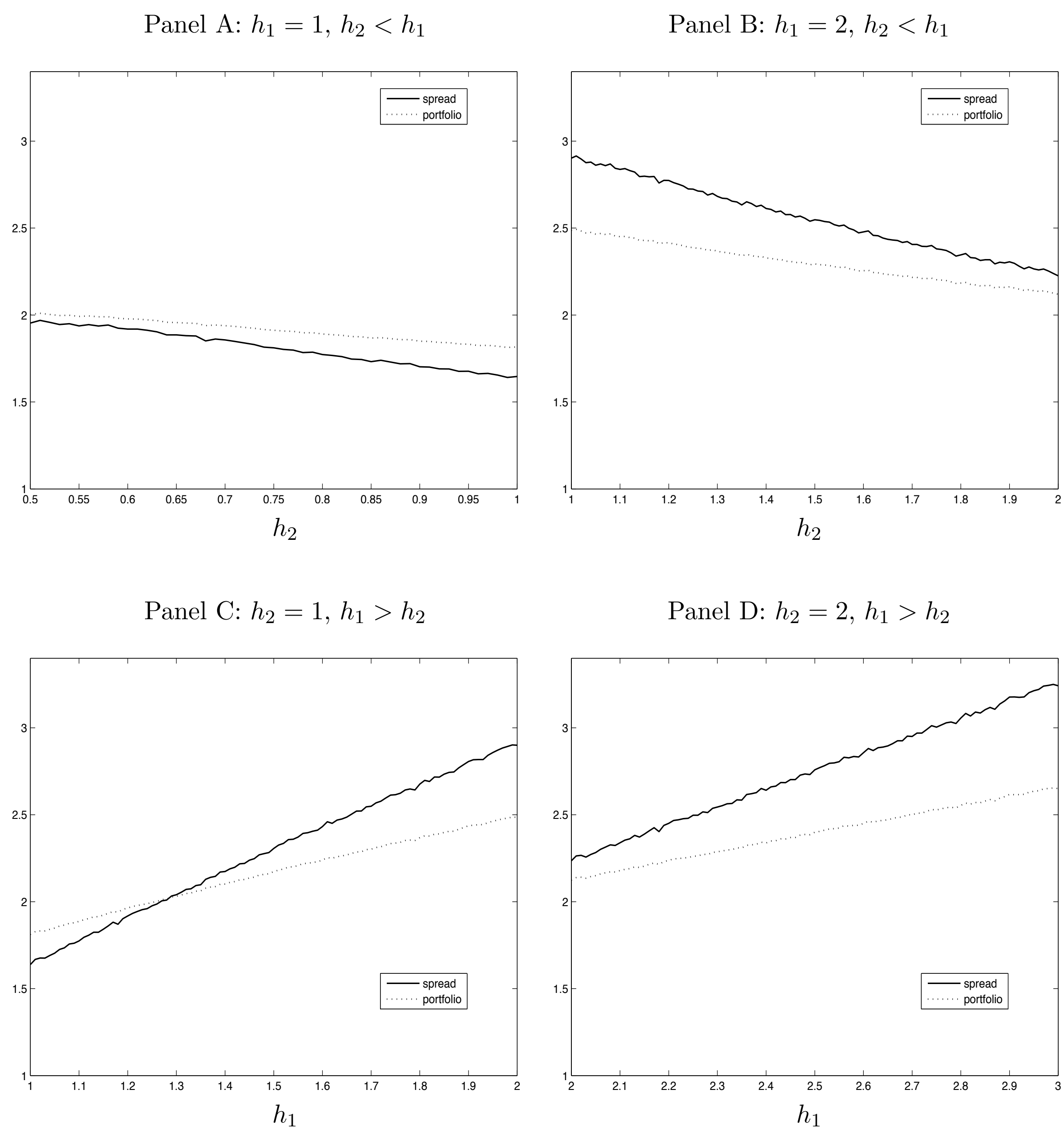


Figure 4: Fraction of innovating firms in the market portfolio

The figure plots the quarterly time series of the number (market capitalization) of innovating firms expressed as the fraction of the total number (market capitalization) of all non-financial firms available in CRSP/Compustat Merged Quarterly Database in the 1978-2003 period. A firm is innovating in a technology class at a given month if the firm has been awarded at least one patent in this technology class during the last 36 months, and has filed patent applications in this technology class in at least 20 percent of months over the same 36 months period. A technology class is the technology field of innovation which follows Subclass Symbols of the International Patent Classification. For each firm, a quarter is included in the sample of innovating firms if there is at least one month during this quarter in which the firm is innovating in at least one technology class.

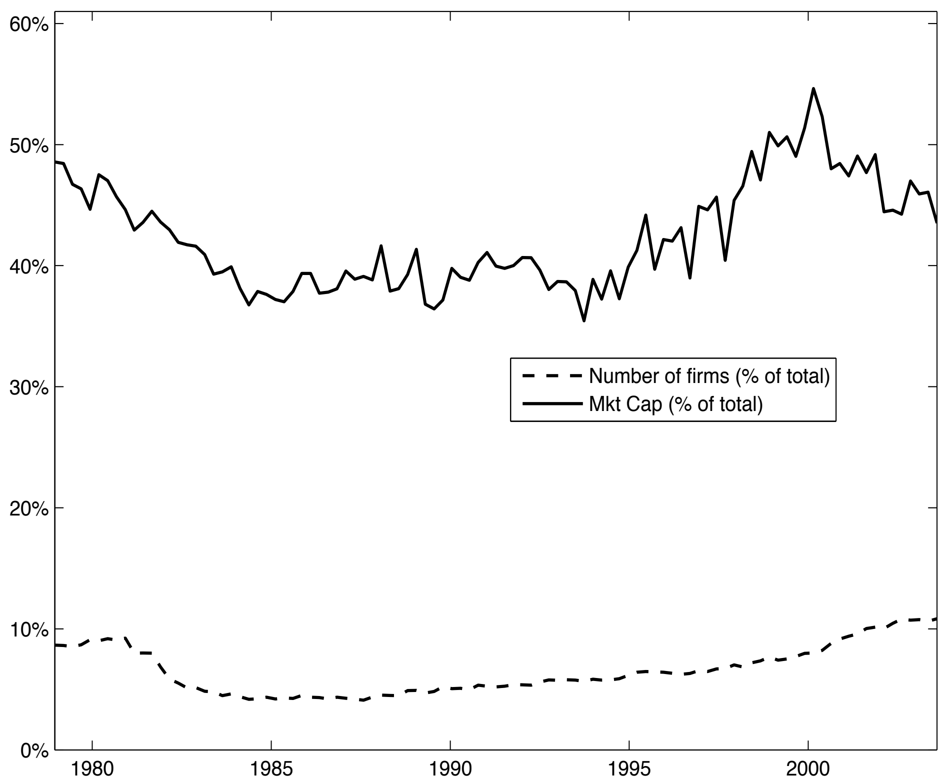


Figure 5: Systematic risk and the number of firms in a race

The figure plots the coefficients from the regression of the beta of the portfolio of innovating firms on the *number of innovating firms* in a race and the average (log of) market capitalization of firms in this portfolio. A race is the technology field of innovation (i.e., a Subclass Symbol of the International Patent Classification) in which there are innovating firms. The sample consists of race-month observations in the 1978-2003 period with at least one innovating firm in a race-month. A firm is innovating in a race at a given month if the firm has been awarded at least one patent in the race during the last 36 months, and has filed patent applications in this race in at least 20 percent of months over the same 36 months period. The *number of innovating firms* in a race variable is entered as a set of dummies; for each value of the variable from 2 to 60 we enter a separate dummy variable. The race-month observations with the *number of innovating firms* in a race equal to one form the base group. The beta is measured using the *equally-weighted market beta*, the *equally-weighted sum beta*, and the *high-frequency beta* computed using 25-minute returns from the TAQ database, respectively. When computing the beta of the portfolio of innovating firms in a race-month we weight each firm's beta equally.

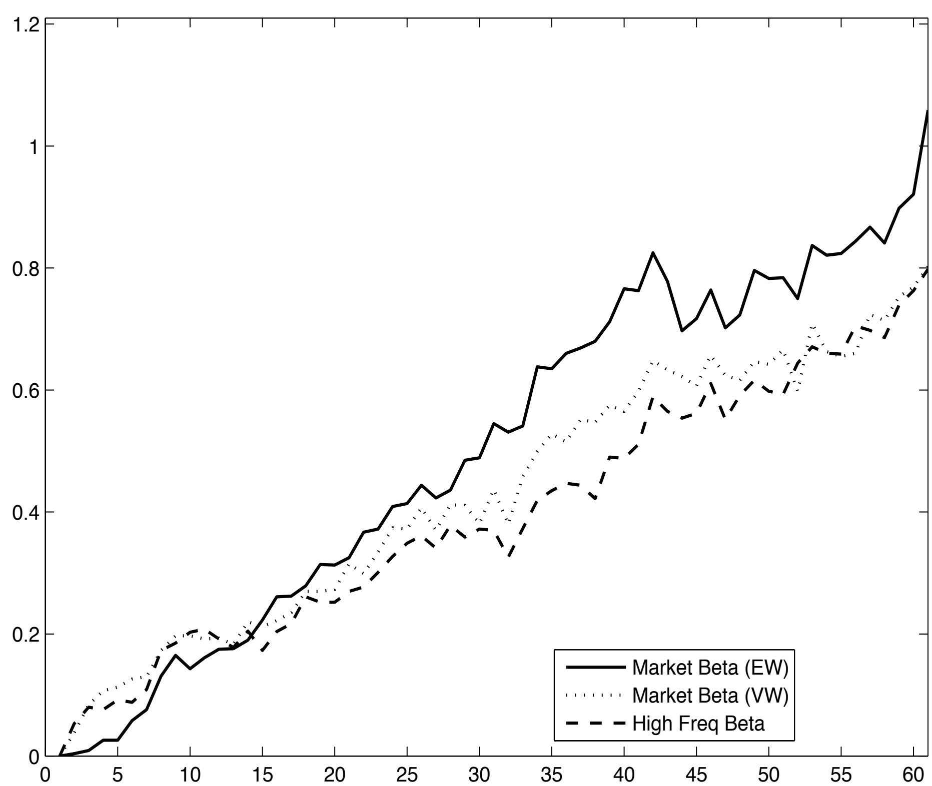


Table 1: Innovating firms: Firm-Quarter Data in 1978-2003

The table shows summary statistics of the characteristics of the sample of innovating firms and of the sample of all non-financial firms (i.e., we exclude firms with four-digit SIC codes between 6000 and 6999) available in the CRSP/Compustat Merged Quarterly Database from January 1978 to December 2003. A firm is innovating in a technology class at a given month if the firm has been awarded at least one patent in this technology class during the last 36 months, and has filed patent applications in this technology class in at least 20 percent of months over the same 36 months period. A technology class is the technology field of innovation which follows Subclass Symbols of the International Patent Classification. For each firm, a quarter is included in the sample of innovating firms if there is at least one month during this quarter in which the firm is active in innovation in at least one technology class. *Market Capitalization* is the price (data199) times shares outstanding (data25). Assets is total assets (data6). *Profitability* is operating income before depreciation (data13) scaled by total assets (data6). *Tobin's Q* is defined as (total assets + market value of equity−common equity−balance sheet deferred taxes and investment tax credit)/total assets [(data6 + (data199 × data25 − data60) − item35)/data6]. *Book/Market Equity*, as in Davis, Fama, and French (2000), is defined as BE/ME. Book value of equity (BE) is the stockholders' equity (data216), plus balance sheet deferred taxes and investment tax credit (data35), minus book value of preferred stock (in the following order: data56 or data10 or data130). Market value of equity ME is the price (data199) times shares outstanding (data25). *R&D/Sales* is R&D expense (data46) scaled by sales (data12). Following Lerner (2006), we assume that any firm that reports total assets but not R&D expense had no R&D expense in that quarter. *Capital Expenditures/Sales* is capital expenditures (data128) scaled by sales (data12). *R&D/Total Investment* is defined as R&D expense/(R&D expense + capital expenditures) [data46 /(data46 + data128)]. *Cash/Assets* is cash and short-term investments (data1) scaled by total assets (data6). *Market Leverage*, as in Titman, Wei, and Xie (2004), is defined as long-term debt/(long-term debt + market value of equity) [data9/(data9 + data199 × data25)]. *Book Leverage* is the sum of long term debt and debt in current liabilities, scaled by total assets [(data9 + data34)/data6]. N is the number of non-missing firm-quarter observations for each variable. In the calculation of the reported statistics, we drop observations in the top and bottom 1% of the distribution of each variable to remove outliers.

		Innovating Firms				All Non-Financial Firms			
	Unit	Mean	S.D.	Median	N	Mean	S.D.	Median	N
Market Capitalization	USD mil.	8,208	26,007	1,512	29,468	1,176	7,944	76	468,632
Assets	USD mil.	7,779	25,600	1,581	30,538	1,332	7,965	94	485,054
Profitability	%	2.9	4.5	3.7	24,673	1.9	5.4	2.9	397,708
Tobin's Q		2.15	1.64	1.57	24,072	1.86	1.52	1.32	426,296
Book/Market Equity		0.57	0.47	0.46	24,507	0.74	0.63	0.59	428,110
R&D/Sales	%	13.8	40.5	2.3	29,980	6.1	28.2	0.0	477,844
Capital Expenditures/Sales	%	10.4	20.4	5.4	17,731	12.1	28.1	4.1	249,820
R&D/Total Investment	%	31.0	35.2	7.0	25,251	14.2	29.7	0.0	382,256
Cash/Assets	%	16.4	19.3	8.4	29,936	14.2	18.5	6.0	476,416
Market Leverage	%	16.0	16.9	11.0	28,969	20.7	22.1	13.0	459,397
Book Leverage	%	20.5	15.3	19.9	28,335	24.4	20.0	22.4	452,126

Table 2: Innovation races

The table describes innovation races using the sample of innovating firms over the 1978-2003 period. Panel A reports transition probabilities between a race-month with a given *number of innovating firms* in a race and the *number of innovating firms* this race has the next month. The race-months just before the race-months in which we observe one or more innovating firms for the first time are coded as 'Enter'. The race-months immediately after the last race-months in which we observe one or more innovating firms are coded as 'Exit'. Panel B reports transition probabilities between the *rank* a firm has in a given race-month and the *rank* this firm has in the same race the next month. The firm-race-month just before the firm-race-month in which we observe the firm as active in innovation in this race for the first time is coded as 'Enter'. The firm-race-month immediately after the last firm-race-month in which we observe the firm as active in innovation in this race is coded as 'Exit'. A race is the technology field of innovation (i.e., a Subclass Symbol of the International Patent Classification) in which there are innovating firms. For each firm-race, all months in which a firm satisfies our definition of being innovating in a race are included in the sample. A firm is innovating in a race at a given month if the firm has been awarded at least one patent in the race during the last 36 months, and has filed patent applications in this race in at least 20 percent of months over the same 36 months period. The *number of innovating firms* is the number of innovating firms in a race-month. We order innovating firms in a race-month according to the amount of patenting output each firm has achieved in the race during the last 36 months relative to the total amount of patenting output achieved by all innovating firms in this race over the same period. The firm's *rank* in a race is equal to one for the firm with the highest output in a race-month, the second firm has rank two, etc.

Panel A: Transition Probabilities of the Number of Innovating Firms Variable (in %)

	Number of Innovating Firms (next month)															
No. of innovating firms (current month)	1	2–5	6–10	11–15	16–20	21–25	26–30	31–35	36–40	41–45	46–50	51–55	56–60	>60	Exit	Total
Enter	83.6	9.7	2.9	1.3	0.6	0.5	0.5	0.3	0.3		0.1			0.1		100.0
1	91.8	4.2													3.4	100.0
2–5	2.9	95.1	1.9												0.1	100.0
6–10		4.4	92.3	3.3												100.0
11–15			5.0	90.7	4.3											100.0
16–20				5.5	89.5	5.0										100.0
21–25					5.8	87.6	6.5									100.0
26–30						7.5	87.0	5.5								100.0
31–35							7.9	84.1	8.0							100.0
36–40								8.4	83.3	8.3						100.0
41–45									7.9	83.7	8.3	0.1				100.0
46–50										11.7	80.9	7.4				100.0
51–55											11.3	80.1	8.6			100.0
56–60												7.4	83.7	9.0		100.0
> 60													3.9	96.1		100.0
Total	25.6	34.0	13.4	7.5	5.0	3.6	2.8	1.7	1.3	1.1	0.7	0.4	0.4	0.8	0.9	100.0

Table 2 (cont.): Innovation races

Panel B: Transition Probabilities of the Firm's Rank in a Race Variable (in %)

Firm's Rank in a Race (current month)	Firm's Rank in a Race (next month)														
	1	2–5	6–10	11–15	16–20	21–25	26–30	31–35	36–40	41–45	46–50	51–55	56–60	>60	Exit	Total
Enter	8.4	22.0	15.8	11.0	8.9	7.2	6.1	4.6	3.7	3.1	2.1	1.6	1.4	4.2		100.0
1	94.4	3.8													1.6	100.0
2–5	1.9	93.2	2.9												1.7	100.0
6–10		4.5	89.3	4.2											1.7	100.0
11–15			6.9	85.8	5.3										1.7	100.0
16–20				8.4	83.6	5.8									1.8	100.0
21–25					9.7	81.4	6.5								2.0	100.0
26–30					0.1	11.2	79.4	6.6	0.1						2.2	100.0
31–35						0.1	11.7	77.4	7.8	0.1					2.4	100.0
36–40							0.2	13.3	75.6	7.8	0.1				2.6	100.0
41–45								0.3	14.7	73.9	7.9	0.1			2.8	100.0
46–50								0.1	0.3	15.4	72.5	8.4	0.1		2.8	100.0
51–55										0.5	15.4	70.5	10.3	0.1	2.7	100.0
56–60										0.1	0.8	17.9	68.0	10.4	2.3	100.0
> 60												0.2	3.2	94.4	1.9	100.0
Total	11.2	24.5	17.2	11.7	8.7	6.3	4.5	3.2	2.4	1.7	1.2	0.9	0.6	2.7	1.8	100.0

Table 3: Number and rank of firms in a race: firm-race-month data in 1978-2003

For the sample of innovating firms over the 1978-2003 period, the table shows summary statistics broken down by the *number of innovating firms* in a race and the firm's *rank* in a race. Panel A reports the number of firm-race-month observations based on the number non-missing values of market capitalization available in the CRSP Monthly Stock File. Panel B reports the average beta of innovating firms computed using firm-race-month observations for each combination of the *number of innovating firms* in a race and the firm's *rank* in a race variables. We use daily returns from CRSP Daily Stock File to estimate beta for each firm-month using separate short-window CAPM regressions based on equally-weighted market portfolio. Panel C reports the average buy-and-hold one-year return from investing into innovating firms for each combination of the *number of innovating firms* in a race and the firm's *rank* in a race variables. The return is computed using monthly returns (available in the CRSP Monthly Stock File) from one-month ahead to twelve-months ahead for each firm-race-month observation. Panel D reports the average market capitalization (available in the CRSP Monthly Stock File) of innovating firms computed using firm-race-month observations for each combination of the *number of innovating firms* in a race and the firm's *rank* in a race variables. Panel E reports the average *Book/Market Equity* of innovating firms computed using firm-race-month observations for each combination of the *number of innovating firms* in a race and the firm's *rank* in a race variables. A race is the technology field of innovation (i.e., a Subclass Symbol of the International Patent Classification) in which there are innovating firms. For each firm-race, all months in which a firm satisfies our definition of being innovating in a race are included in the sample. A firm is innovating in a race at a given month if the firm has been awarded at least one patent in the race during the last 36 months, and has filed patent applications in this race in at least 20 percent of months over the same 36 months period. The *number of innovating firms* is the *number of innovating firms* in a race-month. We order innovating firms in a race-month according to the amount of patenting output each firm has achieved in the race during the last 36 months relative to the total amount of patenting output achieved by all innovating firms in this race over the same period. The firm's *rank* in a race is equal to one for the firm with the highest output in a race-month, the second firm has *rank* two, etc. *Book/Market Equity* , as in Davis, Fama, and French (2000), is defined as BE/ME. Book value of equity (BE) is the stockholders' equity (data216), plus balance sheet deferred taxes and investment tax credit (data35), minus book value of preferred stock (in the following order: data56 or data10 or data130). Market value of equity ME is the price (data199) times shares outstanding (data25). We use CRSP/Compustat Merged Quarterly Database to construct this variable.

		Number of Innovating Firms														
		1	2-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	>60	Mean
		Panel A: Number of Observations														
Firm's Rank in a Race	1	14,632	20,626	8,153	4,654	3,070	2,092	1,698	1,039	821	766	424	208	224	571	11.6
	2-5		39,982	31,298	16,917	11,026	8,042	6,507	4,076	3,156	2,516	1,582	869	846	1,909	25.3
	6-10			20,083	20,909	13,493	10,289	8,213	4,358	3,509	3,033	2,060	1,136	1,066	2,328	17.7
	11-15				11,330	14,026	10,273	8,112	4,432	3,583	3,227	2,072	1,201	1,159	2,357	12.1
	16-20					8,114	10,475	8,003	4,830	3,934	3,414	2,097	1,290	1,127	2,301	8.9
	21-25						5,889	7,747	4,871	3,922	3,476	2,156	1,284	1,345	2,469	6.5
	26-30							4,536	5,025	3,914	3,194	2,171	1,261	1,265	2,447	4.7
	31-35								3,002	3,943	3,333	2,136	1,287	1,110	2,245	3.3
	36-40									2,263	3,449	2,177	1,321	1,188	2,407	2.5
	41-45										2,009	2,134	1,232	1,151	2,495	1.8
	46-50											1,247	1,233	1,242	2,449	1.2
	51-55												738	1,237	2,550	0.9
	56-60													714	2,652	0.7
	>60														14,279	2.8
	% of Total	2.9	11.9	11.7	10.6	9.8	9.2	8.8	6.2	5.7	5.6	4.0	2.6	2.7	8.5	100

Table 3 (cont.): Number and rank of firms in a race: firm-race-month data in 1978-2003

Firm's Rank in a Race	Number of Innovating Firms: 1	2-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	>60	Mean
Panel B: Beta															
1	1.27	1.28	1.29	1.31	1.36	1.41	1.43	1.35	1.37	1.38	1.46	1.56	1.36	1.38	1.30
2-5		1.26	1.29	1.30	1.33	1.34	1.33	1.30	1.35	1.47	1.44	1.45	1.38	1.56	1.30
6-10			1.33	1.33	1.38	1.36	1.30	1.37	1.47	1.61	1.49	1.39	1.39	1.58	1.37
11-15				1.37	1.41	1.42	1.36	1.39	1.46	1.58	1.31	1.42	1.36	1.49	1.41
16-20					1.41	1.46	1.45	1.43	1.46	1.59	1.48	1.48	1.40	1.64	1.46
21-25						1.56	1.50	1.50	1.47	1.56	1.54	1.58	1.44	1.68	1.53
26-30							1.58	1.60	1.59	1.67	1.48	1.59	1.45	1.61	1.58
31-35								1.74	1.65	1.69	1.48	1.48	1.41	1.75	1.64
36-40									1.68	1.69	1.63	1.55	1.37	1.69	1.63
41-45										1.78	1.63	1.49	1.54	1.70	1.65
46-50											1.61	1.61	1.62	1.76	1.67
51-55												1.60	1.60	1.76	1.69
56-60													1.70	1.83	1.80
>60														1.95	1.95
Mean	1.27	1.27	1.31	1.33	1.38	1.42	1.41	1.46	1.51	1.62	1.51	1.51	1.47	1.76	1.42
Panel C: Return (in %)															
1	15.9	16.1	15.9	16.4	16.9	13.6	17.3	12.4	15.9	13.2	10.8	14.9	20.4	12.1	15.9
2-5		16.1	16.4	15.1	13.9	14.1	16.9	16.1	15.1	18.1	13.7	17.3	22.9	11.1	15.8
6-10			16.4	15.9	15.7	13.2	15.8	15.5	19.3	21.3	16.4	16.1	15.9	14.4	15.9
11-15				18.2	18.3	15.3	15.8	16.4	19.1	19.3	15.0	18.8	15.3	15.6	17.2
16-20					18.6	16.8	17.3	19.5	19.1	18.8	16.2	15.3	24.5	13.4	17.8
21-25						16.2	18.4	19.6	20.3	17.1	13.2	20.9	23.6	14.8	18.0
26-30							19.8	17.1	17.5	15.4	19.7	20.8	14.9	17.0	17.8
31-35								25.3	23.2	20.7	17.9	17.9	17.8	18.9	21.0
36-40									21.8	20.6	18.8	19.7	18.0	15.5	19.3
41-45										21.9	15.9	18.9	21.8	16.8	18.7
46-50											22.8	19.9	20.2	17.2	19.6
51-55												23.2	20.9	14.2	17.7
56-60													18.1	14.8	15.6
>60														20.1	20.1
Mean	15.9	16.1	16.4	16.2	16.5	15.0	17.1	17.9	19.2	18.9	16.6	18.7	19.5	16.5	16.8

Table 3 (cont.): Number and rank of firms in a race: firm-race-month data in 1978-2003

Firm's Rank in a Race	Number of Innovating Firms: 1	2-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	>60	Mean
Panel D: Market Capitalization (USD bil.)															
1	16.0	25.0	36.5	24.8	33.3	42.4	40.1	24.8	31.9	44.5	31.9	53.1	66.8	71.7	26.9
2-5		19.8	19.2	22.1	27.6	36.0	27.8	27.8	32.6	37.0	34.2	43.2	47.6	62.8	24.1
6-10			16.1	19.8	19.1	24.3	21.9	20.0	29.4	30.2	23.8	27.5	29.9	47.1	21.3
11-15				16.1	16.6	20.8	18.8	16.8	22.5	26.8	28.1	31.2	27.7	23.6	19.5
16-20					14.1	19.1	19.2	21.3	19.7	24.3	22.8	22.3	19.8	29.2	19.7
21-25						15.8	14.9	17.5	16.6	21.6	35.5	30.9	25.7	29.5	19.8
26-30							14.4	15.0	15.5	16.6	31.1	19.7	24.8	27.8	18.7
31-35								14.2	20.9	18.5	20.1	15.3	20.6	25.1	19.3
36-40									19.7	14.9	19.2	14.0	16.4	18.5	17.2
41-45										8.8	15.2	14.1	14.9	17.2	14.1
46-50											13.6	13.1	11.4	15.3	13.7
51-55												8.9	7.9	13.9	11.5
56-60													9.5	10.9	10.6
>60														9.4	9.4
Mean	16.0	21.5	20.6	20.2	20.3	24.1	20.4	19.2	22.2	22.8	24.7	22.1	21.8	21.0	21.2
Panel E: Book/Market Equity															
1	0.66	0.62	0.61	0.54	0.55	0.53	0.40	0.41	0.41	0.36	0.36	0.43	0.48	0.44	0.60
2-5		0.66	0.66	0.63	0.60	0.57	0.56	0.50	0.53	0.48	0.49	0.43	0.36	0.35	0.62
6-10			0.66	0.62	0.60	0.60	0.65	0.55	0.54	0.48	0.47	0.53	0.51	0.41	0.60
11-15				0.63	0.60	0.59	0.61	0.55	0.55	0.48	0.46	0.54	0.53	0.47	0.58
16-20					0.63	0.54	0.60	0.57	0.60	0.51	0.49	0.57	0.54	0.50	0.57
21-25						0.57	0.60	0.58	0.63	0.55	0.51	0.54	0.54	0.48	0.57
26-30							0.60	0.59	0.59	0.51	0.52	0.57	0.57	0.50	0.57
31-35								0.55	0.59	0.54	0.54	0.60	0.57	0.46	0.55
36-40									0.56	0.53	0.48	0.54	0.60	0.48	0.53
41-45										0.53	0.51	0.59	0.55	0.49	0.53
46-50											0.53	0.56	0.53	0.52	0.53
51-55												0.54	0.55	0.47	0.51
56-60													0.51	0.45	0.47
>60														0.40	0.40
Mean	0.66	0.65	0.65	0.62	0.60	0.57	0.60	0.56	0.58	0.51	0.50	0.55	0.54	0.44	0.58

Table 4: Systematic risk and number of innovating firms

The table reports the regressions of the beta of the portfolio of innovating firms on the *number of innovating firms* in a race and the average (log of) market capitalization of firms in this portfolio. A race is the technology field of innovation (i.e., a Subclass Symbol of the International Patent Classification) in which there are innovating firms. The sample consists of race-month observations in the 1978-2003 period with at least one innovating firm in a race-month. In Panel A, the *number of innovating firms* in a race is entered as a continuous variable. In Panel B, the *number of innovating firms* in a race variable is entered as a set of dummies for ranges of values of the variable, and the race-month observations with the *number of innovating firms* in a race equal to one form the base group. A firm is innovating in a race at a given month if the firm has been awarded at least one patent in the race during the last 36 months, and has filed patent applications in this race in at least 20 percent of months over the same 36 months period. The *number of innovating firms* is the *number of innovating firms* in a race-month. In columns 1-3, systematic risk is measured using the *equally-weighted market beta*, the *equally-weighted sum beta* , and the high-frequency beta computed using 25-minute returns from the TAQ database, respectively. When computing the beta of the portfolio of innovating firms in a race-month we weight each firm's beta equally. In columns 4-6, systematic risk is measured using the *value-weighted market beta*, the *value-weighted sum beta*, and the high-frequency beta computed using 25-minute returns from the TAQ database, respectively. When computing the beta of the portfolio of innovating firms in a race-month we weight each firm's beta by its market capitalization. All specifications include race and month fixed effects. Robust standard errors (clustered at race level) are reported in parentheses; *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively.

Panel A: Linear Specification

	Equally-Weighted Beta			Value-Weighted Beta		
	Market	Sum	High-Freq	Market	Sum	High-Freq
Number of Innovating Firms	0.012***	0.012***	0.009***	0.008***	0.008***	0.008***
	(0.003)	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)
Market Capitalization	0.038***	0.035***	0.097***	0.077***	0.045***	0.124***
	(0.008)	(0.010)	(0.008)	(0.007)	(0.008)	(0.008)
Race FE	Yes	Yes	Yes	Yes	Yes	Yes
Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Number of Races	397	397	355	397	397	355
Observations	71,380	71,340	31,312	71,391	71,375	31,300
R^2	0.29	0.22	0.31	0.13	0.10	0.24

Table 4 (cont.): Systematic risk and number of innovating firms

Panel B: Semi-Parametric Specification

		Equally-Weighted Beta			Value-Weighted Beta		
		Market	Sum	High-Freq	Market	Sum	High-Freq
Number of Innovating Firms	2-5	0.008	-0.009	-0.054**	0.059***	0.060**	0.062**
		(0.025)	(0.030)	(0.021)	(0.019)	(0.024)	(0.024)
	6-10	0.086**	0.081**	-0.071**	0.118***	0.106***	0.102***
		(0.035)	(0.041)	(0.031)	(0.027)	(0.033)	(0.032)
	11-15	0.154***	0.122**	-0.005	0.151***	0.128***	0.134***
		(0.043)	(0.048)	(0.038)	(0.033)	(0.039)	(0.038)
	16-20	0.253***	0.243***	0.086*	0.201***	0.191***	0.174***
		(0.051)	(0.058)	(0.050)	(0.039)	(0.043)	(0.045)
	21-25	0.343***	0.319***	0.186***	0.283***	0.272***	0.239***
		(0.064)	(0.071)	(0.054)	(0.051)	(0.058)	(0.052)
	26-30	0.418***	0.403***	0.268***	0.341***	0.331***	0.290***
		(0.070)	(0.078)	(0.059)	(0.058)	(0.063)	(0.057)
	31-35	0.538***	0.542***	0.316***	0.398***	0.409***	0.301***
		(0.076)	(0.083)	(0.060)	(0.061)	(0.066)	(0.063)
	36-40	0.655***	0.620***	0.389***	0.488***	0.471***	0.371***
		(0.083)	(0.090)	(0.065)	(0.075)	(0.083)	(0.073)
	41-45	0.714***	0.718***	0.478***	0.556***	0.546***	0.471***
		(0.100)	(0.108)	(0.070)	(0.078)	(0.089)	(0.073)
	46-50	0.710***	0.705***	0.527***	0.572***	0.567***	0.507***
		(0.094)	(0.099)	(0.072)	(0.069)	(0.080)	(0.074)
	51-55	0.757***	0.711***	0.565***	0.591***	0.556***	0.554***
		(0.132)	(0.143)	(0.081)	(0.095)	(0.109)	(0.083)
	56-60	0.828***	0.809***	0.634***	0.658***	0.653***	0.624***
		(0.117)	(0.123)	(0.091)	(0.092)	(0.102)	(0.095)
	>60	1.011***	0.991***	0.733***	0.731***	0.722***	0.704***
		(0.114)	(0.122)	(0.083)	(0.099)	(0.114)	(0.084)
Market Capitalization		0.040***	0.037***	0.099***	0.076***	0.044***	0.122***
		(0.008)	(0.010)	(0.008)	(0.007)	(0.008)	(0.008)
Race FE		Yes	Yes	Yes	Yes	Yes	Yes
Month FE		Yes	Yes	Yes	Yes	Yes	Yes
Number of Races		397	397	355	397	397	355
Observations		71,380	71,340	31,312	71,391	71,375	31,300
R^2		0.29	0.22	0.32	0.14	0.10	0.24

Table 5: Systematic risk and firm's rank in a race

The table reports the regressions of a firm's beta on the firm's *rank* in a race, the *number of innovating firms* in a race, and the firm's (log of) market capitalization. A race is the technology field of innovation (i.e., a Subclass Symbol of the International Patent Classification) in which there are innovating firms. The sample consists of firm-race-month observations over the 1978-2003 period and includes race-months with at least two innovating firms. In Panel A, the firm's *rank* in a race and the *number of innovating firms* in a race are entered as continuous variables. In Panel B, the *number of innovating firms* in a race variable is entered as the full set of dummies (denoted firms in a race) for ranges of values of the variable. The firm's *rank* in a race is entered as a continuous variable directly and is also interacted with firms in a race dummies. A firm is innovating in a race at a given month if the firm has been awarded at least one patent in the race during the last 36 months, and has filed patent applications in this race in at least 20 percent of months over the same 36 months period. The *number of innovating firms* is the *number of innovating firms* in a race-month. We order innovating firms in a race-month according to the amount of patenting output each firm has achieved in the race during the last 36 months relative to the total amount of patenting output achieved by all innovating firms in this race over the same period. The firm's *rank* in a race is equal to one for the firm with the highest output in a race-month, the second firm has *rank* two, etc. and it is scaled by the *number of innovating firms* in a race. In columns 1-2, systematic risk is measured using the *equally-weighted market beta* and the *equally-weighted sum beta* , respectively. In columns 3-4, systematic risk is measured using the *value-weighted market beta* and the *value-weighted sum beta*, respectively. In column 5, systematic risk is measured using the high-frequency beta computed using 25-minute returns from the TAQ database. All specifications include race and month fixed effects. Robust standard errors (clustered at race level) are reported in parentheses; *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively.

Panel A: Linear Specification

	Equally-Weighted Beta		Value-Weighted Beta		High-Freq Beta
	Market	Sum	Market	Sum	
Firm's Rank in a Race	0.253***	0.287***	0.163***	0.204***	0.206***
	(0.027)	(0.032)	(0.018)	(0.022)	(0.022)
Number of Innovating Firms	0.006***	0.005**	0.004**	0.004**	0.004**
	(0.002)	(0.002)	(0.001)	(0.002)	(0.002)
Market Capitalization	0.053***	0.048***	0.084***	0.062***	0.113***
	(0.004)	(0.004)	(0.002)	(0.002)	(0.003)
Race FE	Yes	Yes	Yes	Yes	Yes
Month FE	Yes	Yes	Yes	Yes	Yes
Number of Races	319	319	319	319	292
Observations	495,501	495,314	495,340	495,421	264,640
R^2	0.18	0.13	0.16	0.09	0.38

Table 5 (cont.): Systematic risk and firm's rank in a race

Panel B: Semi-Parametric Specification

	Equally-Weighted Beta		Value-Weighted Beta		High-Freq Beta
	Market	Sum	Market	Sum	
Firm's Rank in a Race	0.359***	0.357***	0.228***	0.213***	0.268***
	(0.061)	(0.078)	(0.049)	(0.050)	(0.057)
2-10 Firms in a Race	0.972***	0.843***	0.917***	0.880***	0.562***
	(0.033)	(0.037)	(0.027)	(0.032)	(0.022)
11-20 Firms in a Race	0.998***	0.847***	0.935***	0.892***	0.567***
	(0.043)	(0.046)	(0.031)	(0.038)	(0.034)
21-30 Firms in a Race	1.039***	0.856***	0.963***	0.901***	0.608***
	(0.061)	(0.069)	(0.041)	(0.052)	(0.045)
31-40 Firms in a Race	1.152***	0.995***	1.033***	1.018***	0.655***
	(0.076)	(0.088)	(0.051)	(0.064)	(0.055)
41-50 Firms in a Race	1.312***	1.183***	1.141***	1.140***	0.769***
	(0.080)	(0.091)	(0.054)	(0.067)	(0.063)
51-60 Firms in a Race	1.381***	1.250***	1.184***	1.216***	0.842***
	(0.105)	(0.115)	(0.074)	(0.083)	(0.072)
>60 Firms in a Race	1.461***	1.321***	1.257***	1.272***	0.964***
	(0.101)	(0.107)	(0.066)	(0.081)	(0.056)
2-10 Firms in a Race × Firm's Rank	-0.309***	-0.308***	-0.198***	-0.173***	-0.175***
	(0.065)	(0.082)	(0.052)	(0.054)	(0.060)
11-20 Firms in a Race × Firm's Rank	-0.206***	-0.183**	-0.134**	-0.085	-0.134**
	(0.068)	(0.083)	(0.053)	(0.056)	(0.065)
21-30 Firms in a Race × Firm's Rank	-0.056	0.034	-0.026	0.075	-0.015
	(0.072)	(0.087)	(0.056)	(0.057)	(0.065)
31-40 Firms in a Race × Firm's Rank	0.077	0.144	0.072	0.138	0.041
	(0.112)	(0.141)	(0.079)	(0.096)	(0.077)
41-50 Firms in a Race × Firm's Rank	-0.036	-0.002	-0.020	0.037	0.009
	(0.071)	(0.090)	(0.057)	(0.058)	(0.061)
51-60 Firms in a Race × Firm's Rank	—	—	—	—	—
>60 Firms in a Race × Firm's Rank	0.168*	0.192	0.087	0.159***	-0.069
	(0.095)	(0.119)	(0.063)	(0.060)	(0.075)
Market Capitalization	0.054***	0.049***	0.084***	0.062***	0.113***
	(0.003)	(0.004)	(0.002)	(0.002)	(0.003)
Race FE	Yes	Yes	Yes	Yes	Yes
Month FE	Yes	Yes	Yes	Yes	Yes
Number of Races	319	319	319	319	292
Observations	495,501	495,314	495,340	495,421	264,640
R^2	0.65	0.44	0.69	0.49	0.79

Table 6: Lagged beta specifications

Panel A of the table reports the results of regressions analogous to ones in panel A of Table 4, while Panel B of the table reports the results of regressions analogous to ones in panel A of Table 5. Lagged beta is entered as an additional control variable. Samples and definitions of the variables are identical to the ones used in panel A of Table 4 and panel A of Table 5, respectively. All specifications include race and month fixed effects. Robust standard errors (clustered at race level) are reported in parentheses; *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively.

	Equally-Weighted Beta			Value-Weighted Beta			High-Freq Beta
	Market	Sum	High-Freq	Market	Sum	High-Freq	
Panel A: Number of Innovating Firms							
Number of Innovating Firms	0.010***	0.011***	0.005***	0.006***	0.007***	0.004***	
	(0.002)	(0.003)	(0.001)	(0.002)	(0.002)	(0.001)	
Market Capitalization	0.031***	0.031***	0.050***	0.057***	0.038***	0.069***	
	(0.007)	(0.010)	(0.005)	(0.005)	(0.008)	(0.006)	
Lagged Beta	0.190***	0.074***	0.516***	0.270***	0.125***	0.484***	
	(0.009)	(0.007)	(0.018)	(0.010)	(0.008)	(0.018)	
Race FE	Yes	Yes	Yes	Yes	Yes	Yes	
Month FE	Yes	Yes	Yes	Yes	Yes	Yes	
Number of Races	396	396	353	396	396	353	
Observations	70,261	70,186	30,728	70,281	70,249	30,714	
R^2	0.32	0.22	0.50	0.20	0.12	0.42	
Panel B: Firm's Rank in a Race							
Firm's Rank in a Race	0.179***	0.243***		0.108***	0.169***		0.073***
	(0.019)	(0.028)		(0.012)	(0.018)		(0.008)
Number of Innovating Firms	0.004***	0.005**		0.002**	0.004**		0.001*
	(0.001)	(0.002)		(0.001)	(0.001)		(0.001)
Market Capitalization	0.038***	0.041***		0.056***	0.052***		0.039***
	(0.003)	(0.004)		(0.002)	(0.002)		(0.001)
Lagged Beta	0.285***	0.132***		0.327***	0.161***		0.662***
	(0.006)	(0.004)		(0.006)	(0.004)		(0.008)
Race FE	Yes	Yes		Yes	Yes		Yes
Month FE	Yes	Yes		Yes	Yes		Yes
Number of Races	319	319		319	319		292
Observations	480,283	479,881		480,065	480,182		254,336
R^2	0.25	0.14		0.25	0.12		0.66

Table 7: Systematic risk and number of rank transitions in a race

The table reports the regressions of the beta of the portfolio of innovating firms on the number of *rank transitions* in a race and the average (log of) market capitalization of firms in this portfolio. A race is the technology field of innovation (i.e., a Subclass Symbol of the International Patent Classification) in which there are innovating firms. The sample consists of race-month observations with at least two innovating firms over the 1978-2003 period and we only use race-month observations for which the *number of innovating firms* in a race does not change relative to the immediately preceding race-month. The *number of innovating firms* is the *number of innovating firms* in a race-month. The number of *rank transitions* in a race is entered as three separate dummy variables for 1, 2, and 3 or more *rank transitions.* The race-month observations with no *rank transitions* in a race form the base group. A firm is innovating in a race at a given month if the firm has been awarded at least one patent in the race during the last 36 months, and has filed patent applications in this race in at least 20 percent of months over the same 36 months period. We order innovating firms in a race-month according to the amount of patenting output each firm has achieved in the race during the last 36 months relative to the total amount of patenting output achieved by all innovating firms in this race over the same period. The firm's rank in a race is equal to one for the firm with the highest output in a race-month, the second firm has rank two, etc. The number of *rank transitions* in a race-month is the number of changes in the firms' *ranks* relative to the ranks the same firms had in the immediately preceding race-month. In columns 1-3, systematic risk is measured using the *equally-weighted market beta*, the *equally-weighted sum beta*, and the high-frequency beta computed using 25-minute returns from the TAQ database, respectively. When computing the beta of the portfolio of innovating firms in a race-month we weight each firm's beta equally. In columns 4-6, systematic risk is measured using the *value-weighted market beta*, the *value-weighted sum beta*, and the high-frequency beta computed using 25-minute returns from the TAQ database, respectively. When computing the beta of the portfolio of innovating firms in a race-month we weight each firm's beta by its market capitalization. All specifications include race and month fixed effects. Robust standard errors (clustered at race level) are reported in parentheses; *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively.

	Equally-Weighted Beta			Value-Weighted Beta		
	Market	Sum	High-Freq	Market	Sum	High-Freq
1 Rank Transition	0.031***	0.030**	-0.006	0.023**	0.010	0.007
	(0.011)	(0.014)	(0.008)	(0.009)	(0.012)	(0.009)
2 Rank Transitions	0.086***	0.103***	0.012	0.052***	0.041**	0.026**
	(0.018)	(0.022)	(0.012)	(0.016)	(0.018)	(0.013)
$\geq$ 3 Rank Transitions	0.185***	0.169***	0.063***	0.132***	0.111***	0.064***
	(0.028)	(0.032)	(0.017)	(0.022)	(0.024)	(0.017)
Market Capitalization	0.015	0.013	0.078***	0.062***	0.016	0.105***
	(0.010)	(0.013)	(0.010)	(0.008)	(0.011)	(0.011)
Race FE	Yes	Yes	Yes	Yes	Yes	Yes
Month FE	Yes	Yes	Yes	Yes	Yes	Yes
Number of Races	314	314	286	314	314	286
Observations	38,484	38,476	17,040	38,484	38,481	17,028
R^2	0.34	0.26	0.29	0.15	0.13	0.20

Table 8: Robustness to estimation methods

Panels A, B, and C of the table report the regressions of the beta of the portfolio of innovating firms on the *number of innovating firms* in a race and the average (log of) market capitalization of firms in this portfolio. A race is the technology field of innovation (i.e., a Subclass Symbol of the International Patent Classification) in which there are innovating firms. The sample consists of race-month observations in the 1978-2003 period with at least one innovating firm in a race-month. Panel A reports the results obtained using the OLS estimator, Panel B reports the results obtained using the random-effects model, and Panel C reports the results obtained using the feasible GLS estimator. In Panels A and B, standard errors are clustered at race level. In Panel C, standard errors are robust to heteroscedasticity across races as well as to autocorrelation within races, i.e., we allow for the autocorrelation coefficient to be race-specific. Panel D of the table reports the results of OLS regressions of a firm's beta on the firm's *rank* in a race, the *number of innovating firms* in a race, and the firm's (log of) market capitalization. The sample consists of firm-race-month observations over the 1978-2003 period and includes race-months with at least two innovating firms. The *number of innovating firms* is the *number of innovating firms* in a race-month. We order innovating firms in a race-month according to the amount of patenting output each firm has achieved in the race during the last 36 months relative to the total amount of patenting output achieved by all innovating firms in this race over the same period. The firm's *rank* in a race is equal to one for the firm with the highest output in a race-month, the second firm has *rank* two, etc. and it is scaled by the *number of innovating firms* in a race. In columns 1-3, systematic risk is measured using the *equally-weighted market beta*, the *equally-weighted sum beta* , and the high-frequency beta computed using 25-minute returns from the TAQ database, respectively. When computing the beta of the portfolio of innovating firms in a race-month we weight each firm's beta equally. In columns 4-6, systematic risk is measured using the *value-weighted market beta*, the *value-weighted sum beta*, and the high-frequency beta computed using 25-minute returns from the TAQ database, respectively. When computing the beta of the portfolio of innovating firms in a race-month we weight each firm's beta by its market capitalization. In column 7, systematic risk is measured using the high-frequency beta computed using 25-minute returns from the TAQ database. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively.

	Equally-Weighted Beta			Value-Weighted Beta			High-Freq Beta
	Market	Sum	High-Freq	Market	Sum	High-Freq	
			Panel A: OLS				
Number of Innovating Firms	0.005***	0.005***	0.003***	0.003***	0.002***	0.005***	
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	
Market Capitalization	0.012*	0.005	0.083***	0.056***	0.028***	0.112***	
	(0.007)	(0.008)	(0.005)	(0.006)	(0.006)	(0.006)	
Observations	71,380	71,340	31,312	71,391	71,375	31,300	
R^2	0.01	0.00	0.16	0.04	0.01	0.23	
			Panel B: Random-Effects Model				
Number of Innovating Firms	0.010***	0.007***	0.008***	0.006***	0.003***	0.007***	
	(0.002)	(0.001)	(0.002)	(0.001)	(0.001)	(0.002)	
Market Capitalization	0.034***	0.023***	0.096***	0.073***	0.037***	0.123***	
	(0.007)	(0.008)	(0.008)	(0.005)	(0.006)	(0.008)	
Month FE	Yes	Yes	Yes	Yes	Yes	Yes	
Number of Races	397	397	355	397	397	355	
Observations	71,380	71,340	31,312	71,391	71,375	31,300	

Table 8 (cont.): Robustness to estimation methods

	Equally-Weighted Beta			Value-Weighted Beta			High-Freq Beta
	Market	Sum	High-Freq	Market	Sum	High-Freq	
			Panel C: Feasible GLS				
Number of Innovating Firms	0.005***	0.005***	0.003***	0.003***	0.002***	0.006***	
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	
Market Capitalization	0.038***	0.021***	0.094***	0.079***	0.034***	0.128***	
	(0.002)	(0.003)	(0.001)	(0.002)	(0.002)	(0.001)	
Month FE	Yes	Yes	Yes	Yes	Yes	Yes	
Number of Races	396	396	353	396	396	353	
Observations	71,379	71,339	31,310	71,390	71,374	31,298	
			Panel D: OLS				
Firm's Rank in a Race	0.227***	0.262***		0.147***	0.187***		0.175***
	(0.025)	(0.030)		(0.017)	(0.021)		(0.022)
Number of Innovating Firms	0.005***	0.005***		0.003***	0.004***		0.003***
	(0.001)	(0.001)		(0.001)	(0.001)		(0.001)
Market Capitalization	0.048***	0.041***		0.077***	0.057***		0.108***
	(0.004)	(0.004)		(0.002)	(0.003)		(0.003)
Observations	495,501	495,314		495,340	495,421		264,640
R^2	0.02	0.01		0.06	0.02		0.19

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