R&D Dynamics and Corporate Cash

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Abstract

High-tech firms hold substantial cash reserves. Potential explanations in the literature for this phenomenon include R&D adjustment costs, financial frictions, knowledge spillover, innovation uncertainty, and market competition. We build a parsimonious industry equilibrium model that incorporates all of the cited explanations and determines which factors are the most important for understanding the cash policy of high tech firms. We find that innovation uncertainty is the major driver behind the phenomenon, followed by knowledge spillover and financial frictions. Market competition has non-monotonic effects, while R&D adjustment costs play a relatively minor role since R&D investment is naturally persistent. We also discover that R&D tax credits are more effective in improving productivity when innovation uncertainty and R&D adjustment costs are lower.

JEL Classification: G32; L11; O32

Keywords: Cash holdings; R&D investment; R&D adjustment costs; financial frictions; knowledge spillover; innovation uncertainty; market competition

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1 Introduction

High-tech firms in the United States hold massive cash reserves. During the 2000s, high-tech firms' median and mean cash-to-assets ratio are 0.32 and 0.37, respectively, which are 3.8 times and 2.4 times as large as those of non-high-tech firms. This empirical regularity is evidenced by the significant positive correlation between R&D expenditures and cash holdings observed by Bates, Kahle, and Stulz (2009). Previous studies attribute the large cash stocks to various factors relevant for high-tech industries: R&D adjustment costs (Brown and Petersen, 2011), financial frictions caused by the non-collaterability of R&D (Falato, Kadyrzhanova, and Sim, 2013), knowledge spillover (Qiu and Wan, 2015), innovation uncertainty (Lyandres and Palazzo, 2014; Hsu, Li, and Lin, 2016), and intense market competition (Ma, Mello, and Wu, 2014; Lyandres and Palazzo, 2016).[1]

The goal of this paper is to understand the quantitative importance of these proposed economic forces that drive high-tech firms' substantial cash reserves. This step is necessary and important because it helps identify the main determinant(s) of high-tech firms' strong cash demand, address issues regarding the interaction between cash and R&D spending, and guide effective policy tools that the government can use to boost productivity given that R&D is a key driver of productivity and economic growth. Moreover, each of these factors has been studied in the absence of others, which is potentially problematic because it may bias their respective contribution and provide a misleading picture of how each mechanism influences cash decisions. For instance, if there is a high correlation between R&D adjustment costs and financial frictions, only including one of these factors in a model will tend to overstate the relative importance of the included factor. In this paper, we examine the role of all of these possible mechanisms within a unified framework.

Identifying the impacts of these factors on cash demand is empirically challenging. Most factors are unobservable and thus hard to measure accurately. They are also potentially correlated which makes it difficult to disentangle their effects. To address this issue, we take a

[1] In addition to the factors mentioned above, Foley, Hartzell, Titman, and Twite (2007) also link the high cash holdings with tax policy. They find that multinationals facing higher repatriation taxes tend to store more cash. We compare the average cash ratios for high-tech firms with and without foreign income. Interestingly, multinational high-tech firms tend to have lower cash-to-assets and cash-to-sales ratios than their counterparts: 0.33 versus 0.40 and 0.86 versus 2.51, respectively. It seems reasonable to conjecture that factors other than the tax-avoidance motive are responsible for high-tech firms' cash stock. As such, we abstract from a tax-based explanation in this paper.

structural approach. We incorporate all of these mechanisms into a parsimonious model and use estimated parameters to characterize them. We then extract the information on each factor from firms' R&D and cash choices, and systematically investigate and quantify their impacts.

Specifically, we build a dynamic industry equilibrium model of R&D and cash with endogenous entry and exit. In the model, firms hire labor to produce differentiated products and compete in the product market. They invest in R&D to improve their competitive positions, but face knowledge spillover and innovation risks. Also, adjusting R&D expenditures incurs costs. The capital market is assumed to be imperfect, so firms have no access to debt financing due to prohibitive collateralization of R&D; they can, however, borrow funds through equity issuance (Brown, Fazzari, and Petersen, 2009; Hall and Lerner, 2010; Hall, Moncada-Paternò-Castello, Montresor, and Vezzani, 2015). Equity inflow (equity issuance) and equity outflow (dividend distribution) are costly. This generates a precautionary motive for holding cash, even though firms are risk neutral (Zhao, 2016). That is, to avoid external financing costs in case of a liquidity shortage, firms accumulate internal funds. Meanwhile, the presence of other frictions—R&D adjustment costs, knowledge spillover, innovation uncertainty, and market competition—affects the strength of the precautionary motive.

To examine the model's quantitative implications for cash and R&D policies, we estimate the model and validate it by demonstrating its ability to match relevant data moments. We then use the structural estimates obtained to assess how each factor affects cash and R&D choices jointly. Each factor is encapsulated by one or more estimated parameters. We change one parameter at a time and perform two sets of counterfactual analysis: (i) changing the value of each parameter by 5%, and (ii) shutting down each channel. These two exercises produce the following results.

Innovation uncertainty has the strongest effect, and financial frictions and knowledge spillover are also significant drivers behind high-tech firms' strong cash demand. These results support the conclusions of Falato, Kadyrzhanova, and Sim (2013), Qiu and Wan (2015) and Hsu, Li, and Lin (2016). However, our results deviate from previous studies along two dimensions. First, our model differentiates between incremental innovation and radical innovation, and suggests that innovation uncertainty captured by innovation volatility (the probability of realizing extreme productivity including radical innovation) is the key to explain the large cash balance. Second, knowledge spillover affects cash policy through a channel different from that proposed by Qiu and Wan (2015). In particular, we find that in response to an increase in knowledge spillover, firms cut R&D investments. The decline in precautionary cash demand, however, is fully offset by the increase in the substitution away from R&D to cash (substitution effect) and the increase in income that spillover brings (income effect). This generates a pattern in line with the empirical observation that cash holdings increase with knowledge spillover.

R&D adjustment costs play a smaller role in generating cash holdings than the other factors, because the absence of adjustment costs only reduces the real price of investment—and thus affects the level of R&D expenditures. As long as financial frictions and income uncertainty are present, cash will be valuable regardless of the magnitude of the adjustment costs. R&D investment is also naturally persistent since productivity improvements are stochastic.

Market competition has important but non-monotonic impacts on high-tech firms' cash policy, regardless of the sources of competitive pressure—product substitutability or entry barriers induced by fixed operating costs. The non-monotonicity arises from a composition change in the stationary distribution. When changes in market competition prompt low-productivity firms to stay, many of them choose to increase their R&D spending in order to compete in the market. Those firms tend to be financially constrained and have few resources to save, which drives down the average cash ratio. When changes in market competition drive out low-productivity firms, firms that continue to operate tend to be less likely to run into financial distress and have weaker cash demand, which also reduces cash holdings.

We further examine the policy implications of our model. First, we find significant R&D underinvestment caused by knowledge spillover, but no support for that caused by financial frictions. This finding suggests that the existence of corporate cash holdings largely eliminates the market failures produced by imperfect capital markets. Second, R&D tax credits can effectively address the underinvestment problem caused by spillover and boost productivity. We find that R&D tax credits are more effective in improving productivity when innovation uncertainty and R&D adjustment costs are lower.

This paper contributes in three ways. First, it complements the literature of corporate cash management by systematically analyzing the role of R&D features in explaining high-tech firms' substantial cash reserves. A number of these features have been studied in the literature;

however, little is known about their relative quantitative importance, which is the key step toward understanding the rationale behind high-tech firms' cash holdings. Furthermore, these factors have been examined in isolation, and this may cause erroneous conclusions to be reached. We determine in our study that some results from previous work are overturned once all the features are analyzed jointly.

Second, our paper develops a novel and computationally tractable framework to study firms' R&D choices. In particular, it proposes a theoretically appealing approach to model the transition probabilities that govern the evolution of endogenous productivity. In contrast to previous studies that restrict firms from moving beyond the technology level that is closest to their current one (Ericson and Pakes, 1995; Xu, 2008; Hashmi and Van Biesebroeck, 2016), our approach allows for the realization of different levels of innovation—radical innovation vs. incremental innovation—and neatly captures a wide range of possible innovation dynamics.

Lastly, this paper contributes to the literature on R&D by studying R&D decisions, cash holdings, and financial frictions within a unified framework. A large literature addresses the role of financial frictions in R&D investments in the absence of internal cash stocks.[2] However, in response to financial frictions, firms will endogenously choose to accumulate cash, which has important implications for the R&D-financial friction relationship. As such, the inclusion of cash choices in the model helps to generate important insights overlooked in previous studies and, more importantly, is necessary for a full understanding of the role of financial frictions in R&D and their long-term effects on productivity.

The remainder of the paper is structured as follows. Section 2 lays out a dynamic industry equilibrium model of R&D and cash with endogenous entry and exit. Section 3 provides intuition about how R&D features influence high-tech firms' cash and R&D choices and reports the estimation results of the model. Section 4 quantitatively evaluates the role of each feature in explaining high-tech firms' cash demand and discusses policy implications of the model for R&D tax credits. Section 5 concludes.

[2]Hall, Moncada-Paternò-Castello, Montresor, and Vezzani (2015) give a comprehensive review of the available literature on the relationship between R&D and financial constraints.

2 Model

In this section, we consider an industry equilibrium model of corporate R&D investment and cash holdings, which nests Hopenhayn (1992), Riddick and Whited (2009), and Xu (2008). In the model, time is discrete and infinite. Within the industry, a continuum of firms with mass one operate in a monopolistically competitive market and specialize in the production of differentiated goods. Firms compete in the product market and face financial frictions. Each period, incumbent firms make their exit decisions.[3] Firms that choose to continue to operate produce goods and make financial, R&D-investment, and dividend-distribution choices. Potential entrants make their entry decisions by weighing the expected benefits and costs, and firms that eventually choose to enter decide their R&D spending.

We first specify the demand function that each firm faces and its production technology, knowledge accumulation process, and financing options, then state the firm's problem and the industry equilibrium.

2.1 Demand and Technology

Assume there is a unit measure of firms and firm $i \in [0, 1]$ produces output with labor l_i,

$$y_{i,t} = z_{i,t} l_{i,t}. \tag{1}$$

Here, $z_{i,t}$ is the firm's relative technological position within the industry at period t and is determined stochastically and is dependent on the firm's investment in knowledge, its past technological position, and the intra-industry knowledge spillover.

We do not include physical capital in our model. This simplifying assumption is unlikely to affect our model's key implications for a variety of reasons. First, the capital-to-assets ratio of R&D intensive firms is only about one third as much and exhibits less autocorrelation when compared to R&D non-intensive firms. Next, R&D intensity is almost independent of physical capital stock for high-tech firms.[4] Finally, the static productive response to endogenous

[3]We model firm entry and exit endogenously, because exogenous entry and exit assumption can force high-productive firms to exit, which is not a desirable feature.

[4]The correlation between the R&D-to-sales ratio and beginning-of-period net capital stock is -0.067 for high-tech firms during the 2000s. See, also, Klette and Kortum (2004).

productivity changes in the model mimics the quick and efficient outsourcing of production by innovative firms in the real world. We do recognize, however, that introducing physical capital in our model as well as any other feature could change the dynamics and results.

The firm faces a demand function taking the following form:

$$y_{i,t}^{d} = \left(\frac{p_{i,t}}{P_t}\right)^{-\sigma} Y_t, \tag{2}$$

where $P_t = \left[\int_0^1 p_{i,t}^{1-\sigma} di\right]^{\frac{1}{1-\sigma}}$ and $Y_t = \left[\int_0^1 y_{i,t}^{\frac{\sigma-1}{\sigma}} di\right]^{\frac{\sigma}{\sigma-1}}$. Here, σ denotes the elasticity of substitution between goods, $p_{i,t}$ denotes the price charged by firm i, P_t and Y_t are industry price and quantity level, and $y_{i,t}^{d}$ is the quantity demanded for good i. This demand curve can be derived from the optimal choices of households. They consume a composite consumption good that is a Dixit-Stiglitz index of differentiated goods in the industry.

2.2 Knowledge Investment and Production

In every period t, firm i invests in R&D and learns via spillover from competing firms that have relatively more advanced technologies. The firm's total input of knowledge production, $D_{i,t}$, at period t is therefore given by

$$D_{i,t} = d_{i,t} + \theta S_{i,t-1}. \tag{3}$$

Here, $d_{i,t}$ is firm i's own R&D spending, θ captures the magnitude of knowledge spillover, and $S_{i,t-1}$ is the average previous-period knowledge investment by firms that have stronger technological positions than firm i in the current period, that is, $S_{i,t-1} = \int_{\{j:z_{j,t}>z_{i,t}\}} d_{j,t-1} dj$. From this point on, we drop subscript i to simplify notation.

The firm must pay costs for adjusting its knowledge investment level, defined as

$$A(d_{t-1}, d_t) = \gamma_0 \mathbf{1}_{d_t \neq d_{t-1}} + \gamma_2 \frac{(d_t - d_{t-1})^2}{d_t + d_{t-1}}, \tag{4}$$

where $\gamma_0 \geq 0$ is the fixed adjustment cost, $\gamma_2 \geq 0$ is the convex adjustment cost, and $\mathbf{1}_{d_t \neq d_{t-1}}$ is an indicator function that equals one if current R&D investment deviates from previous R&D spending. Adjustment costs can be justified by the fact that a large share of R&D expenses goes to scientists' salaries, and turnover in skilled workers can trigger large costs and losses (Hall, 1993; Bond, Harhoff, and Van Reenen, 2005). This specification is close to the one assumed for physical capital adjustment costs (Abel and Eberly, 2002; Christiano, Eichenbaum, and Evans, 2005; Schmitt-Grohe and Uribe, 2005; Cooper and Haltiwanger, 2006; and Del Negro and Schorfheide, 2008, among others).

The fixed cost reflects the loss from disruption in restructuring knowledge production factors. The convex adjustment cost reflects an increasing marginal cost of adjustment, and is quadratic in changes in R&D investment. To allow for zero R&D spending, the second term is quadratic in the midpoint percentage change (i.e., changes in investment relative to the average of the previous and current expenditures $\frac{2(d_t-d_{t-1})}{d_t+d_{t-1}}$), rather than changes in rates (i.e., $\frac{d_t}{d_{t-1}}-1$) as employed by Christiano, Eichenbaum, and Evans (2005) and Schmitt-Grohe and Uribe (2005).

The firm's future productivity level z_{t+1} is determined by its total knowledge input D_t, innovation uncertainty δ and ρ, and current status z_t, where the current productivity level z_t reflects the firm's knowledge stock and past R&D effort. The transition in productivity from z_t to z_{t+1} is specified as follows:

$$\Gamma(z_{t+1}|z_t) = \begin{cases} \bar{z} \geq z_{t+1} > z_t & \text{with probability } \Pr(z_{t+1} > z_t) \times \Pr(z_{t+1}|z_{t+1} > z_t), \\ z_{t+1} = z_t & \text{with probability } \Pr(z_{t+1} = z_t), \\ \underline{z} \leq z_{t+1} < z_t & \text{with probability } \Pr(z_{t+1} < z_t) \times \Pr(z_{t+1}|z_{t+1} < z_t), \end{cases} \tag{5}$$

where

$$\Pr(z_{t+1}|z_{t+1} > z_t) = \frac{\frac{1}{(z_{t+1}-z_t)^\rho}}{\sum\limits_{z_{t+1}>z_t} \frac{1}{(z_{t+1}-z_t)^\rho}}, \tag{6}$$

and

$$\Pr(z_{t+1}|z_{t+1} < z_t) = \frac{\frac{1}{(z_t-z_{t+1})^\rho}}{\sum\limits_{z_{t+1}<z_t} \frac{1}{(z_t-z_{t+1})^\rho}}. \tag{7}$$

Specifically, the probability of transitioning from current level z_t to future level z_{t+1} is equal to the product of the probability of directional movement and the probability of reaching z_{t+1} conditional on the directional changes. We follow Xu (2008) to specify the probability of directional movement. We assume that the firm improves its relative technological position and reaches a higher level with probability $\Pr(z_{t+1} > z_t) = \frac{(1-\delta)D_t}{1+D_t}$, maintains its past technological position with probability $\Pr(z_{t+1} = z_t) = \frac{1-\delta+\delta D_t}{1+D_t}$, and loses its position and falls behind with probability $\Pr(z_{t+1} < z_t) = \frac{\delta}{1+D_t}$. The parameter δ captures three knowledge-related risks: knowledge obsolescence or depreciation, firms' inability to keep up with competitors, and the uncertainty associated with innovation output. This specification also implies that higher investment in R&D improves firms' relative competitive positions by raising the likelihood of technological advancement.

Previous studies restrict firms from moving beyond the technology level that is closest to their current one, which is equivalent to the assumption that firms are only allowed to conduct incremental innovation and improve their technology gradually (Ericson and Pakes, 1995; Xu, 2008; Hashmi and Van Biesebroeck, 2016). Unlike those studies, we relax the assumption by incorporating radical innovation in the model. Incremental and radical innovations differ in several respects. In this paper, we focus on their differential effects on technology and revenue—that is, radical innovation improves technology more rapidly than incremental innovation and helps generate higher revenue. Specifically, we assume that firms' future technology z_{t+1} can move to any level, with the probability changing with its distance from current level z_t. The parameter ρ controls the likelihood of realizing extreme productivity, including radical innovation. The greater the value of ρ, the less likely firms will realize radical innovation and high income. Moreover, the parameter ρ captures a wide range of possibilities. When $\rho \to \infty$, the firm will move to the value closest to z_t with near certainty, which is equivalent to the assumption made by previous studies. When $\rho = 0$, the firm will have an equal chance of reaching any level other than z_t, that is, an equal probability of realizing incremental innovation or radical innovation. When $\rho \to -\infty$, the firm will move to the farthest value of z_{t+1} with near certainty. We denote the conditional probability distribution for z_{t+1} by $\Gamma(z_{t+1}|z_t)$.

2.3 Financing

Firms can finance R&D investment through three different sources: current-period revenue, internal cash balance, and external borrowing.

Cash balance, c_t, earns a risk-free rate r. The amount of interest earned is taxed at the corporate tax rate τ_c when taxable income is positive.

External borrowing takes the form of equity issuance. This assumption follows the observation by Brown, Fazzari, and Petersen (2009) that equity finance is a more relevant substitute for internal cash flow because of the intangible nature and low collateral value of R&D.[5] Issuing equity incurs both fixed costs, λ_0, and linear costs, λ_1 (Hennessy and Whited, 2007; Nikolov and Whited, 2014). Following previous studies, we describe negative equity flow $e_t < 0$ as equity issuance and positive equity flow $e_t \geq 0$ as dividend distribution.

2.4 The Firm's Problem

2.4.1 The Incumbent's Problem

Each period, after productivity z_t is realized, the firm decides whether to leave the market by weighing the expected benefits of continuing to operate and of exiting.

If the firm chooses to stay, it hires labor l_t at the wage rate w to produce output and sets a price p_t on its product. Its taxable income is

$$\pi_t = p_t y_t - w l_t - c_F + r c_t - d_t, \tag{8}$$

in which c_F is the fixed operational cost. Upon receiving its profit, the firm makes decisions about R&D investment and cash savings. If available internal resources are insufficient to cover those expenses, the firm borrows externally by issuing equity; otherwise, it distributes dividends. Net cash flow is

$$g_I(e_t) = -\mathbf{1}_{e_t<0}\lambda_0 + (1 - \mathbf{1}_{e_t\geq 0}\tau_d + \mathbf{1}_{e_t<0}\lambda_1) e_t(\pi_t, c_t, c_{t+1}, d_{t-1}, d_t), \tag{9}$$

where

$$e_t(\pi_t, c_t, c_{t+1}, d_{t-1}, d_t) = (1 - \tau_c \mathbf{1}_{\pi_t \geq 0})\pi_t + (c_t - c_{t+1}) + \tau_{rd} d_t - A(d_{t-1}, d_t). \tag{10}$$

The first term of e_t is the firm's net income, and the other terms are the net change in cash, R&D subsidy, and adjustment costs, respectively. Parameters τ_c and τ_{rd} are the corporate

[5] Also, we find that the median short-term debt-to-assets ratio and long-term debt-to-assets ratio are 0.005 and 0.005, respectively, for high-tech firms during the 2000s. This confirms high-tech firms' low reliance on debt financing.

income tax rate and R&D tax-credit rate. The indicator function $\mathbf{1}_{e_t \geq 0}$ equals one if the firm distributes dividends and zero otherwise, while $\mathbf{1}_{e_t < 0}$ equals one if the firm issues equity and zero otherwise. On the other hand, the indicator function $\mathbf{1}_{\pi_t \geq 0}$ means that the firm is only taxed when taxable income is positive.

If the firm chooses to exit, the corresponding net cash flow is

$$g_X(e_t) = -\mathbf{1}_{e_t<0}\lambda_0 + (1 - \mathbf{1}_{e_t\geq 0}\tau_d + \mathbf{1}_{e_t<0}\lambda_1)e_t(\pi_t, c_t, c_{t+1} = 0, d_{t-1}, d_t = 0). \tag{11}$$

The risk-neutral incumbent maximizes its value. Moving on to the recursive formulation, let $V_I(z, c, d_{-1}; \mu)$ and $V_X(z, c, d_{-1}; \mu)$ denote the value functions of continuing to operate and exiting, respectively. The parameter μ is the current-period joint distribution of idiosyncratic productivity level, cash balances, and previous R&D spending, which will be specified in Subsection 2.5. Also, let x' denote the continue/exit decision where $x' = 0$ indicates that the firm continues and $x' = 1$ indicates that the firm exits. Then the incumbent's problem becomes

$$V(z, c, d_{-1}; \mu) = \max_{x' \in \{0,1\}} \{V_I(z, c, d_{-1}; \mu), V_X(z, c, d_{-1}; \mu)\}, \tag{12}$$

where

$$V_I(z, c, d_{-1}; \mu) = \max_{c', d} \{g_I(e) + \beta \mathbb{E} V(z', c', d; \mu')\}, \tag{13}$$

and

$$V_X(z, c, d_{-1}; \mu) = g_X(e). \tag{14}$$

Here, subscript -1 denotes a variable in the preceding period, and a prime denotes a variable in the subsequent period. The parameter β is the discount factor and equals $\frac{1}{1+r}$.

2.4.2 The Potential Entrant's Problem

A potential entrant pays a cost, c_E, at the beginning of a period to draw a z with probability

$$\Pr(z > \underline{z}) = \frac{\frac{1}{(z-\underline{z})^\rho}}{\sum\limits_{z>\underline{z}} \frac{1}{(z-\underline{z})^\rho}}, \tag{15}$$

where $\underline{z}$ is the lowest productivity level. This probability specification is the same as the one that incumbents face, and its corresponding probability distribution is denoted as $\Gamma_E(z)$.

Upon seeing z, the potential entrant can either choose to throw away the draw, or commit to enter the economy and produce y. If the potential entrant commits to enter, it carries $c = 0$ and $d_{-1} = 0$ from the previous period because it was not operational, and chooses c' and d to maximize the expected discounted value of the firm.

With this form of entry, the potential entrant throws away low-z draws because potential profits are low and it does not want to pay the adjustment costs. On the other hand, high-z draws induce entry in order to capture more substantial profits. If a firm enters, it also invests in cash and R&D to set itself up for the future.

The free-entry condition is

$$\int \max\{V_I(z, 0, 0; \mu), 0\} d\Gamma_E(z) \leq c_E, \tag{16}$$

and the condition holds with equality when there is a non-zero mass of entry. Note that the entrant cost c_E is endogenously determined by this condition.

2.5 Law of Motion for Distribution μ

Conditional on the current-period joint distribution $\mu(z, c, d_{-1})$ of idiosyncratic productivity level, cash balances, and previous R&D spending, the next-period distribution is determined by

$$\begin{aligned} \mu'(z', c', d) = &\int I(z, c, d_{-1}; \mu) d\Gamma(z'|z) d\mu(z, c, d_{-1}) \\ &+ M' \int I(z, 0, 0; \mu) d\Gamma(z'|z) d\Gamma_E(z), \end{aligned} \tag{17}$$

where $I(z, c, d_{-1}; \mu) \equiv \mathbf{1}_{\mathcal{C}(z,c,d_{-1};\mu)=c'} \mathbf{1}_{\mathcal{D}(z,c,d_{-1};\mu)=d} \mathbf{1}_{\mathcal{X}(z,c,d_{-1};\mu)=0}$ is a combined indicator function for incumbents, $I(z, 0, 0; \mu) \equiv \mathbf{1}_{\mathcal{C}(z,0,0;\mu)=c'} \mathbf{1}_{\mathcal{D}(z,0,0;\mu)=d} \times \mathbf{1}_{\mathcal{X}(z,0,0;\mu)=0}$ is a combined indicator function for potential entrants, and M' is the mass of potential entrants. Note that $\mathcal{C}(z, c, d_{-1}; \mu)$, $\mathcal{D}(z, c, d_{-1}; \mu)$, and $\mathcal{X}(z, c, d_{-1}; \mu)$ are the cash, R&D, and exit decision rules, respectively, for incumbents, while $\mathcal{C}(z, 0, 0; \mu)$, $\mathcal{D}(z, 0, 0; \mu)$, and $\mathcal{X}(z, 0, 0; \mu)$ are the cash, R&D, and exit decision rules, respectively, for potential entrants. The "exit" decision $\mathcal{X}(z, 0, 0; \mu) = 1$ for potential entrants means that they throw away the z draws, while the "continue" decision

$\mathcal{X}(z, 0, 0; \mu) = 0$ means that they enter and produce with their z draws.

The entry and exit dynamics in this type of model can be best described as "bottom churning." That is, the worst firms exit every period and are replaced by entrants with higher z draws.

2.6 Industry Equilibrium

In this paper, we focus on the stationary industry equilibrium.

Definition 1 *A* **stationary industry equilibrium** *is a stationary distribution μ, a price P, a quantity Y, and policy functions $\mathcal{C}(z, c, d_{-1}; \mu)$, $\mathcal{D}(z, c, d_{-1}; \mu)$, and $\mathcal{X}(z, c, d_{-1}; \mu)$ such that:*
(i) policy functions solve the firm's problem, given industry price P, industry output Y and distribution μ;
(ii) the distribution μ is invariant over time;
(iii) the free-entry condition is satisfied; and
(iv) the product market clears.

3 Model Estimation

In this section, we apply the model described in Section 2 to data. We first select and construct a set of data moments, using a sample of firms that (i) operate in 3-digit SIC high-tech industries—SIC 283, SIC 357, SIC 366, SIC 367, SIC 382, SIC 384, and SIC 737—and (ii) have positive sales, positive assets, and non-missing R&D investment for the period 2000-2014 from Compustat.[6] We then parameterize the model by matching selected data moments and show that our model is able to replicate high-tech firms' R&D and cash-holding behavior observed in the data.

3.1 Parameterization

We set the length of a period in the model to be one year. The average real risk-free interest rate during the 2000s was 3.1%. We therefore set r to be 3%.

[6] In approximately 17% of the firm-year observations, we have missing R&D expenditures. Although deleting those observations leads to a loss of data, the sample still contains enough information about firms' R&D behavior.

We discretize technology z to 10 levels and calibrate their values as follows. We calculate firms' value-added as the sum of their labor expenses and operating income before depreciation and deflate it by the production price index. Given our production function specification, the technology level is the ratio of firms' real value added to employment. We then normalize the mean technology level to be 1 and set the value of z_i, where $i = \{1, 2, ..., 10\}$, as the median of each decile of the distribution.

We choose the value of elasticity of substitution between goods σ to match the markup charged by high-tech firms during the sample period. Markup is defined as the percentage of sales over cost of goods sold. We set σ to be 2 to match a 100% markup, which falls between the median and mean markup suggested by our sample.

We calibrate dividend tax, corporate income tax, and R&D tax credits as follows. Dividend tax is chosen to be 15%, a rate commonly used in the literature (Hennessy and Whited, 2005). Corporate income tax τ_c is set at 35%, which is the statutory corporate income tax in the 2000s. The Internal Revenue Code provides three methods to calculate R&D tax credits, the simplest of which is called the Alternative Simplified Credit method. Using this approach, firms can claim a tax credit equal to 14% of qualified R&D expenditures that exceed a calculated base amount, while the base amount cannot be less than 50% of their current-year qualified expenditures. Therefore, we set the R&D tax credits to be 6%, slightly lower than half the 14% rate.

[Table 1 about here.]

Parameters are shown in Table 1. Panel A summarizes the parameters that are either directly calibrated from data or borrowed from other relevant studies. Panel B reports the remaining parameters, which are estimated using a Simulated Method of Moments (SMM) approach. That is, we recover underlying parameters from a list of selected moments by minimizing the distance between the moments constructed from model-simulated data and the moments computed with actual data. The match is quite close and the details are discussed in Subsection 3.2.2.

3.2 Comparative Statics and Parameter Identification

To identify the parameters that are not predetermined, we need moments that are informative—that is, sensitive to parameter changes. To this end and also to provide intuition about how each R&D feature influences high-tech firms' cash and R&D decisions, we report comparative statics of the following parameters: R&D adjustment costs (γ_0 and γ_2), innovation uncertainty (δ and ρ), knowledge spillover (θ), external borrowing costs (λ_0 and λ_1), and market competition (σ and c_F). These parameters take the values of equally spaced points in the following intervals, respectively: $\gamma_0 \in [0, 0.1]$, $\gamma_2 \in [1, 3]$, $\delta \in [0.1, 0.3]$, $\rho \in [0, 2]$, $\theta \in [0, 1]$, $\lambda_0 \in [0, 0.1]$, $\lambda_1 \in [0, 0.2]$, $\sigma \in [1.9, 2.1]$, and $c_F \in [0.4, 0.8]$. These intervals represent reasonable bounds on each parameter since the estimated parameter values are close to the center of the corresponding intervals. We change one parameter at a time, holding all other parameters at the calibrated or estimated values reported in Table 1.

3.2.1 Comparative Statics

Figures 1-3 plot the comparative statics results. Panels in the left column show the sensitivity of the first quartile, second quartile, third quartile, and industry mean of cash-to-firm value ratios with respect to each parameter, and panels on the right present the sensitivity of the first quartile, second quartile, third quartile of R&D-to-firm value ratios and exit rates.[7] We report exit rates to give information about the changes in the stationary distribution of firms.

[Figure 1 about here.]

[Figure 2 about here.]

[Figure 3 about here.]

3.2.1.1 R&D Adjustment Costs γ_0 and γ_2

Brown and Petersen (2011) argue that adjusting R&D spending is costly, and therefore firms facing financial frictions tend to accumulate valuable internal funds to smooth their R&D investment and avoid potentially large adjustment costs. More specifically, a large share of

[7] To limit the effects of extreme outliers generated by sales data, we examine R&D-to-firm value and cash-to-firm value ratios, instead of R&D- and cash-to-sales ratios.

R&D expenses goes to pay the salaries of highly educated scientists, engineers, and other specialists. Their effort creates a firm's knowledge base, which is embedded in its human capital. Turnover among these skilled workers can erode the firm's knowledge base and lead to dissemination of proprietary information. Firms, therefore, have strong incentives to retain skilled employees, as reflected by the highly persistent R&D spending—which, in turn, implies substantial adjustment costs.

The effects of R&D adjustment costs (γ_0 and γ_2) are shown in the top four panels of Figure 1. An increase in γ_0 raises investment costs uniformly for firms, regardless of the magnitude of their investment adjustment, while a rise in γ_2 increases the investment costs proportional to the square of adjustment. Both costs place a heavier financial burden on firms and tend to prompt them to keep more cash.

However, quantitatively, these effects are rather minor. R&D investment tends to be naturally quite persistent, and R&D adjustment costs therefore do not have a large impact on cash holdings. In particular, productivity is stochastic, so that raising or lowering R&D investment does not have a direct effect on productivity and, accordingly, firms change R&D levels only when necessary. This implies that higher adjustment costs raise the cost of investment moderately and predictably without strengthening the precautionary motive much.

3.2.1.2 Innovation Efficiency δ

The parameter δ captures innovation efficiency, which affects the marginal product of R&D investment (Lyandres and Palazzo, 2014; Hsu, Li, and Lin, 2016). Hsu, Li, and Lin (2016) suggest a positive role of innovation efficiency in shaping high-tech firms' cash policies. They argue that an increase in innovative efficiency (i.e., a drop in δ) generates stronger precautionary considerations by raising the likelihood of innovation success and higher opportunity costs of being financially distressed.

The responses of cash and R&D ratios to changes in δ are reported in the bottom two panels of Figure 1. Overall, firms at different levels of R&D intensity react to changes in δ in the same way. An increase in δ makes innovation less efficient. Facing a higher probability of innovation failure, firms decide to invest more in R&D so as to improve innovation success rates and compete in the market. This explains the upward trend of R&D ratio. However, as δ further increases, fewer firms can survive in such uncertain environments. Followers that decide to stay choose to take advantage of knowledge spillover and reduce their R&D investment to zero, while leaders struggle to maintain their R&D spending. This explains the decline in the R&D ratio when δ is high.

An increase in δ affects firms' cash policy through three interesting channels. First is the precautionary consideration. A higher R&D spending generates stronger demand for precautionary cash. Second is the substitution effect. Shifting more resources to R&D implies fewer left for cash savings. Third is the income effect. Lower chance of innovation success reduces cash flow that can be allocated to cash stock. When δ is small, the first channel dominates: a higher δ leads to an increase in cash holdings. As δ continues to increase, the latter two channels become important, and cash ratios start to decrease with δ.

3.2.1.3 Innovation Volatility ρ

Incremental and radical innovations have different impacts on firms' competitive positions and revenue. Little attention so far has been paid to the effect of this feature on cash policies. As shown in the top two panels of Figure 2, a rise in ρ—that is, a decline in the probability of realizing extreme outcomes—plays a role similar to an increase in δ.

In response to an increase in ρ which implies a lower chance of drawing extremely negative and positive productivity, all firms become less concerned about radical failure and choose to increase their R&D expenditures to improve the likelihood of realizing radical innovation, yet in different magnitudes. High R&D intensive firms are the ones that respond more aggressively.

An increase in ρ impacts firms' cash decisions in a way similar to δ. First, it strengthens firms' incentives to invest in R&D, which increases firms' needs for precautionary cash. Second, it shifts more resources to R&D, which reduces the resources available for cash reserves. These two channels compete with each other. When ρ is high, the second channel dominates.

3.2.1.4 Knowledge Spillover θ

Qiu and Wan (2015) emphasize a positive effect of technology spillover on cash policies. They argue that the enhancement of the marginal product of R&D via spillover provides firms with stronger incentives to apply external knowledge and perform R&D, which in turn leads to a higher demand for cash.

Results of the effect of spillover on cash holdings are reported in the middle two panels of

Figure 2. They are in line with the findings by Qiu and Wan (2015), yet suggest a different mechanism. As spillover becomes greater, high R&D intensive firms effectively have lower returns to knowledge investment. They are discouraged from innovating and choose to cut their R&D spending. Meanwhile, followers free ride leaders and reduce their own R&D expenditures.

Lower R&D investment weakens the precautionary motive for cash. However, the decrease in precautionary cash savings is fully compensated by the increase in the substitution away from R&D to cash (substitution effect) and the increase in income that knowledge spillover brings (income effect). As such, an increase in the externality θ drives up cash ratios.

3.2.1.5 Financial Frictions λ_0 and λ_1

One of the features frequently used to explain high-tech firms' large cash positions is financial frictions (Falato, Kadyrzhanova, and Sim, 2013, Falato, Sim, Falato, and Sim, 2014; Hall and Lerner, 2010). Due to information asymmetries and low collateral value of R&D, high-tech firms face expensive equity-issuance costs. To avoid underinvestment in R&D caused by financial constraints, firms accumulate internal funds.

Our results, reported in the bottom two panels of Figure 2 and the top two panels of Figure 3, tell a story in accordance with previous studies: An increase in financing costs, λ_0 and λ_1, has no significant adverse effects on R&D investment, except for high R&D intensive firms who choose to cut their R&D ratio by 2%. This finding implies that firms' internal cash reserves largely eliminate the problem of underinvestment in R&D caused by financial frictions. At a certain point, further increases in financing costs do not have an impact on firms since they choose to self finance.

In addition, fixed and linear equity issuance costs have different impacts on cash-poor firms' cash policies. They choose to increase their cash ratios in response to an increase in λ_0, in order to economize on the fixed issuance costs. On the other hand, they reduce their cash holdings as λ_1 increases. That is, financially-constrained firms issue equity and keep proceeds in cash. When they face worse credit market conditions due to a proportional increase in external-financing costs, they choose to issue less equity and save less.

3.2.1.6 Market Competition σ and c_F

Market competition is another often-discussed determinant of high-tech firms' cash policies (He and Wintoki, 2015; Lyandres and Palazzo, 2016; Ma, Mello, and Wu, 2014). It can be captured by two parameters in our model: elasticity of substitution between differentiated goods (σ) and fixed operating costs (c_F), with comparative statics shown in the last four panels of Figure 3.

Elasticity of substitution σ reflects the degree of responsiveness in demand with respect to price changes and determines the markup ($\frac{1}{\sigma-1}$) that firms can charge above their marginal costs ($\frac{w}{z}$). An increase in the elasticity σ intensifies product market competition, and reduces markup and the expected benefit of entry. It drives up exit rates and induces higher-productivity firms to enter, which further increases competitive pressures in the industry. Firms therefore raise their R&D spending to compete and demand more precautionary cash savings. However, higher R&D investment implies higher expenditures, which compete for resources with cash savings. The second channel dominates the first at high values of σ and generates a hump-shaped response of cash ratios.

Compared to an increase in σ, an increase in operating costs c_F—another measure of intensified market competition—has qualitatively similar but quantitatively different impacts on high-tech firms' cash and R&D policies. Therefore, disentangling different sources of market competition is necessary and has important implications for the choice of pro-competition policies.

3.2.2 Parameter Identification

Given the comparative statics shown above, we choose the following moments to estimate our undetermined model parameters: the 25^{th} and 75^{th} percentiles of R&D-to-firm value and cash-to-firm value ratios, serial correlation of within-firm R&D and cash ratios, their correlation, fraction of firms with zero R&D investment, and firm exit rates.

In particular, in the face of high fixed costs of adjusting R&D expenses γ_0, firms may select into non-R&D performers. The fraction of firms with zero R&D investment therefore can be used to infer γ_0. Given the degree of innovation uncertainty, the persistence of within-firm R&D ratio provides information on the magnitude of convex R&D adjustment costs γ_2.

The persistence of within-firm cash ratios can be used to infer the magnitude of fixed equity-issuance costs λ_0. A smaller λ_0 leads to less lumpy equity issuance and a more smooth cash ratio. Cash-poor firms tend to be more sensitive to changes in credit market conditions.

The 25^{th} percentile of cash ratio thus contains information about linear equity-issuance costs λ_1.

An increase in δ has significant impacts on firms' R&D effort. It implies a higher chance of innovation failure and induces firms to invest more in R&D in order to promote success rates. We therefore use the 25^{th} percentile of R&D ratio to identify δ. Changes in ρ affect the prospects for realizing breakthrough, which has impacts on leaders' income and R&D effort and in turn affects their cash holdings through both substitution and income effects. We thus use the 75^{th} percentile of cash ratio to estimate ρ. An increase in θ tends to have a discouraging effect on R&D investments. The 75^{th} percentile of R&D ratio, therefore, is informative about the size of knowledge spillover θ.

We infer fixed operating costs c_F from firm exit rates. As c_F increases, fewer firms can cover the costs and are more likely to choose to exit the market. Lastly, we estimate wage costs w from the correlation between R&D investment and cash holdings. In response to a higher wage rate, firms pass the increased production costs to customers by setting higher product prices. The corresponding changes in income move cash and R&D investment in the same direction through the income effect, which generates a higher correlation between them.

3.3 Estimation Results

In this subsection, we report estimation results of the model described in Section 2.

3.3.1 Parameter Estimates

Parameter estimates are reported in Panel B of Table 1. The estimated γ_0 is 0.057, which implies that the fixed R&D adjustment cost is roughly equal to 2% of an average firm's sales. The estimated γ_2 is 2.30. This value suggests that if current R&D investment deviates from the past value by 10%, the convex adjustment costs would amount to approximately 1% of R&D investment. Very few structural estimates of R&D adjustment costs are available in the literature. Li and Liu (2012) find the convex R&D *stock* adjustment cost is larger than that of physical capital; their estimates range from 3.26 to 67.47, depending on model specifications. Kung (2014) sets the convex R&D adjustment cost parameter to be 3.3 by matching the relative volatility of R&D investment growth to consumption growth in the data. Our estimate of the convex adjustment costs γ_2 appears to be close to the lower bound of their estimates. Given the different adjustment-cost specifications, one should be cautious about making direct comparisons. However, our estimate delivers a message consistent with that of Li and Liu (2012) and other R&D studies—that is, R&D adjustment costs are high.

Two other parameters inferred from firms' R&D and cash behavior are innovation efficiency δ and knowledge spillover θ. The estimate of δ is 0.1959, which implies moderate risks associated with innovation in general. The estimate of θ is critical for measuring returns to R&D for policy considerations. Our estimate of θ is 0.5789, which is lower than the estimate provided by Xu (2008) and indicates relatively small intra-industry externalities among publicly traded technology companies.

The estimated fixed and linear equity-issuance costs, λ_0 and λ_1, are 0.0456 and 0.1198, respectively. The linear cost is higher than the value estimated by Hennessy and Whited (2007) who find it to be approximately 0.091. We conjecture that our higher estimate arises from a different sample of firms. We examine high-tech companies who tend to be collateral poor due to information asymmetries and thus face higher external borrowing costs.

The parameter ρ is newly introduced to the R&D literature. It relaxes the restriction imposed by previous studies in which firms can only conduct incremental innovation and move to a productivity level that is equal or close to their current positions (Xu, 2008; Hashmi and Van Biesebroeck, 2016). When ρ equals zero, there is an equal chance of realizing incremental and radical innovation and reaching any level other than the current one. The larger the parameter, the greater the likelihood that firms will move to the closest value. The estimated ρ is 0.7578, implying a 5.7% chance of moving from median productivity to technological frontier.

Lastly, the fixed operating cost c_F is 0.6583. This value amounts to roughly 32% of an average firm's sales.

3.3.2 Simulated Model Moments

Tables 2 and 3 report the data moments and their corresponding simulated model moments, including the moments of R&D-to-firm value and cash-to-firm value ratios, share of non-R&D performers, and exit rates. To be consistent with our model, we treat it as an exit if firms are deleted from Compustat due to bankruptcy (data item *dlrsn* is 2), liquidation (data item *dlrsn* is 3), or acquisition and merger (data item *dlrsn* is 1, 4, or 6) when previous sales growth is negative.

Table 2 presents the targeted model moments at the point estimates reported in Table 1. As shown, most targets are well matched. The model-implied first and third quartiles of R&D and cash distributions, within-firm serial correlation of R&D investment and cash holdings, fraction of non-R&D performers, and exit rates are all close to data moments. The correlation between R&D and cash is slightly undershot by the model, 0.368 vs. 0.285.

[Table 2 about here.]

We further evaluate model performance by comparing the model-implied distributions of R&D and cash ratios with the empirical distributions derived from data. We consider the following nontargeted moments: industry average, cross-sectional dispersion, industry median, and the k^{th} percentile of variable distribution with $k = \{1, 5, 10, 90, 95, 99\}$. Results are reported in Table 3. As can be seen, model-implied distributions closely resemble the data. The industry average, cross-sectional dispersion, and the right tails of R&D and cash distributions are all close to their data counterparts. An exception is the left tail of cash-to-firm value ratio. Compared to the data, the model implies a slightly thinner left tail of cash distribution—5^{th} and 10^{th} percentiles—and overshoots the industry median cash ratio.

[Table 3 about here.]

Overall, the model is able to achieve a good match for both cross-sectional heterogeneity and within-firm dynamics and explain the key patterns of firms' R&D and cash-holding behavior observed in the data. This validates and serves as a test of our model to strengthen the reliability of parameter estimates reported in Table 1.

4 Model Implications

In the following subsections, we use the parameter estimates obtained in Section 3 to quantitatively evaluate the role of each R&D feature in explaining the observed large cash stocks maintained by high-tech firms. We further use the model to shed light on the effectiveness of R&D tax credits. In particular, we explore the transmission channels of the policy, which provides important implications for productivity improvement.

4.1 Why Do High-tech Firms Hold So Much Cash?

In this subsection, we rely on the structural estimates obtained above to quantify the importance of key R&D features in explaining innovative firms' cash and R&D choices. We consider the following factors: R&D adjustment costs (γ_0 and γ_2), innovation uncertainty (δ and ρ), knowledge spillover (θ), financial frictions caused by the non-collaterability of R&D and information asymmetry between firms and investors (λ_0 and λ_1), and market competition (σ and c_F). We change one parameter at a time, holding all other parameters constant. Two effects are examined: (i) local effects by changing the value of each parameter by 5%, and (ii) global effects by shutting down each feature.

4.1.1 Local Effects

First, we explore the effects of each feature locally by changing their parameter values by 5%. Results are reported in Table 4.

[Table 4 about here.]

Our estimation results suggest that R&D adjustment costs may not be a first-order factor in explaining innovative firms' high cash balances, which echoes the comparative statics analysis in Subsection 3.2.1. A 5% increase in adjustment costs has little effect on firms' cash demand and R&D choices.

A 5% increase in innovation efficiency, which is captured by a drop in δ, barely changes the average cash ratio. The minor change is caused by the interaction between the precautionary motive, substitution effect, and income effect. A decrease in δ drives down the likelihood of innovation failure. It discourages R&D spending and generates higher revenue. The weakened precautionary motive is offset by the increase in cash brought by substitution and income effects.

A 5% decrease in ρ increases innovation volatility and generates a 8.2% increase in the average cash ratio. It is the most important contributor to high-tech firms' cash demand locally. Knowledge spillover θ is the second most important factor in driving high-tech firms' cash policy. A 5% increase in the externality drives up the mean cash ratio by 6.4%.

Financial frictions also matter. The fixed equity issuance cost λ_0 is another main driver, while the linear equity issuance cost λ_1 plays a limited role. To economize on the fixed issuance costs, firms on average increase their cash ratios by 2.7% in response to a 5% increase in λ_0.

Intensified market competition—a higher elasticity of substitution σ or a high operating cost c_F—reduces firms' cash holdings. In particular, a 5% higher elasticity induces a 67.1% drop in the average cash ratio, and a 5% rise in fixed operating costs reduces cash ratio by 19.2%. Both are due to the resource substitution away from cash to R&D investment.

4.1.2 Robustness

The potential concern over the results in Table 4 is that the 5% change in each parameter may have different economic meanings and thus make the effects of each feature incomparable. To alleviate this concern, we next change the value of each parameter such that the average firm value increases by 1% and re-evaluate the effects of each feature on firms' cash choices. Results are reported in Table 5.

[Table 5 about here.]

Overall, our results are robust. A higher innovation volatility and a greater knowledge spillover remain the key contributors to high-tech firms' large cash balances. They drive up the average cash ratio by more than 7%, followed by financial frictions.

Moreover, one result in Table 4 is overturned. As the fixed R&D adjustment cost γ_0 further increases, it starts to play a sizeable role in shaping innovative firms' cash policies. In particular, a 8% increase in γ_0 strengthens the precautionary motive for holding cash among cash-poor firms and pushes up the mean cash ratio by 5%.

4.1.3 Global Effects

Next, we quantify the effects of each feature globally by shutting them down alternately. We reset the value of each parameter such that the average firm value changes by 25% but subject to the constraints that each parameter is non-negative. Specifically, we set adjustment costs (γ_0 and γ_2), knowledge spillover (θ), and financial frictions (λ_0 and λ_1) to be zeros. We raise δ and ρ to lower the level of innovation efficiency and innovation volatility, respectively, and cut σ and c_F to reduce the degree of market competition, each of which changes firm value by 25%. Results are reported in Table 6. To ease the comparison between the importance of each feature in explaining innovative firms' high cash balances, we report the percentage changes in average cash ratio relative to our benchmark model in the third column.

[Table 6 about here.]

Results in Table 6 suggest that the key contributor to high-tech firms' cash stock is innovation volatility associated with the probability of realizing breakthroughs. When we shut down the innovation uncertainty channel by raising ρ from 0.7578 to 1.33, the chance of moving from median productivity to the technological frontier falls from 5.7% to 1.7%. Firms then devote more resources to R&D to improve innovation success rates. Higher expenses, together with lower income, leave fewer resources for cash savings. Firms' average cash ratio drops by 53%. Results of global perturbations also confirm the importance of knowledge spillover and financial frictions. Closing these channels reduces the average cash ratio by 36.5% and 32.9%, respectively.

In addition, market competition is another factor that is critical for understanding innovative firms' large cash reserves; yet, it exhibits non-monotonic effects as shown and explained in Subsection 3.2.1.6. The non-monotonicity arises from the change in the stationary distribution of firms. A lower product substitutability implies a higher markup and profitability, which leads more low-productivity firms to stay and compete in the market by investing in R&D. These low-productivity firms tend to be financially constrained and have fewer resources to allocate to cash stocks, which drives down the average cash ratio. A lower fixed operating cost reduces competition by producing a higher expected return of entry and driving up the entry cost. It leads to a lower cash demand due to lower R&D investment and operating expenses.

R&D adjustment costs play a less important role than the other four elements. The absence of adjustment costs mainly reduces the real costs of investment and, in turn, raises the level of R&D expenditures. The presence of financial frictions and innovation uncertainty guarantees the value of cash, regardless of the magnitude of R&D adjustment costs.

In sum, Tables 4-6 shed light on the main drivers behind innovative firms' large cash balances. Our results suggest that the main contributor is innovation uncertainty, followed by knowledge spillover and financial frictions. Market competition has non-monotonic effects on firms' cash policy, and R&D adjustment costs matter the least.

4.2 Policy Implications

We next explore policy implications of our model. Two classic questions in the R&D innovation literature are the impacts of knowledge spillover and financing frictions on R&D investment. Previous studies argue that both factors can cause market failure for R&D. An extensive body of empirical evidence supports the former, while the empirical support for the latter is more mixed.[8]

Our comparative statics results in Section 3.2.1 are in line with previous empirical findings. We find severe market failure induced by knowledge spillover, but find no strong support for the underinvestment problem caused by financial frictions. Worse credit conditions are absorbed by changes in cash policy, which largely alleviates the induced market failure.

One of the often-used solutions to the underinvestment problem stemming from knowledge spillover is the use of R&D tax credits. We use our model to evaluate the effects of this tax policy on productivity and explore its transmission channels. To do so, we first compute the industry average productivity implied by our benchmark model with and without R&D tax credits. Their difference gives the effects of tax credits on productivity. We then shut down each R&D feature alternately and examine their respective role in policy transmission by comparing the resulting average productivity for $\tau_{rd} = 0$ and $\tau_{rd} = 0.06$. Results are reported in Table 7.

[Table 7 about here.]

Panel A of Table 7 suggests that in our benchmark model, a 6% R&D tax credit alleviates the underinvestment issue and drives up the average productivity by 3.5%. Panel B reports the role of each R&D feature other than spillover in affecting the effectiveness of R&D tax credits. We find the following. Fixed R&D adjustment costs hinder the benefits of tax credits. Without fixed adjustment costs, tax credits would improve productivity by 4%. Innovation volatility, financial frictions, and market competition induced by low entry costs also weaken the effectiveness of tax credits. Without these features, the productivity improvement generated by tax credits would rise to 5.7%, 5.3% and 6.5%, respectively. The convex R&D adjustment cost

[8]See, for example, the literature review provided by Hall and Lerner (2010).

has no impacts on the effectiveness of tax-credit policy. However, the absence of this feature would significantly improve productivity, 1.214 vs. 1.190 (without tax credits) and 1.256 vs. 1.232 (with tax credits).

Innovation efficiency improves the effectiveness of R&D tax credits in boosting productivity. A higher δ would reduce the beneficial effects of tax incentives from 3.5% to 3.0%. Moreover, a higher δ reduces the average productivity in the industry, 1.152 vs. 1.190 (without tax credits) and 1.187 vs. 1.232 (with tax credits). Market competition generated by an increase in product substitutability is another channel to enhance the effectiveness of R&D tax credits. In particular, a drop in elasticity of substitution would limit the effectiveness of tax credits from 3.5% to 3.3%.

Our results suggest two possible ways to further improve productivity as well as the effectiveness of R&D tax credits. One is to enhance innovation efficiency by facilitating cross-functional collaboration in teams during product development. The other is to reduce R&D adjustment costs by encouraging sharing of research resources among product lines so as to overcome the cost disadvantage coming from the difference between existing products and expected innovations.

5 Conclusion

High-tech firms hold a large amount of cash. A better understanding of their joint R&D and cash choices can help design policies to promote R&D investment and productivity. In this paper, we systematically analyze how unique features of R&D shape R&D and cash decisions and assess their respective importance in explaining the observed high cash balances.

The model embeds five key factors highly relevant for high-tech industries: R&D adjustment costs, financial frictions, knowledge spillover, innovation uncertainty, and market competition. We show that our estimated model successfully replicates the empirical patterns of industry-level and firm-level R&D and cash choices. We then use the validated model to determine the quantitative importance of relevant R&D features in explaining high-tech firms' substantial cash reserves. We find the following. Innovation uncertainty matters the most for the observed strong cash demand, followed by knowledge spillover and financial frictions. R&D adjustment costs have a relatively weak relationship with cash policy, and market competition has non-monotonic effects on cash holdings.

Our model also has policy implications. It sheds light on the sources of R&D underinvestment, the effectiveness of R&D tax credits, and the transmission channels. We find that greater knowledge spillover significantly reduces R&D spending, while worse credit market conditions have minor impacts on R&D effort and mainly influence firms' cash choices. We also find that R&D tax credits can effectively alleviate the underinvestment issue, and enhancing innovation efficiency and encouraging resource sharing to reduce R&D adjustment costs can further improve productivity and the effectiveness of the tax policy.

A Appendix

A.1 Model Solution

First recall that the firm i's output y_i is a function of productivity shock z_i and labor l_i:

$$y_i = z_i l_i.$$

A relationship between aggregate price P and individual price p_i is derived by minimizing the cost of acquiring a fixed amount of aggregate good $\bar{Y}$. Therefore, we want to solve the following minimization problem:

$$\min_{y_i} \{PY\} = \min_{y_i} \left\{ \sum_i p_i y_i \right\}$$

subject to,

$$\left(\sum_i y_i^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} = \bar{Y}.$$

The Lagrangian is expressed as,

$$\mathcal{L} = \sum_i p_i y_i + \eta \left[\bar{Y} - \left(\sum_i y_i^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} \right]$$

where η is the Lagrange multiplier. The first-order condition with respect to y_i is,

$$p_i = \eta \left(\sum_i y_i^{\frac{\sigma-1}{\sigma}} \right)^{\frac{1}{\sigma-1}} y_i^{-\frac{1}{\sigma}},$$

which then simplifies to,

$$p_i^{\sigma} y_i = P^{\sigma} Y,$$

since the Lagrange multiplier η is equal to P. Then to find the profit maximizing price, we solve

$$\max_{p_i} \{\pi_i\} = \max_{p_i} \{p_i y_i - w l_i\}.$$

The first order condition with respect to p_i gives the optimal price as a markup over marginal cost,

$$p_i = \frac{\sigma}{\sigma - 1}\frac{w}{z_i}.$$

Finally, profit can be rewritten as,

$$\begin{aligned}\pi_i =& p_i y_i - w l_i - c_f + r c_i - d_i \\ =& (P^\sigma Y) p_i^{1-\sigma} - (P^\sigma Y) w p_i^{-\sigma} z_i^{-1} - c_f + r c_i - d_i \\ =& (P^\sigma Y) \sigma^{-\sigma} (\sigma - 1)^{\sigma - 1} w^{1-\sigma} z_i^{\sigma - 1} - c_f + r c_i - d_i \\ =& (P^\sigma Y) \left(\frac{(\sigma - 1) z_i}{\sigma w} \right)^{\sigma - 1} \frac{1}{\sigma} - c_f + r c_i - d_i.\end{aligned}$$

Without loss of generality and for simplicity, we normalize $P^\sigma Y$ to 1 rather than w to 1 as in Melitz (2003).

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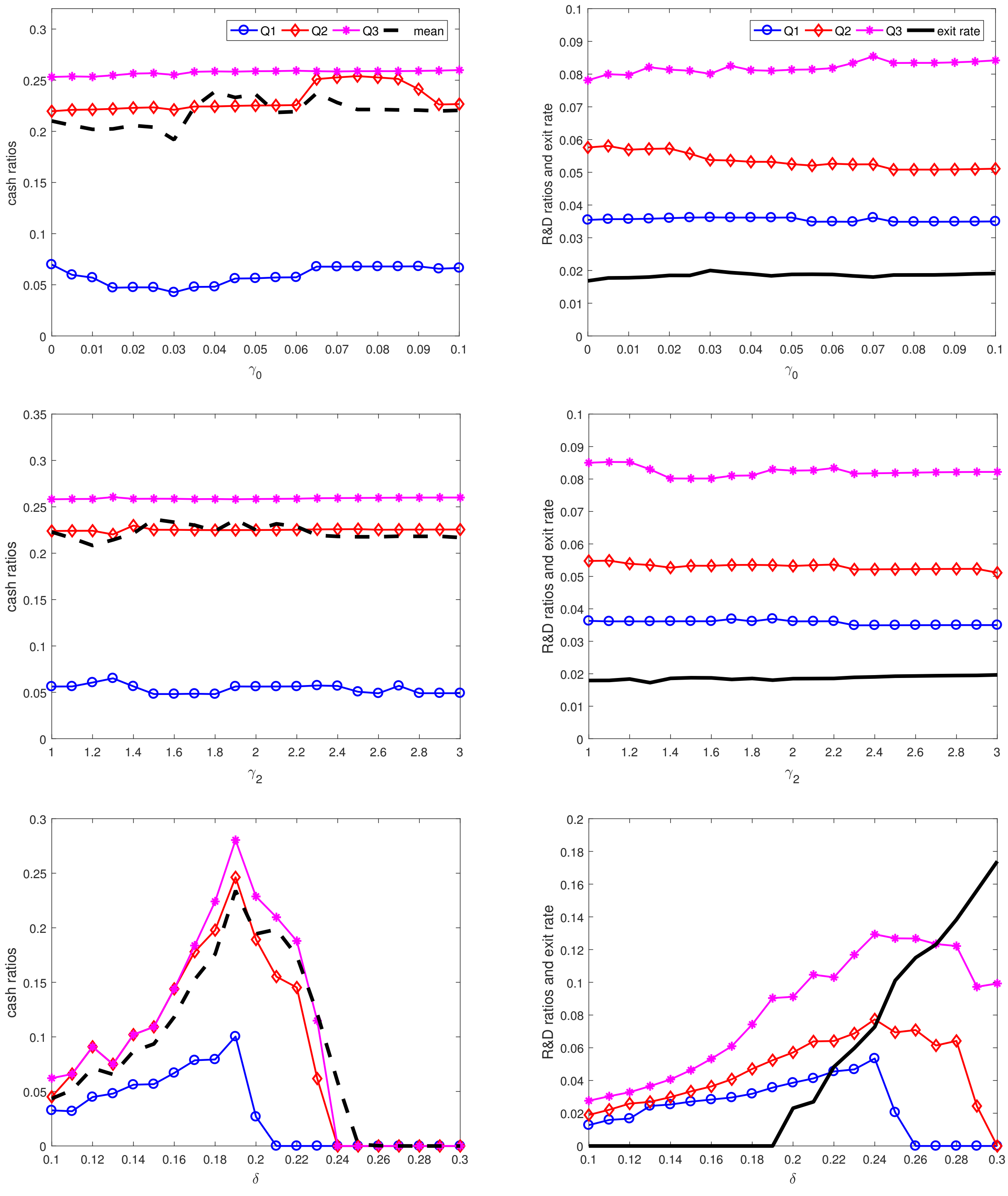

Figure 1: **Comparative Statics I.** This figure plots the effects of fixed R&D adjustment costs γ_0, convex R&D adjustment costs γ_2, and innovation efficiency δ on (i) cash-to-firm value ratio, (ii) R&D-to-firm value ratio, and (iii) exit rates.

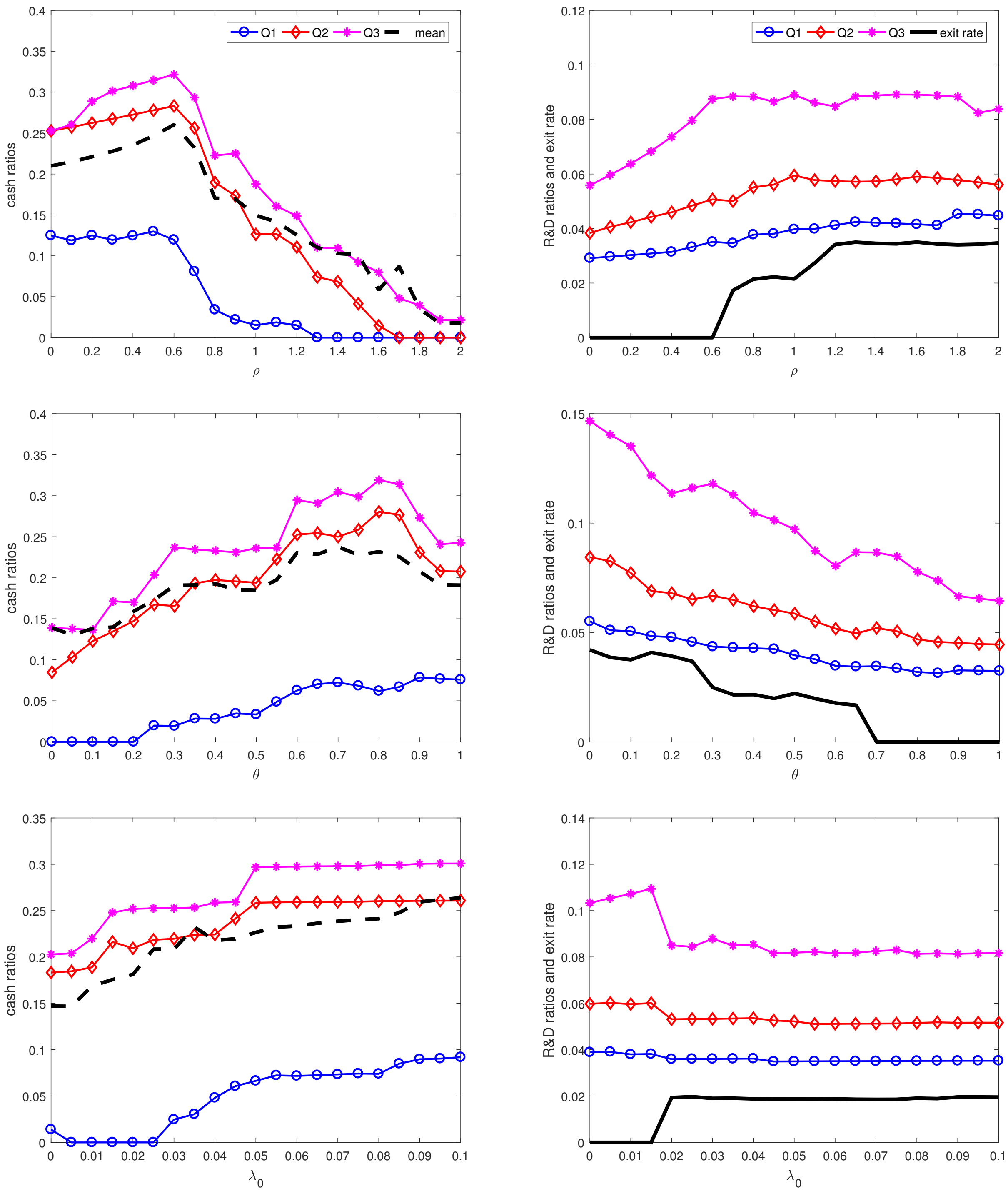

Figure 2: **Comparative Statics II.** This figure plots the effects of innovation volatility ρ, knowledge spillover θ, and fixed equity issuance costs λ_0 on (i) cash-to-firm value ratio, (ii) R&D-to-firm value ratio, and (iii) exit rates.

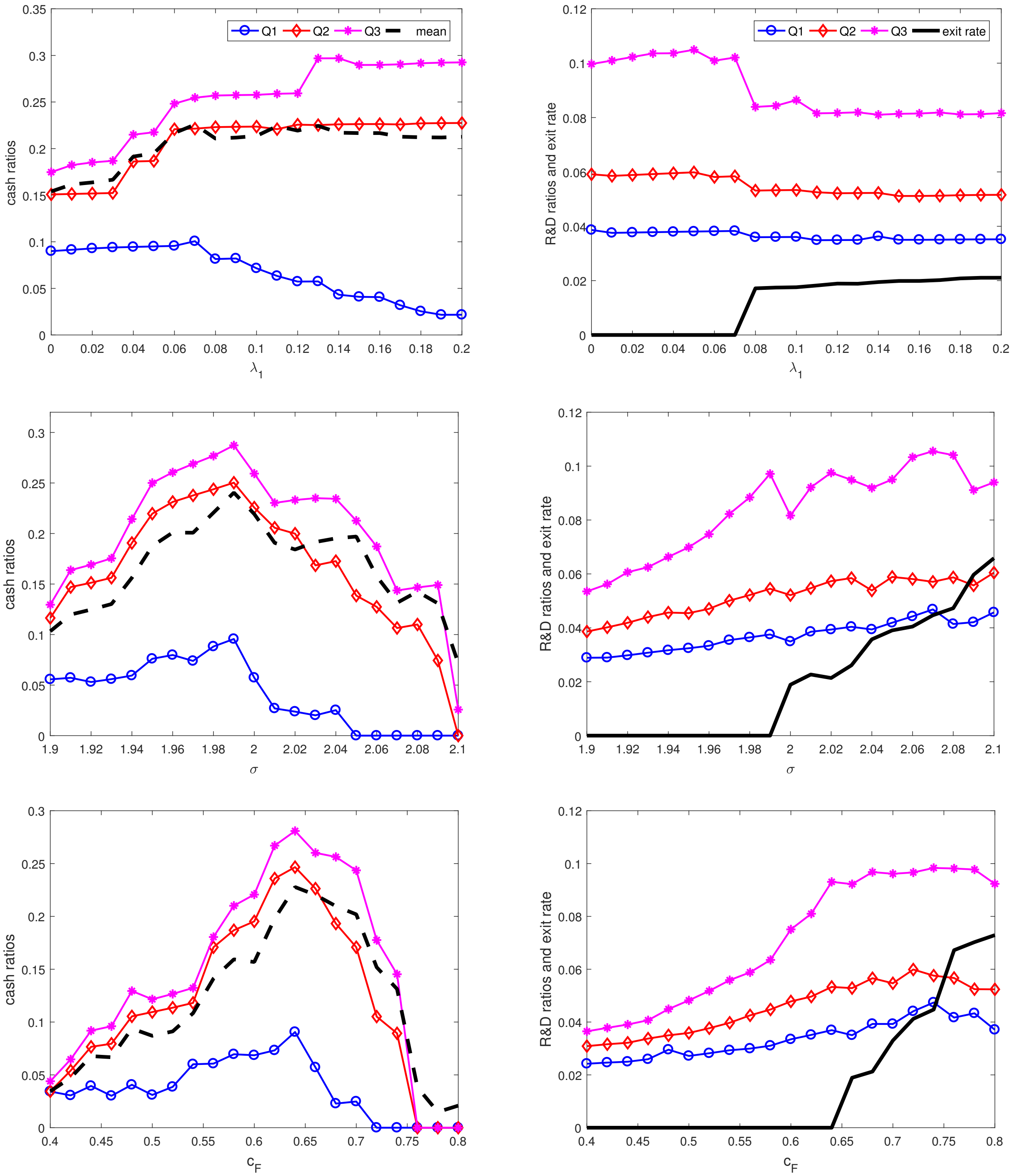

Figure 3: **Comparative Statics III.** This figure plots the effects of linear equity issuance costs λ_1, elasticity of substitution σ, and fixed operating costs c_F on (i) cash-to-firm value ratio, (ii) R&D-to-firm value ratio, and (iii) exit rates.

Table 1: **Model Parameterizations**

Table 1 summarizes the parameters used to solve the model at annual frequency. Panel A reports the parameters calibrated separately from data or borrowed from other studies. Panel B presents estimation results by taking parameters in Panel A as given and jointly matching nine selected data moments. Standard errors are presented in parentheses.

Panel A: Parameters Calibrated Separately

Real risk-free rate (r)	0.03
Elasticity of substitution (σ)	2.00
Dividend tax (τ_d)	0.15
Statutory corporate income tax (τ_c)	0.35
R&D tax credits (τ_{rd})	0.06

Panel B: Parameters Estimated by SMM

Fixed costs of external finance (λ_0)	0.0456	(0.0003)
Linear costs of external finance (λ_1)	0.1198	(0.0300)
Fixed adjustment cost (γ_0)	0.0570	(0.0198)
Convex adjustment cost (γ_2)	2.3018	(0.7006)
Innovation efficiency (δ)	0.1959	(0.0019)
Knowledge spillover (θ)	0.5789	(0.0017)
Innovation volatility (ρ)	0.7578	(0.0069)
Fixed operating cost (c_F)	0.6583	(0.0058)
Wage cost (w)	0.2265	(0.0008)

Table 2: **Simulated Model Moments: Targeted Moments**

Table 2 reports both data and corresponding model moments. Data moments are calculated based on a sample of Compustat high-tech firms over the period 2000-2014.

Moments	Data	Model
(i) R&D:		
25^{th} percentile of R&D-to-firm value ratio	0.022	0.035
75^{th} percentile of R&D-to-firm value ratio	0.100	0.082
Serial correlation of within-firm R&D-to-firm value ratio	0.519	0.536
Fraction of firms with zero R&D investment	0.020	0.020
(ii) Cash:		
25^{th} percentile of cash-to-firm value ratio	0.061	0.057
75^{th} percentile of cash-to-firm value ratio	0.250	0.259
Serial correlation of within-firm cash-to-firm value ratio	0.693	0.631
Correlation with R&D-to-firm value ratio	0.368	0.285
(iii) Market competition:		
Exit rate	0.019	0.019

Table 3: **Simulated Model Moments: Nontargeted Moments**

Table 3 presents nontargeted moments for R&D-to-firm value ratio and cash-to-firm value ratio. Data moments are calculated based on a sample of Compustat high-tech firms over the period 2000-2014.

Moments	Data	Model
(i) R&D:		
Industry average R&D-to-firm value ratio	0.082	0.084
Cross-sectional dispersion of R&D-to-firm value ratio	0.109	0.113
Industry median R&D-to-firm value ratio	0.048	0.052
1-percentile of R&D-to-firm value ratio	0.000	0.000
5-percentile of R&D-to-firm value ratio	0.003	0.031
10-percentile of R&D-to-firm value ratio	0.008	0.035
90-percentile of R&D-to-firm value ratio	0.182	0.156
95-percentile of R&D-to-firm value ratio	0.260	0.239
99-percentile of R&D-to-firm value ratio	0.513	0.603
(ii) Cash:		
Industry average cash-to-firm value ratio	0.193	0.219
Cross-sectional dispersion of cash-to-firm value ratio	0.212	0.200
Industry median cash-to-firm value ratio	0.135	0.226
1-percentile of cash-to-firm value ratio	0.000	0.000
5-percentile of cash-to-firm value ratio	0.008	0.000
10-percentile of cash-to-firm value ratio	0.021	0.000
90-percentile of cash-to-firm value ratio	0.425	0.418
95-percentile of cash-to-firm value ratio	0.582	0.534
99-percentile of cash-to-firm value ratio	1.012	0.976

Table 4: **Local Role of R&D Features**

Table 4 summarizes the effects of each key R&D feature on firms' R&D and cash choices locally, by changing the value of each parameter by 5%. The percentage change in average firm value compared to the benchmark model is reported in the last column.

	Cash			R&D			Firm Value
	Mean	1^{st} quartile	3^{rd} quartile	Median	1^{st} quartile	3^{rd} quartile	% change
Benchmark Model	0.219	0.057	0.259	0.052	0.035	0.082	
R&D Adjustment Costs							
Fixed adjustment cost ($\gamma_0 \uparrow 0.060$)	0.219	0.057	0.259	0.053	0.035	0.082	0.1%
Convex adjustment cost ($\gamma_2 \uparrow 2.417$)	0.218	0.057	0.259	0.052	0.035	0.082	−0.2%
Innovation Uncertainty							
Innovation efficiency ($\delta \downarrow 0.186$)	0.218	0.096	0.271	0.050	0.033	0.083	16.6%
Innovation volatility ($\rho \downarrow 0.720$)	0.237	0.082	0.294	0.051	0.035	0.082	3.4%
Externality							
Knowledge spillover ($\theta \uparrow 0.608$)	0.233	0.062	0.294	0.050	0.035	0.080	2.0%
Financial Frictions							
Fixed equity-issuance cost ($\lambda_0 \uparrow 0.048$)	0.225	0.061	0.297	0.052	0.035	0.082	0.5%
Linear equity-issuance cost ($\lambda_1 \uparrow 0.126$)	0.220	0.057	0.260	0.052	0.035	0.082	−0.2%
Market Competition							
Elasticity of substitution ($\sigma \uparrow 2.100$)	0.072	0.000	0.026	0.061	0.046	0.094	−41.5%
Fixed operating costs ($c_F \uparrow 0.691$)	0.177	0.020	0.205	0.058	0.040	0.103	−18.2%

Table 5: **Local Role of R&D Features: Robustness**

Table 5 summarizes the effects of each key R&D feature on firms' R&D and cash choices when we change the value of each parameter such that the average firm value increases by 1%.

	Cash			R&D		
	Mean	1^{st} quartile	3^{rd} quartile	Median	1^{st} quartile	3^{rd} quartile
Benchmark Model	0.219	0.057	0.259	0.052	0.035	0.082
R&D Adjustment Costs						
Fixed adjustment cost ($\gamma_0 \uparrow 0.0616$)	0.230	0.068	0.259	0.052	0.035	0.083
Convex adjustment cost ($\gamma_2 \downarrow 1.944$)	0.218	0.056	0.258	0.054	0.036	0.083
Innovation Uncertainty						
Innovation efficiency ($\delta \downarrow 0.195$)	0.231	0.060	0.258	0.052	0.035	0.081
Innovation volatility ($\rho \downarrow 0.750$)	0.235	0.061	0.288	0.052	0.035	0.081
Externality						
Knowledge spillover ($\theta \uparrow 0.592$)	0.242	0.061	0.287	0.052	0.035	0.081
Financial Frictions						
Fixed equity-issuance cost ($\lambda_0 \uparrow 0.048$)	0.226	0.066	0.297	0.052	0.035	0.082
Linear equity-issuance cost ($\lambda_1 \downarrow 0.108$)	0.232	0.064	0.259	0.052	0.035	0.081
Market Competition						
Elasticity of substitution ($\sigma \downarrow 1.997$)	0.228	0.056	0.257	0.052	0.036	0.080
Fixed operating costs ($c_F \downarrow 0.655$)	0.226	0.056	0.257	0.053	0.036	0.080

Table 6: **Global Role of R&D Features**

Table 6 summarizes the effects of each key R&D feature on firms' R&D and cash choices globally, by shutting down each feature alternately. We set adjustment costs (γ_0 and γ_2), knowledge spillover (θ), and financial frictions (λ_0 and λ_1) to be zeros. We lower the levels of innovation efficiency (δ), innovation volatility (ρ), and market competition (σ and c_F) such that each of these parameters changes firm value by 25%. The percentage change in average firm value compared to the benchmark model is reported in the last column.

	Cash		R&D			Firm Value
	Mean	% change	Median	1^{st} quartile	3^{rd} quartile	% change
Benchmark Model	0.219		0.052	0.035	0.082	
R&D Adjustment Costs						
Fixed adjustment cost ($\gamma_0 \downarrow 0$)	0.210	-4.11%	0.058	0.035	0.078	3.3%
Convex adjustment cost ($\gamma_2 \downarrow 0$)	0.204	-6.85%	0.063	0.029	0.086	1.8%
Both adjustment costs (γ_0 and $\gamma_2 \downarrow 0$)	0.232	5.94%	0.060	0.024	0.086	9.8%
Innovation Uncertainty						
Innovation efficiency ($\delta \uparrow 0.212$)	0.173	-21.0%	0.061	0.043	0.102	−25%
Innovation volatility ($\rho \uparrow 1.330$)	0.103	-53.0%	0.057	0.042	0.089	−25%
Externality						
Knowledge spillover ($\theta \downarrow 0$)	0.139	-36.5%	0.084	0.055	0.147	−25.8%
Financial Frictions						
Fixed equity-issuance cost ($\lambda_0 \downarrow 0$)	0.147	-32.9%	0.060	0.039	0.103	−1.5%
Linear equity-issuance cost ($\lambda_1 \downarrow 0$)	0.154	-29.7%	0.059	0.039	0.100	−1.6%
Market Competition						
Elasticity of substitution ($\sigma \downarrow 1.947$)	0.165	-24.7%	0.046	0.036	0.071	25%
Fixed operating costs ($f \downarrow 0.595$)	0.154	-29.7%	0.047	0.033	0.073	25%

Table 7: **Policy Implications: R&D Tax Credits**

Table 7 summarizes the model's implications for R&D tax credits. Panel A reports the average productivity implied by our benchmark model with and without R&D tax credits. Panel B shows the effects of R&D features other than spillover on the transmission of tax incentives, by shutting down each feature alternately. We set adjustment costs (γ_0 and γ_2) and financial frictions (λ_0 and λ_1) to be zeros. We lower the levels of innovation efficiency (δ), innovation volatility (ρ), and market competition (σ and c_F) such that each of these parameters changes firm value by 25%.

	Average productivity ($\tau_{rd} = 0$)	Average productivity ($\tau_{rd} = 0.06$)	Percentage change
Panel A: Benchmark Specification			
Benchmark model	1.190	1.232	3.5%
Panel B: Channel Exploration			
Fixed adjustment cost ($\gamma_0 \downarrow 0$)	1.200	1.248	4.0%
Convex adjustment cost ($\gamma_2 \downarrow 0$)	1.214	1.256	3.5%
Innovation efficiency ($\delta \uparrow 0.212$)	1.152	1.187	3.0%
Innovation volatility ($\rho \uparrow 1.330$)	1.095	1.157	5.7%
Fixed equity-issuance cost ($\lambda_0 \downarrow 0$)	1.175	1.237	5.3%
Linear equity-issuance cost ($\lambda_1 \downarrow 0$)	1.174	1.237	5.4%
Elasticity of substitution ($\sigma \downarrow 1.947$)	1.197	1.236	3.3%
Fixed operating costs ($c_F \downarrow 0.595$)	1.161	1.237	6.5%