The Interest Rate Elasticity of Investment: Micro Estimates and Macro Implications

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Abstract

I estimate the elasticity of investment to interest rates using cross-sectional variation and high-frequency monetary shocks. My estimates imply that a 1 p.p. decrease in interest rates increases capital demand by 4% eight quarters after the shock. This indicates a significant effect of interest rates on investment but is much smaller than prominent estimates of the interest rate elasticity derived from the investment response to tax policy changes. In a quantitative model with heterogeneous firms, I show that the impulse response I estimate provides a powerful tool to discriminate between models with different frictions. The evidence favors models with external financing constraints, while models with large real adjustment costs cannot match evidence from both interest rate and tax policy shocks.

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> The discrepancy between theory and empirical work is perhaps nowhere in macroeconomics so obvious as in the case of the aggregate investment function.
>
> Olivier Blanchard, 1986

1 Introduction

Investment is one of the core macroeconomic aggregates studied by researchers and policymakers and is crucial for understanding business cycles and the effects of interest rate policy. Investment can be a powerful amplifier of monetary policy if higher investment induced by lower interest rates translates into higher labor and capital income and, ultimately, consumption and output. As a result, understanding investment's response to interest rates is vital for understanding the overall effect of monetary policy. Standard models of business cycles predict very large responses to even relatively modest changes in interest rates.

Why is investment so responsive to changes in interest rates? The characteristic of capital goods that drives these large responses is that capital is durable. Consider a firm that purchases an additional unit of capital and uses that capital for production immediately upon purchase. In the next period, the firm retains 1-δ of the value of that unit of capital, where δ represents the rate of economic depreciation. As a result, the firm's return on that investment includes not just the marginal production generated by that capital, but also the value of the capital that remains after depreciation. Thus, the allocative price of capital goods is not the price the firm pays for the additional unit of capital, but rather the *user cost of capital*, or the price of purchasing the capital in period t instead of purchasing in period $t+1$. In neoclassical models, the interest rate affects investment because it is an input into the user cost: the interest rate functions as the opportunity cost of investing in period t. Even in models where firms cannot resell their non-depreciated capital, the durability of capital goods gives firms a powerful incentive to accelerate investment from periods where the user cost is relatively high to periods where the user cost is relatively low.

Despite the importance of investment to our understanding of business cycles, estimates of the investment response to interest rates vary widely. Because monetary policy is endogenous and investment is the most cyclical component of GDP, it is difficult to separate the effect of interest rates from other factors that vary over the business cycle. Traditional VAR methods require potentially implausible identifying assumptions, and high-frequency identification methods offer relatively little power to detect precise effects using time-series methods (Nakamura and Steinsson, 2018*a*). In addition, investment responses to interest rate changes identified through time-series methods reflect a combination of the partial equilibrium response to changes in the cost of capital and the response to general equilibrium effects that are also triggered when interest rates change, such as shifts in aggregate demand and Fed information effects. Disentangling these effects is essential for ensuring macroeconomic models reflect the underlying mechanisms that drive firms' investment choices and accurately computing the effects of counterfactual policies.

A recent literature in macroeconomics has used the well-identified, partial equilibrium consumption response to stimulus checks (the marginal propensity to consume, or MPC) to discipline general equilibrium models. Just as the investment response to interest rates reflects a combination of PE and GE forces, the effects of fiscal stimulus checks depend on both the MPC and the strength of general equilibrium feedback of increased demand on labor incomes. While estimates of the MPC alone cannot provide a comprehensive estimate of the aggregate effects of fiscal stimulus policies, they have proven crucial to ensuring macroeconomic models are quantitatively realistic and accurately reflect how households respond to shocks. In contrast, the literature estimating firm-level partial equilibrium investment moments and using those moments to discipline macroeconomic models of the business cycle is less well-developed.

In this project, I use the fact that the durability of capital is precisely the characteristic that gives firms an incentive to accelerate investment in response to transitory interest rate changes to derive a novel estimator of the interest rate elasticity of investment. While it is standard to model a single type of capital good, firms use different types of capital goods with differing depreciation rates. This implies that firms that use different types of capital have differing incentives to increase their capital purchases in response to the exact same change in interest rates. I show that in a simplified, partial equilibrium model of investment, comparing the investment response across firms with different depreciation rates directly identifies the parameter that determines the responsiveness of investment to changes in the cost of capital and, thus, interest rates.

I then implement my estimation strategy in quarterly, firm-level data. I combine cross-sectional variation in depreciation rates across industries with time-series variation in interest rates from high-frequency shocks to monetary policy to identify the investment response to changes in interest rates. Because my empirical strategy includes sector-by-time fixed effects, the regression differences out general equilibrium factors and isolates the partial equilibrium response of investment through changes in the cost of capital.[1] Consistent with neoclassical theory, firms with longer-lived capital goods increase their investment substantially more than

[1] In this paper, I define industries (i) as disaggregated subsets of sectors (s) (e.g. $i \subseteq s$). For example, I define "Durable Manufacturing" as a sector and "Equipment Manufacturing" as an industry that is part of the "Durable Manufacturing" sector.

firms with shorter-lived capital after a surprise monetary easing. Through the lens of the simplified model, the estimates imply substantial effects of interest rates on investment and capital: in response to a 1 p.p. expansionary shock, aggregate capital demand increases by around 3% after one year. The effect reaches its peak eight quarters after the monetary shock when capital demand is around 3.7% higher due to the interest rate shock.

While there are limited partial equilibrium estimates of the investment response to interest rates, recent work (Koby and Wolf, 2020) has used estimates of the investment response to transitory changes in corporate taxes to discipline the investment response to interest rates. In particular, because corporate taxes and interest rates both affect investment by changing the cost of capital, the investment response to tax changes (which I refer to as the "tax rate elasticity") is informative about the investment response to changes in interest rates (which I refer to as the "interest rate elasticity"). In standard models, the interest rate elasticity is simply a rescaling of the tax rate elasticity.

However, I show that my estimates of the interest rate elasticity are substantially smaller than the interest rate elasticities implied by prominent estimates of the tax rate elasticity (Zwick and Mahon, 2017). The *annual* implied interest rate elasticities estimated from tax rate changes are almost 3 times larger than the interest rate elasticities estimated directly from monetary shocks. Thus, my estimates suggest that using the tax rate elasticity to proxy for the investment response to interest rates will likely result in a substantial overestimate of the interest rate elasticity. In addition, the estimates suggest that traditional, neoclassical models where transitory changes in interest rates and tax rates have similar effects on investment are misspecified.

I then bring my empirical estimates to a quantitative model where heterogeneous firms make investment choices to highlight how the empirical moments estimated in this project can discipline the quantitative magnitude of the investment response to interest rates and discriminate between models where firms face different types of frictions. I use the empirical estimates to calibrate two separate models of investment: one in which firms face convex and fixed adjustment costs and another where firms face financial frictions that limit the amount they can borrow to fund investment. I target the estimated empirical impulse response from monetary shocks to calibrate the strength of the adjustment costs and the financial frictions. Consistent with the modest interest rate elasticities estimated in the data, the models require very tight financial frictions or strong adjustment costs to match the data. However, the quantitative results also show that financial constraints alone can generate investment elasticities that match the data without appealing to arbitrary adjustment costs.

I then use the tax rate elasticity from Zwick and Mahon (2017) as an untargeted moment to discriminate between the two types of models. The model with strong real adjustment costs cannot simultaneously match the modest responses to interest rate policy and the larger responses to tax policy changes. In contrast, the model without adjustment costs but with strong financial frictions generates larger responses to tax rate changes than interest rate changes, consistent with both sets of empirical estimates. Why can only the model with financial frictions match both moments simultaneously? In neoclassical models, tax and interest rates both affect investment by changing the cost of capital. Adjustment costs slow the investment response to cost of capital shocks, but have the same effect regardless of the policy instrument that changes the cost of capital. Thus, investment elasticities to tax rates and interest rates will be very similar when adjustment costs are important, just as in frictionless models.

In contrast, in the presence of financial frictions, tax rates have a second important effect. By changing the immediate tax bill the firm owes to the government, tax policy changes the amount of free cash flow available to the firm to fund investment. This cash-flow effect is irrelevant in both frictionless models and models with real adjustment costs: the firm will costlessly borrow and invest optimally. However, this additional cash-flow effect can magnify the investment response when financial frictions constrain firm borrowing or investment. Because changes in interest rates do not generate immediate cash flows of the same magnitude in the presence of financial frictions, tax rate elasticities are larger than interest rate elasticities.[2] Consequently, my estimates suggest that monetary policy is much less effective at stimulating investment spending than tax policy, which has important implications for countercyclical policy design.

To validate the theoretical mechanism, I return to the data and estimate heterogeneous interest rate elasticities by firm characteristics. I estimate whether firms more likely to face tighter financial constraints respond differently to those less likely to be financially constrained after interest rate shocks. I focus on firms' interest expenses to proxy for how close firms are to interest-coverage covenants, which are the most common type of debt covenant (Greenwald, 2019).

I find substantial differences in interest rate elasticities by the firm's level of interest expenses. Firms with high interest expenses exhibit smaller elasticities, while firms with low interest expenses have substantially larger responses than implied by the baseline estimates. The investment response of firms with low interest expenses corresponds to interest rate elasticities that are nearly identical to the large implied interest rate elasticities estimated from changes in corporate taxes. In contrast, I find no evidence of heterogeneous responses by several other characteristics hypothesized to affect the investment response to interest rates: firm leverage,

[2] In the presence of debt financing, monetary policy does generate cash flow by reducing interest expenses (Gürkaynak, Karasoy-Can and Lee, 2021). However, these cash flow benefits are substantially smaller and less immediate than the cash flow effects of tax policy, as discussed in Section 6.

liquidity, and fixed costs. Overall, I interpret these results as providing additional evidence for the core mechanism in the model: financial frictions that limit a firm's external financing play an essential role in reducing the investment response to interest rate changes. These results also imply that tax rate elasticities will be larger than interest rate elasticities because tax policy shocks also free up cash flow within the firm that can be used for investment.

Overall, my empirical strategy provides a novel estimate of the effect of interest rates on investment. Using the quantitative model, I show that this estimate is a useful "portable moment" (Nakamura and Steinsson, 2018*b*) that can be used to discipline and discriminate between competing theoretical models. In particular, when combined with recent estimates of the investment response to tax policy, I show that my estimates provide evidence in favor of models where external financing constraints reduce the investment response to interest rates, as opposed to models with strong real adjustment costs.

1.1 Literature Review

My research is related to three main strands of the literature. In public finance and macroeconomics, a substantial literature has focused on understanding the nature of firms' investment decisions (Hayashi, 1982; Shapiro, Blanchard and Lovell, 1986; Caballero, 1994; Cummins et al., 1994; Caballero, Engel and Haltiwanger, 1995; Chirinko, Fazzari and Meyer, 1999; Hassett and Glenn Hubbard, 2002; House and Shapiro, 2008; Zwick and Mahon, 2017). I add to this literature by deriving a new quasi-experimental estimate of the investment response to changes in the cost of capital from interest rate shocks. I also show that external financing constraints can provide a realistic alternative to real adjustment costs in reducing the large investment elasticities from interest rate changes implied by frictionless models while remaining consistent with other features of the data.

A second body of literature has studied the transmission of monetary policy through firms, which has largely focused on how credit constraints or the firm lifecycle affect the investment response to changes in interest rates (Gertler and Gilchrist, 1994; Jeenas, 2019; Ottonello and Winberry, 2020; Bahaj et al., 2020; Cloyne et al., 2020; Caggese and Pérez-Orive, 2021; Döttling and Ratnovski, 2020; Jeenas and Lagos, 2021; Fang, 2021; Gnewuch and Zhang, 2022). Relative to this work, this project provides a direct estimate of the neoclassical investment elasticity implied by theoretical models. Krusell, Thürwächter and Weiss (2023) and Cao et al. (2024) both use time-series style identification and microdata to estimate the response of interest rates to investment. In contrast, my differences-in-differences strategy provides additional power by combining cross-sectional variation with high-frequency monetary shocks. My identification strategy also directly identifies the effect of changes in the cost of capital, separating those forces from other general equilibrium factors. I also show that a particular type of financial friction, an external financing constraint, can help explain both the lower investment elasticities estimated in this project and the higher elasticities estimated from changes in tax policy.

Two recent papers document sectoral heterogeneity in investment response to interest rates (Howes, 2023; Durante, Ferrando and Vermeulen, 2022). In contrast, this project includes sector-time fixed effects and thus carefully controls for these sectoral differences, and instead looks at differences within sectors in the durability of the investment goods used by each industry in production. Koby and Wolf (2020) combines theoretical models with quasi-experimental results from the literature on bonus depreciation policies to make broader inferences about aggregate and firm-level investment behavior. In contrast, I use similar identifying variation to directly estimate the effects of monetary policy on firms while carefully accounting for the impact of bonus depreciation.

Finally, my work is contributes to the literature on the monetary transmission mechanism (Christiano, Eichenbaum and Evans, 2005; Smets and Wouters, 2007; Kaplan, Moll and Violante, 2018; Auclert, Rognlie and Straub, 2020). I provide new empirical evidence on monetary transmission through investment. In addition, I provide a new portable empirical target that can be used to discipline business-cycle models. Kaplan, Moll and Violante (2018) and Auclert, Rognlie and Straub (2020) emphasize how estimates of the MPC can be used to discipline the consumption response to monetary policy. In this paper, I show how my estimate of the interest rate elasticity can be used to discipline the investment response to monetary policy.

The rest of the paper is organized as follows. Section 2 uses a standard model of investment to provide intuition for the identification strategy and explicitly derives the estimator used in this paper. Section 3 presents the main data sources used in the paper. Section 4 presents the baseline investment results. Sections 5 and 6 develop the New-Keynesian model with heterogeneous firms and show that the empirical results from Section 4 can be used to discriminate between modern, quantitative models featuring different firm-level frictions. In Section 7, I return to the data and provide evidence of heterogeneous responses that validates the core mechanism from the quantitative model. Finally, Section 8 concludes.

2 The Interest Rate Elasticity in a Neoclassical Model

In this section, I present a neoclassical model of firm investment to highlight how investment responds to changes in interest rates and derive a new empirical estimator of the interest rate elasticity of investment. This model highlights a core feature of all neoclassical models of capital accumulation: the durability of capital makes firms' investment choices very sensitive to changes in interest rates. I begin with a one-factor model, where firms produce using capital and are subject to heterogeneous idiosyncratic productivity shocks ($z_{f,t}$). Firms also differ in the rate at which their capital depreciates (δ_f). Firms choose their capital in each period to maximize a discounted stream of dividends:

$$\max_{k_t} \sum_t (\Pi_{s=1}^t (1+R_s+\Theta))^{-1}(z_{f,t}K_{t-1}^{\alpha} - I_t - \psi(K_{t-1},K))$$

Here, the firm's production function takes as its inputs the firm's idiosyncratic productivity and last period's capital.[3] The firm's remitted dividends are then equal to the value of the firm's production, minus its investment choice and any adjustment costs the firm pays. The firm's budget constraint is: $K_t = I_t + (1-\delta_f)K_{t-1}$. Finally, Θ represents a *discount-rate wedge*, which measures the additional return firms require to make the owner indifferent between allocating a marginal dollar to real investment and earning the safe, one-period interest rate (R). This captures the fact that corporate investment is risky, and firms report discounting cash flows at rates that are higher than the safe interest rate (Gormsen and Huber, 2023). Assume the adjustment cost function is differentiable, then the Euler equation that characterizes the firm's choice of capital each period is given by:

$$1+\psi_{K_t}(K_{t-1},K_t) = \frac{1}{1+R_{t+1}+\Theta}(\alpha z_{f,t+1}K_t^{\alpha-1} + (1-\delta_f) - \psi_{K_{t-1}}(K_t,K_{t+1})) \tag{1}$$

Equation 1 states that the firm invests until the marginal costs of additional capital are equal to the marginal benefits. The left-hand side of Equation 1 represents the marginal costs of purchasing an extra unit of capital: the price of capital plus the marginal adjustment cost for installing that capital. The right-hand side of Equation 1 represents the marginal benefits of additional capital: the marginal product of capital from production in period $t+1$, plus the extra value to the firm of the non-depreciated capital stock,[4] and the reduction in future adjustment costs the firm pays from investing today. These benefits are then discounted using the firm's discount rate: $R_{t+1}+\Theta$.

Equation 1 provides intuition for how depreciation rates affect a firm's investment decisions. Firms with more durable capital retain more of the value of that capital after it is used for production. In models where firms can resell that capital to the market, that value is captured by the capital's price.[5] However, even in models where firms cannot resell capital, the durability of capital gives firms strong incentives to respond to transitory interest rate changes because durability allows firms to retime investment from periods when R is relatively high towards

[3] Thus, the model implicitly includes a "time-to-build" friction.

[4] In this model, this is equal to capital's resale value.

[5] Here, the price of capital is normalized to 1, the price of the final good.

periods when R is relatively low, and thus to periods where firms are more patient.

How strongly should firms react to a change in interest rates? Consider a simplified version of the model without adjustment costs. Then, the firm's first-order condition for capital is given by:

$$\alpha z_{f,t+1} K_t^{\alpha-1} = R_{t+1} + \delta_f + \Theta = \mu_{f,t} \tag{2}$$

This is the well-known expression that the firm invests until the marginal product of capital is equal to $\mu_{f,t}$, the *user cost of capital* (Hall and Jorgenson, 1967). In this variant of the model, the extent to which capital responds to changes in interest rates is given by the following expression, where $\Psi = \frac{1}{\alpha-1}$

$$\frac{\partial K_t / K_t}{\partial R_{t+1}} = \frac{\Psi}{\delta_f + R_{t+1} + \Theta} \tag{3}$$

The strength of the investment response to changes in real interest rates is determined by Ψ, which is the user cost elasticity of investment. In this model, Ψ is driven by the curvature of the firm's revenue function.[6] In a standard parameterization (Winberry, 2021), which excludes a discount-rate wedge and has $\alpha = 0.7, R_{t+1} = 0.04$, and $\delta = 0.10$, capital is very responsive to changes in interest rates: in response to a 1 percentage point increase in the annualized interest rate, the capital stock will fall by more than 20%. It is also clear from Equation 3 that the change in capital in response to any given interest rate shock is decreasing in the firm's depreciation rate.

Equation 3 highlights that in models without adjustment costs, the critical parameter governing the investment response to interest rate changes is the user cost elasticity. Equation 3 also shows that the investment response to interest rates will differ with the firm's rate of economic depreciation. I can now derive the estimator in this paper by showing that comparing the investment response for firms with different depreciation rates can directly identify Ψ and thus the interest rate elasticity. Consider two firms, one with a relatively low rate of economic depreciation ($f = l$) and one with a higher rate of economic depreciation ($f = h$). Taking log differences of the first-order conditions for capital across firms and across the period before and after a change in interest rates leads to the following regression specification:

$$\Delta \log(k_{l,t}) - \Delta \log(k_{h,t}) = \Psi\{\Delta \log(\mu_{l,t}) - \Delta \log(\mu_{h,t})\} - \Psi\{\Delta \log(z_{l,t+1}) - \Delta \log(z_{h,t+1})\} \tag{4}$$

Equation 4 specifies that comparing differences in net investment after an interest rate

[6]This can be microfounded either through decreasing returns to scale or through the firm's demand elasticity.

shock for firms with different depreciation rates identifies the interest rate elasticity. This regression equation was derived abstracting from adjustment costs. In Appendix D, I derive a very similar estimator in the presence of adjustment costs under a set of standard assumptions that capital is durable and the interest rate shock is sufficiently temporary.[7] Equation 3 states that the curvature of the revenue function determines the total change in the capital stock. The regression equation in Appendix D states that the rate at which firms invest after an interest rate shock is determined by the adjustment costs. In reality, the timing and magnitude of the response are likely determined by both parameters, as well as other frictions faced by firms. In Section 6, I bring the estimated impulse response to a structural model where all of these forces together determine the magnitude and the timing of the response.

In practice, I estimate a variant of Equation 4 to maintain comparability with previous work. However, rather than putting the period-by-period log change in the user cost on the right-hand side, I estimate the differential response of net investment to an identified monetary shock and then rescale that difference to determine the user cost elasticity. This flexibly allows for a dynamic response where changes in the capital stock do not have to exactly coincide with the dynamics of the changes in interest rates. This also ensures that the interest rate changes are unanticipated. As a result, the response to interest rate shocks will not be attenutated by forward-looking firms responding to expectations of changing interest rates.

Equation 4 also clarifies the identification assumptions underlying the differences-in-differences empirical strategy. If changes in productivity are unobserved, then they will enter the error term in the regression. Define $\epsilon_t = \Delta\log(z_{l,t+1}) - \Delta\log(z_{h,t+1})$. Then, the key assumption for identification is:

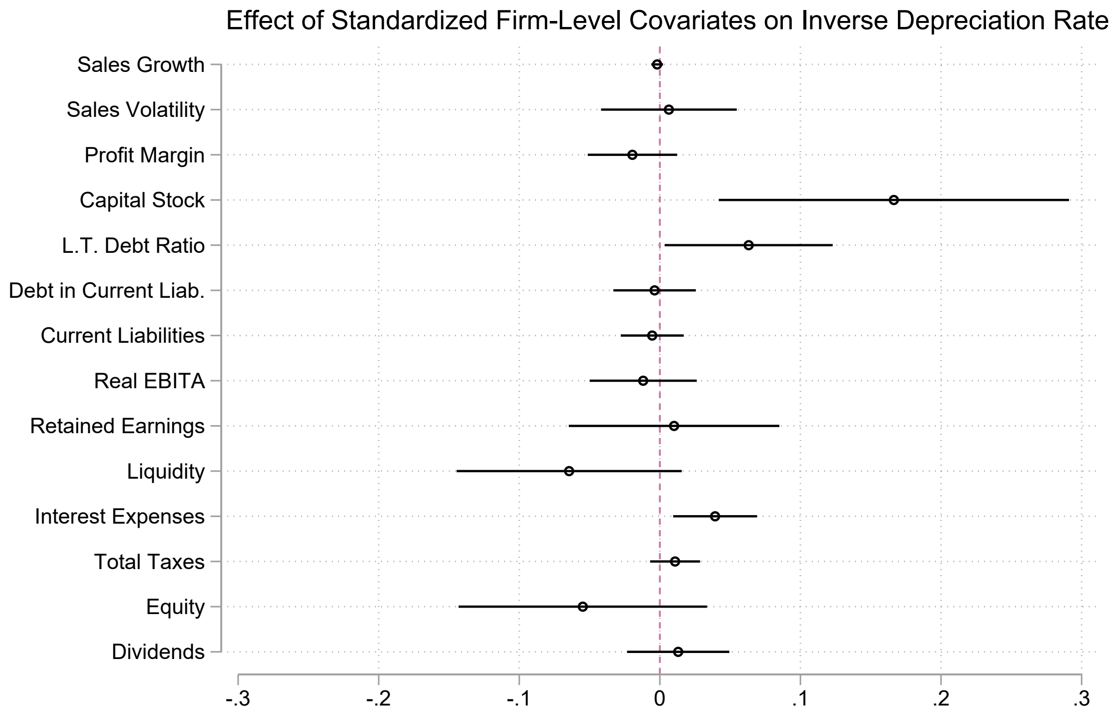
$$E[\epsilon_t\{\Delta\log(\mu_{l,t}) - \Delta\log(\mu_{h,t})\}] = 0 \tag{5}$$

Through the lens of the model, changes in $z_{f,t+1}$ also influence a firm's investment choices. If $z_{f,t+1}$ is unobserved, and changes in $z_{f,t+1}$ are correlated with changes in the user cost, this would lead to biased estimates of Ψ. Because I use high-frequency monetary shocks and differences in depreciation rates to generate changes in the user cost, the identification argument relevant to this project is that, after residualizing on sector-by-year fixed effects, productivity changes, as well as product demand shifts, the responsiveness of firms to Fed information effects, and any other factors that drive investment after monetary shocks are not systematically correlated with depreciation rates.

While this assumption cannot be tested empirically, Figure 1 shows the coefficients from a multivariate regression of time-varying, firm-level characteristics hypothesized to affect in-

[7]These are very similar to the assumptions made in House and Shapiro (2008).

Figure 1: Correlation of Firm-Level Outcomes with Inverse Depreciation Rate



Notes: This figure plots the coefficients of a multivariate regression of standardized, firm-level characteristics on the depreciation rate. 95% error bars are shown, with standard errors two-way clustered at the industry and date levels.

vestment on the economic depreciation rate after residualizing on sector-by-year fixed effects. Nearly all coefficients are near zero and statistically insignificant, implying that underlying firm fundamentals are similar across firms with differing depreciation rates. The one large and statistically significant coefficient is the total size of the capital stock. Firms with lower depreciation rates own more capital. However, this difference provides a validation of the underlying neoclassical theory. Equation 2 states that firms should invest until the point where the marginal product of capital equals the user cost, including the depreciation rate. Taking a derivative with respect to the depreciation rate suggests that, holding all else equal, lower depreciation firms should have more capital.

The second important, non-zero coefficient is the coefficient on the firm's long-term debt ratio. Though only marginally statistically significant, the coefficient implies that lower depreciation firms finance more of their assets with long-term debt, consistent with maturity matching. To investigate whether this affects the interpretation of the main results or sheds light on the underlying mechanisms, in Section 4, I investigate the effect of interest rate shocks on firm debt financing. I also study the investment response to interest rate shocks that affect different parts of the yield curve. As a result, I can test whether the investment response is larger for interest rate shocks that affect longer-term yields, which have more relevance for corporate bond contracts.

Most importantly, this identification assumption is very similar to the identification assumption used in the literature estimating the investment response to bonus depreciation policies in the United States (House and Shapiro, 2008; Zwick and Mahon, 2017; Mark et al., 2021). This literature compares investment among capital goods and firms that are depreciated over longer vs. shorter time periods for tax purposes and which differentially benefit from bonus depreciation policies. In Section 4, I compare the results of my estimation strategy to the estimates from this literature. Because my results rely on a very similar identification strategy, they are directly comparable to these estimates of the tax rate elasticity.

3 Data

I implement my estimation strategy in quarterly firm- and capital-good level data.

Industry-Level Capital Stocks: The primary source of identification in the paper comes from industry-level differences in the type of capital used in production, based on data from the Bureau of Economic Analysis (BEA). The BEA provides data on the fixed-cost net capital stock of private nonresidential fixed assets across various industries and a crosswalk between the BEA industries and the corresponding NAICS industries. In addition, BEA provides implied depreciation rates at the asset type-industry-year level. I use these two data sources to measure average industry-level depreciation, using a weighted average of the implied depreciation rates with the asset type's share in the total capital stock used as the weighting variable. I use data from 1990, four years before the main sample period, to create the industry-level depreciation rate. Appendix Table A1 shows the economic depreciation rate for the highest and lowest depreciation industries after residualizing the depreciation rates on sector fixed effects.

Firm-Level Data: I use quarterly data from Compustat (provided through WRDS) to estimate the effect of monetary policy shocks across industries. The primary outcome variable of interest is net investment: the log change in the firm-level capital stock, which I construct by summing changes in net plant, property, and equipment across quarters. Within each year, I winsorize the value of the dependent variable at the 1% level. I follow standard practice and exclude firms in finance and utilities. Table 1 presents summary statistics of the main firm-level variables.

Table 1: Summary Statistics for the Compustat Sample

	N	Mean	Median	SD	P10	P90
D.Log Capital	263,450	0.00	-0.00	0.08	-0.06	0.07
1-Year D.Log Capital	244,256	0.03	-0.00	0.33	-0.25	0.38
2-Year D.Log Capital	225,724	0.06	0.02	0.50	-0.41	0.62
1-Year Cumulative Capex / L.Capital	242,961	0.36	0.24	0.40	0.06	0.78
2-Year Cumulative Capex / L.Capital	221,938	0.66	0.43	0.77	0.11	1.40
D.Log Cash and Short-Term Assets	259,926	0.02	0.00	0.67	-0.61	0.66
Real Sales Growth	263,554	0.01	0.01	0.22	-0.21	0.23
Real Assets (USD Millions)	263,554	5.36	5.37	2.33	2.34	8.37
Share Current Assets in Total Assets	263,554	-0.03	0.00	1.01	-1.47	1.32

Notes: This table presents summary statistics for the sample of U.S. firms from Compustat.

Monetary-Policy Shocks: To identify the effect of monetary policy, I use replication data from Gürkaynak, Karasoy-Can and Lee (2021) to construct monetary-policy shocks using high-frequency changes in asset prices around monetary-policy announcements. I use the first principal component of the change in the same five asset prices as Gürkaynak, Sack and Swanson (2005) and Nakamura and Steinsson (2018*a*) to measure the policy changes. I sum all the shocks occurring within a quarter to aggregate shocks to the quarterly level. Appendix Figure A1 shows the time series of the high-frequency monetary shocks during my sample period.

Investment-Network Data: To construct measures of exposure to monetary policy through the production of capital, I use data from 1990 on industries that produce investment goods and industry crosswalks from vom Lehn and Winberry (2021).

Capital Prices and Aggregate Quantities: I use data from BEA to measure nominal gross investment and capital prices for 37 investment goods from 1994 to 2017. I also use information from House and Shapiro (2008) and Zwick and Mahon (2017) to construct capital-good-level measures of exposure to bonus depreciation. For analysis using aggregate BEA data, the primary variables of interest are gross investment and prices of capital goods. Table 2 shows summary statistics for the primary variables from the BEA data.

Table 2: Summary Statistics for Aggregate Quantities and Prices of Capital Purchases

	N	Mean	Median	SD	P10	P90
Gross Investment (s.a., ann., USD Mill.)	3,456	28,123.51	18,378.50	29,476.59	4,048.00	73,119.00
Capital Price Index	3,456	0.95	0.86	0.80	0.58	1.02
1-Year D.Log Investment	3,312	0.04	0.05	0.22	-0.19	0.26
1-Year D.Log Prices	3,312	0.01	0.02	0.05	-0.02	0.05

Notes: This table presents summary statistics for capital goods quantities and prices.

4 Empirical Results

4.1 Empirical Strategy

This section presents the baseline empirical results. I test whether lower interest rates lead to higher investment through partial equilibrium changes in the cost of capital. I estimate the following regression using Jordà (2005)-style local projections.

$$\log k_{f,t+h} - \log k_{f,t-1} = \beta_h \epsilon_t \delta_i + \alpha_{f,h} + \alpha_{s\times t,h} + \Gamma' Z + \eta_h z_{i,t} + e_{f,t,h} \tag{6}$$

In this specification, h indexes the forecast horizon, $f \subseteq i \subseteq s$ indexes firms (f) that are part of industries (i) and sectors (s) and t indexes time (in quarters). The primary outcome variable, $\log k_{f,t+h} - \log k_{f,t-1}$ is the winsorized log change in the firm-level capital stock. In this regression, the primary variable of interest is $\epsilon_t \delta_i$, which represents (standardized) industry-level depreciation rate interacted with ϵ_t, high-frequency monetary policy shocks.

The primary coefficients of interest are β_h, which represent the estimated differential impulse response of capital investment in industries with lower vs. higher rates of economic depreciation in response to monetary policy shocks. Because the identifying variation is at the time by industry level, I two-way cluster standard errors by industry and date. To rescale the β_h coefficients into user cost and interest rate elasticities that can be compared to theoretical models and the existing empirical literature, I apply Equations 3 and 4, derived using the simplified model without adjustment costs.

The regressions include $\alpha_{f,h}$, firm fixed effects, and $\alpha_{s\times t,h}$ sector-by-time fixed effects. Thus, identification of the relative effects of monetary policy shocks comes from variation within a sector, and results are not driven by differential response of particular sectors (e.g. durable manufacturing, nondurable manufacturing, construction) to monetary policy. $Z_{f,t-1}$ is a vector of controls, including variation in firm-level financial constraints, proxied by the leverage ratio, and the interaction of the leverage ratio with the monetary policy shock (Ottonello and

Winberry, 2020).[8]

Other controls include firm-level (lagged) sales, assets, current assets, and a dummy indicating if the firm is in its fourth fiscal quarter, given the investment spikes in the fourth fiscal quarter documented by Xu and Zwick (2021). Finally, I include an interaction of the monetary policy shock with an indicator for whether a firm is in an industry that produces capital goods (vom Lehn and Winberry, 2021). This captures whether interest rates stimulate investment in companies that produce capital goods, such as machinery-manufacturing firms.

Given the tight link between the interest rate and bonus depreciation elasticity, a potential confound is that the results are driven by bonus depreciation rather than monetary policy. I address this concern in two ways: first, in both regressions, I only use shocks to monetary policy that can be identified through high-frequency variation, which should be orthogonal to bonus depreciation policies. Indeed, during the primary sample, the correlation between the quarterly monetary policy shock and the generosity of bonus depreciation is 0.04. Second, in all regressions, I include $z_{i,t}$: the Zwick and Mahon (2017) measure of bonus-depreciation generosity, which varies at the 4-digit NAICS industry by quarter level.[9]

Finally, I use the unemployment rate to identify periods when the economy is in an expansion or contraction and interact both measures with the industry-level depreciation rate. Though the high-frequency identification should mitigate any concern about the correlation between monetary policy and the business cycle biasing the results, this ensures that the results are not driven by cyclical behavior in industries with more- or less-durable capital goods, conditional on sector-time fixed effects.

4.2 The Effect of Monetary Shocks on Interest Rates

First, I show that monetary shocks have a significant effect on interest rates. In neoclassical models, the short-run, one-period interest rate is the relevant interest rate for firms' investment decisions. As a result, I use the 3-month nominal interest rate as the baseline interest rate, to match the quarterly frequency of the data and the quantitative model in Section 6.

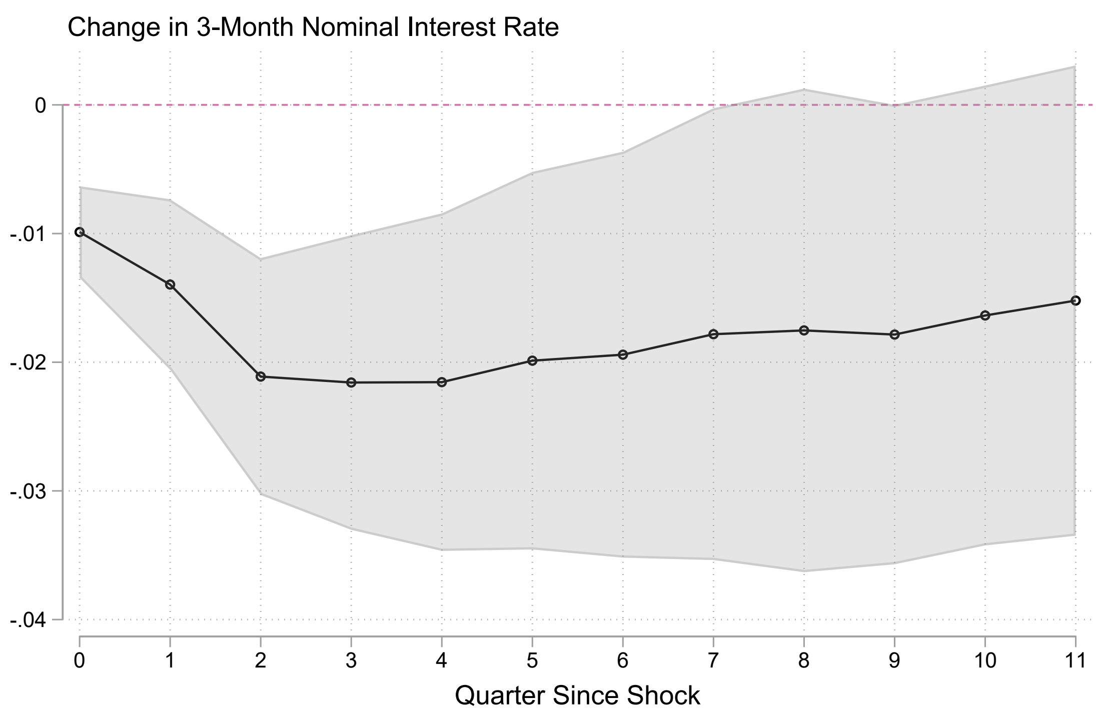
Figure 2 shows the impulse response of nominal three-month rates to a one-unit, expansionary monetary shock. Importantly, because I use movements in futures prices to construct

[8] Allowing for young and middle-aged firms to respond differently to monetary shocks does not affect the results, ensuring that the age and life-cycle effects studied by Cloyne et al. (2020), Gnewuch and Zhang (2022), and Krusell, Thürwächter and Weiss (2023) do not affect the estimates.

[9] Given the tight link between the bonus depreciation and interest rate elasticities, the Zwick and Mahon (2017) measure of industry-level *exposure* to bonus depreciation (z_0) is highly correlated with the rate of economic depreciation. However, because tax depreciation is distinct from economic depreciation and because bonus depreciation generosity is uncorrelated with high-frequency monetary shocks, substantial variation exists to allow for separate identification of the effects of bonus depreciation and interest rate shocks.

the shocks, the shocks contain forward guidance about short-term rates in future quarters. I scale the monetary shock such that a one-unit shock leads to an immediate 1 p.p. fall in the nominal interest rate. Thus, by construction, nominal rates fall by 1 p.p. in the shock quarter. The three-month rate continues to fall until 2 quarters after the shock, when the nominal rate plateaus at approximately 2 p.p. lower than the baseline. The nominal rate then slowly increases to its baseline level, reaching zero around 15 quarters after the shock. Notably, these shocks are much more persistent than conventional Taylor-Rule shocks in most quantitative macro calibrations.

Figure 2: The Effect of Monetary Shocks on Short-Term Interest Rates



Notes: This figure plots the impulse response of 3-month nominal treasury yields to a unit monetary policy shock.

Following the results in Nakamura and Steinsson (2018*a*) that inflation expectations do not respond to these high-frequency monetary shocks, I assume that changes in nominal interest rates pass through one-for-one to real interest rates. In addition, Appendix Table A2 shows no significant effect of monetary shocks on inflation, providing additional evidence of full pass-through to real rates.[10]

[10]Because TIPS were first issued in 1997, and the market was quite illiquid prior to 2000, I cannot directly test the effect of monetary shocks on expected inflation in my full sample period.

4.3 The Effect of Interest Rates on Investment

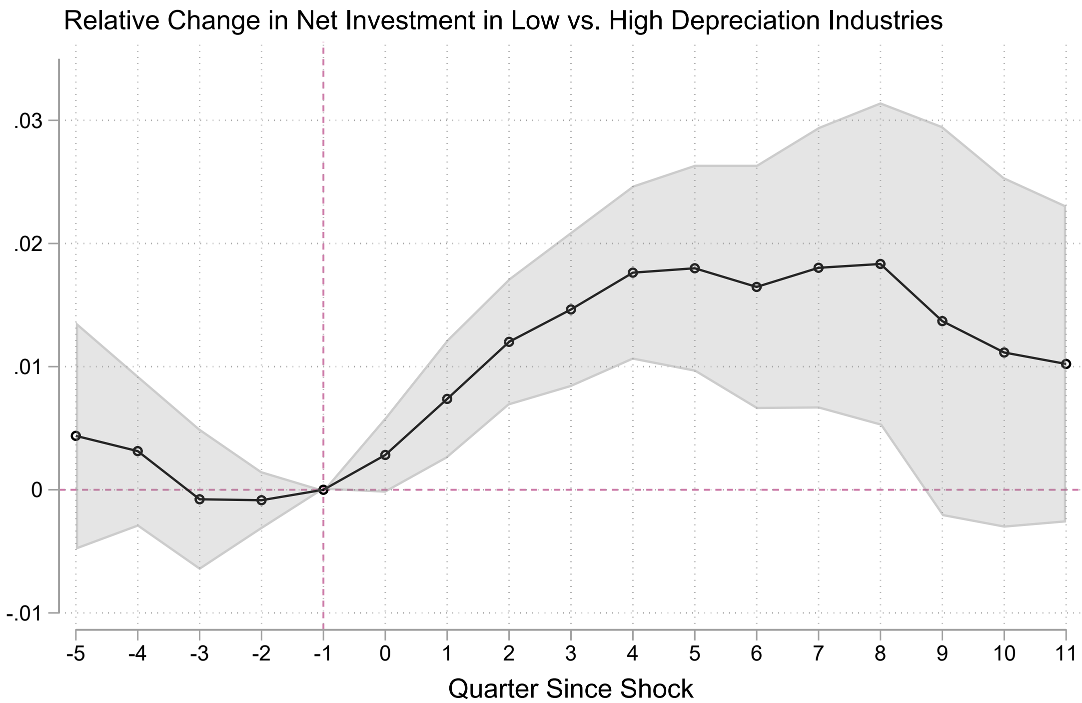
Next, I show that movements in interest rates induced by monetary shocks lead to significant changes in investment. Figure 3 shows the estimated β_h coefficients from Equation 6, which represent the interaction of the monetary policy shock with the industry-level depreciation rate.

Figure 3 shows that after an expansionary monetary policy shock, firms with lower depreciation rates increase investment more than firms with higher depreciation rates, consistent with the theoretical model introduced in Section 2. Before the monetary shock, firms with different depreciation rates have similar trends in investment. The pre-shock coefficients are all close to zero, statistically insignificant, and show no evidence of pre-existing trends. In the quarter of the shock, this flat trend changes sharply: low-depreciation industries start increasing their investment at substantially faster rates than high-depreciation industries. This increasing rate of investment continues until about four quarters after the monetary shock, at which point the coefficients flatten and plateau. The coefficients remain at this level until about nine quarters after the monetary shock, when they begin to decline back towards zero. The coefficients are statistically significant at the 5% level beginning the quarter after the shock and remain statistically significant until more than two years after the shock.

The magnitude of the effect is economically significant: consider a quarter with a unit monetary shock. Four quarters after the shock, the estimates in Figure 2 imply that short-term safe interest rates will have fallen by just over 2 percentage points. In response, the capital stock will be about 1.75 p.p. larger in firms with depreciation rates at the sample mean ($\delta_i = 7.3\%$) relative to a firm with a depreciation rate that is one standard deviation above the mean ($\delta_i = 10.1\%$). Table 1 shows that this increase is substantial relative to average capital growth during the sample period. On average, firms increase their capital by 3 p.p. over four quarters, implying that the effect size is approximately half of the average capital growth rate after a large monetary shock. The effect size peaks two years after the monetary shock. At that horizon, capital is almost 2 p.p. larger for each standard deviation decrease in the depreciation rate. This is around one-third of the mean increase in capital for firms over this horizon.

Overall, I find that monetary policy has significant effects on capital accumulation. This is consistent with a model where a fall in interest rates reduces the cost of capital and leads firms to increase investment spending. The results suggest that the overall effect of monetary policy on investment, including policy changes priced into financial assets outside of the window immediately surrounding Fed announcements, is likely to be economically substantial.

Figure 3: Monetary Policy Shocks Increase Net Investment



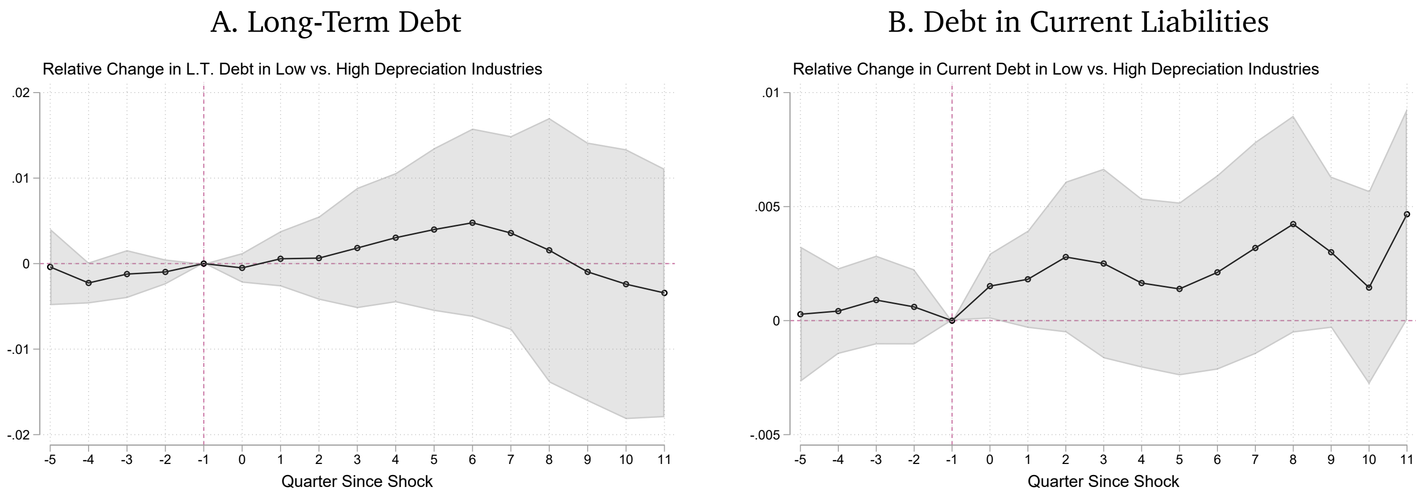
Notes: This figure plots the β_h coefficients from Equation 6. The coefficients represent the Jordà (2005)-style impulse response for the effect of monetary policy shocks on net investment, comparing low vs. high depreciation firms. 95% confidence intervals are plotted, and standard errors are two-way clustered at the industry and date level.

4.4 The Effect of Monetary Shocks on Firm Financing

I next investigate how firms adjust their financing in response to changes in interest rates and higher investment. I reestimate Equation 6, replacing the dependent variable with firm-level financial variables. Figure 4, Panel (A) compares total long-term debt, normalized by lagged assets, for low and high-depreciation industries after a monetary easing. In the quarters after the shock, there is no change in total long-term debt for low-depreciation firms: the coefficients are very close to zero and statistically insignificant. After a year, the coefficients begin to become more positive, but they are always statistically insignificant and quickly return back to zero. I find no evidence that firms in long-duration industries finance their higher investment by accumulating more long-term debt. This suggests that longer-term debt is not the marginal source of financing for firms changing their investment behavior in response to interest rate shocks

Figure 4, Panel (B) shows the same coefficients but with debt in current liabilities as the dependent variable. In contrast to the long-term debt results, the coefficient jumps in the quarter of the shock and is statistically significant. The coefficients remain positive throughout the estimation horizon, but quickly become statistically insignificant. Overall, while I find no evidence that firms finance this investment by issuing more long-term debt, I find suggestive evidence for an immediate increase in shorter-term debt. Appendix Figure A2 shows a significant increase in total liabilities after the monetary shock for low-depreciation firms used to finance their increased investment.

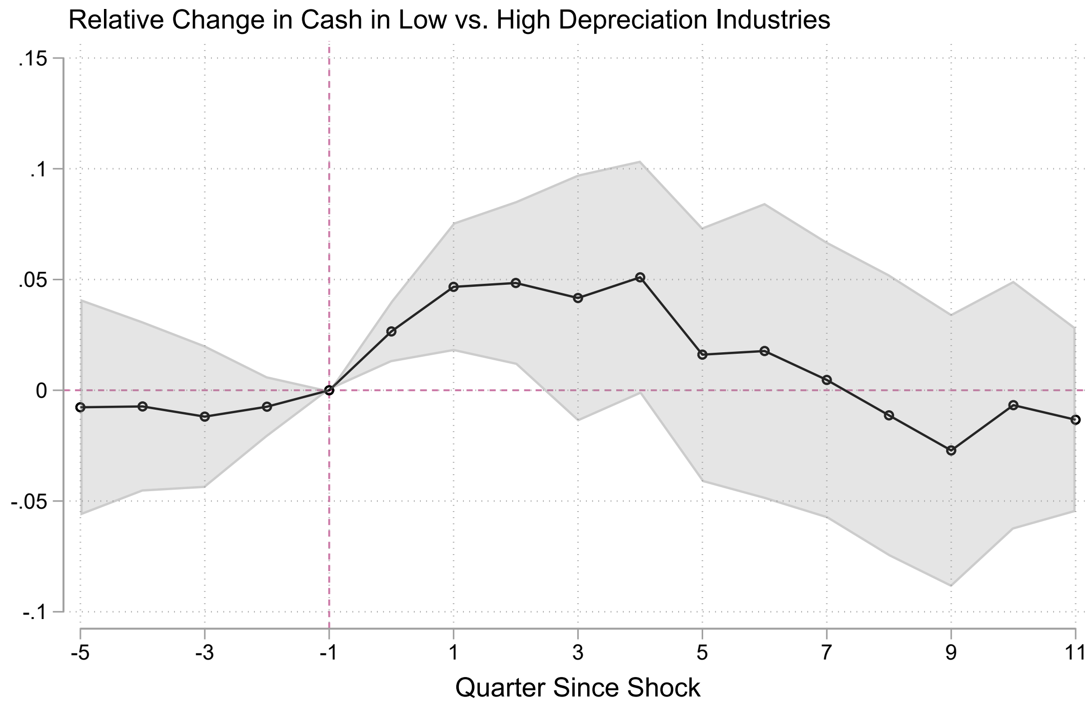
Figure 4: The Effect of Monetary Shocks on Firm Financing



Notes: This figure plots the β_h coefficients from Equation 6. The coefficients represent the Jordà (2005)-style impulse response for the effect of monetary policy shocks on total firm-level debt. Panel (A) shows the effect on long-term debt, normalized by lagged assets, while Panel (B) shows the effect on debt in current liabilities, normalized by lagged assets. 95% confidence intervals are plotted, and standard errors are two-way clustered at the industry and date level.

Figure 5 shows that more responsive, low-depreciation firms also quickly increase their holdings of cash and short-term assets. After the shock, cash and short-term asset holdings increase rapidly for these firms with larger increases in net investment. The relative increase in cash holdings is larger and more accelerated than the increase in investment. The coefficients plateau about two quarters after the shock and begin to decline about a year after the shock, as opposed to more than two years after the shock for net investment spending. In magnitude, firms with a depreciation rate that is one standard deviation lower increase their holdings of cash and short-term investments by around 5 p.p. after an expansionary monetary shock. This is approximately twice the magnitude of the relative increase in net investment. Overall, the financing results suggest firms with more durable capital see increases in total liabilities which they can use to finance investment. There is suggestive evidence of increases in shorter-term debt, which they use to quickly accumulate cash and short-term assets that can then be used to pay for capital goods. However, I find no evidence that these firms finance additional investment by increasing their stock of long-term debt.

Figure 5: Firms Increase Cash Holdings in Response to Changes in Interest Rates



Notes: This figure plots the Jordà (2005)-style impulse response of the effect of monetary policy shocks on firm-level outcomes. The outcome variable is the log change in cash and short-term assets. 95% confidence intervals are plotted, and standard errors are two-way clustered at the industry and date level.

4.5 Which Interest Rates Matter for Investment?

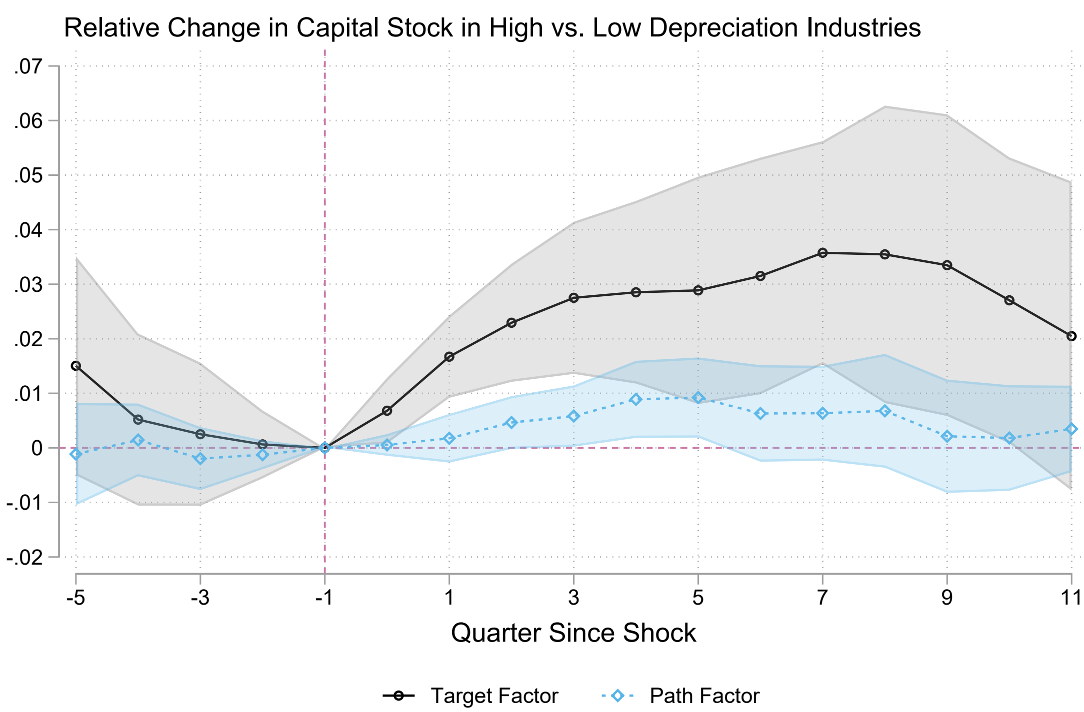
In neoclassical models without adjustment costs, the only interest rate that matters for investment decisions is the short-term, one-period interest rate. In models with more complicated frictions, such as adjustment costs, the whole path of short-term rates affects the magnitude and timing of firm investment (Auerbach and Hassett, 1992). However, in models where the expectation hypothesis does not hold[11] or where firms use longer-term debt to finance investment, long-term rates and changes in risk may affect investment choices. To investigate these potential channels, I follow Gürkaynak, Sack and Swanson (2005) and look separately at the investment response to monetary shocks affecting different interest rates. Gürkaynak,

[11]This would include any model where long-term interest rates are not exclusively determined by expectations about short-term rates.

Sack and Swanson (2005) separate monetary shocks into two components: a "target" factor that corresponds to surprise changes in the current federal funds rate and a "path" factor that contains information about the future path of policy that is orthogonal to the current target. Gürkaynak, Sack and Swanson (2005) show that the path factor contains information about future rates that have large effects on the long end of the yield curve, including the five- and ten-year Treasury yield.

Figure 6 shows the investment response to both the target and path factor. Note that the units of the shock have a different magnitude and interpretation to the baseline estimates. Following Gürkaynak, Sack and Swanson (2005), I scale the target factor so that a 1-unit shock to the target factor corresponds to a 1 p.p. decrease in the Fed Funds Rate target. I then scale the path factor to have the same effect on the 1-year-ahead eurodollar future as the target factor. I then sum all shocks occuring within a quarter.

Figure 6: Response of Investment To Target and Path Factors



Notes: This figure plots the Jordà (2005)-style impulse response of the effect of monetary policy shocks on firm-level outcomes. The outcome variable is the change in net investment. 95% confidence intervals are plotted, and standard errors are two-way clustered at the industry and date level.

Figure 6 shows that the response to the target factor is substantially larger in magnitude than the response to the path factor. The target factor follows the timing of the baseline results, increasing sharply in the quarter of the shock before peaking around 7 quarters after the shock before beginning to return to zero. In contrast, the response to the path factor is small and statistically insignificant, except in a few quarters. The response's magnitude suggests the path factor's peak effect is less than 30% of the maximum response to the target factor. In addition, the response to the path factor is not more persistent than the response to the target factor. The impulse response to the path factor begins to decline faster than the response to the target factor, about 6 quarters after the shock. By 9 quarters after the shock, the coefficients for the path factor are very close to zero and statistically insignificant. These results suggest that the investment response is due to unexpected changes in information about the immediate short rate and path of short rates rather than information about longer-term rates, which might be more relevant for corporate bond financing. Overall, the results from the path factor, as well as the limited response of longer-term debt suggest that the results are driven by changes in short rates, consistent with the primary mechanism in neoclassical models of investment.

4.6 Magnitudes and Comparison to Past Work

Section 2 derives a series of simple formulas to convert the empirical results into an interest rate elasticity that can be compared to previous work and used to discipline quantitative models. Converting the β_h coefficients into user cost and interest rate elasticities requires data on the components of the user cost of capital: $\mu_t = R_t + \delta + \Theta$. I take the average industry-level depreciation rate based on the merged BEA-Compustat sample (approximately 9% per year) as δ and compute R_t as the average, real return on a three-month treasury bill adjusted for inflation (approximately 0% during my sample period).

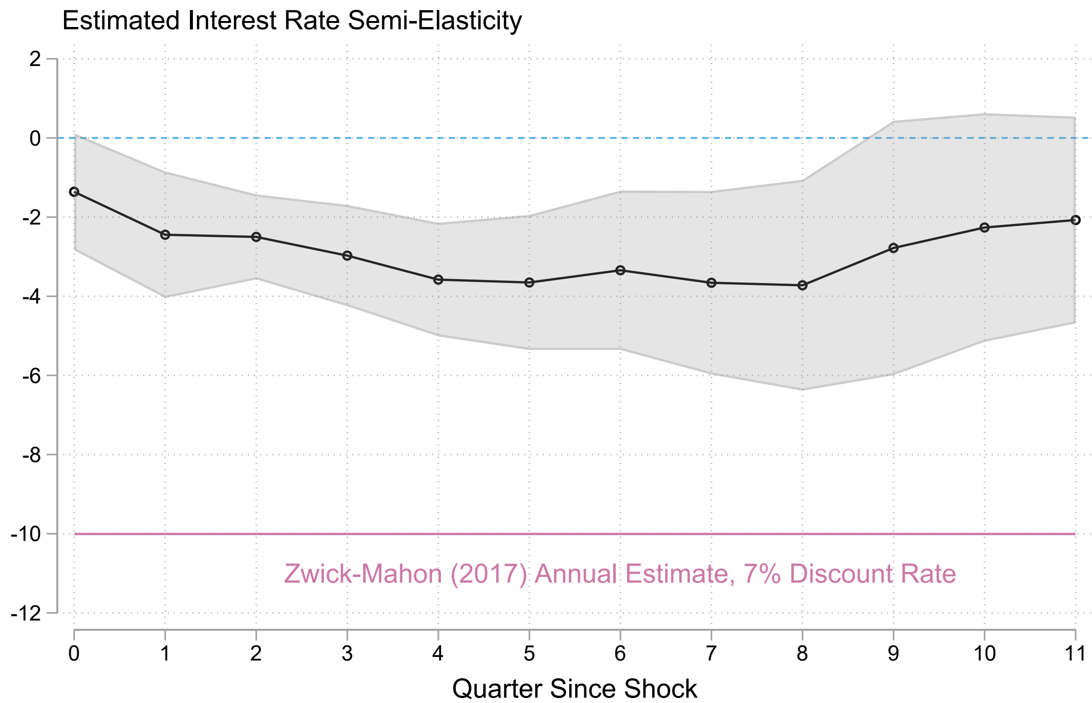
In contrast, Θ, the discount-rate wedge, is unobserved. I follow Zwick and Mahon (2017) in assuming that firms discount cash flows at 7% annually ($R_t + \Theta = 7\%$). I scale the β_h coefficients by the log change in the user cost implied by a one-unit monetary shock.[12]

Figure 7 plots the rescaled coefficients from Figure 3, converted into an interest rate semi-elasticity using Equation 3. Figure 7 shows that the estimates in Figure 3 imply significant partial equilibrium interest rate semi-elasticities. Four quarters after the shock, the estimates imply that a one percentage point decrease in interest rates would increase capital demand by about 3%. After eight quarters, the effect size rises to just under 4%. Overall, these estimates provide a new moment that can be used to discipline models of capital investment.

While there are few other estimates of the partial equilibrium interest rate semi-elasticity es-

[12]This "back of the envelope" calculation provides nearly identical results for the headline user cost and interest rate elasticities as rescaling by the coefficients on a regression of the monetary shock interacted with the depreciation rate on the log change in the user cost (after residualizing on sector-by-quarter fixed effects), where I set Θ so that $R_t + \Theta = 7\%$ on average over the sample period. Appendix Figure A3 plots the coefficients from that impulse response. Appendix Figure A3 shows that, four quarters after a one-unit monetary shock, each standard deviation decrease in the depreciation rate causes the user cost to fall by approximately 3 log points.

Figure 7: Comparing the Estimated Interest Rate Semi-Elasticity to Estimates from Tax Policy



Notes: This figure plots the estimated interest rate semi-elasticities based on the estimates in Figure 3. The graph also features lines indicating the interest rate semi-elasticity derived from Zwick and Mahon (2017).

timated directly from changes in interest rates, the investment response to temporary changes in tax policy can be informative about the response to interest rates. Consider a version of the firm problem from Section 2, which contains features of the corporate tax code. Hall and Jorgenson (1967) show that, without adjustment costs, the tax-adjusted user cost is then given by:

$$\mu_{f,t} = (R_{t+1} + \delta_f + \Theta)\frac{1-\tau\zeta}{1-\tau}$$

Here, τ is the corporate tax rate, and ζ is a parameter that represents the generosity of the tax depreciation system.[13] If $T = \frac{1-\tau\zeta}{1-\tau}$ represents the effect of corporate taxes on the user cost,

[13]As noted in Auerbach and Gale (2021), changes in interest rates may also change the user cost of capital by altering the rate at which firms discount tax depreciation benefits. While this may affect the magnitude of Ψ, I abstract from it in calculating Ψ for three reasons. First, Zwick and Mahon (2017) show that bonus depreciation only stimulates investment because of immediate deductions, rather than by changing the PDV of depreciation deductions. Second, in a calibration that matches the empirical values of the PDV of depreciation deductions from Zwick and Mahon (2017), I find that the "direct effect" of small changes in interest rates on the user cost is almost 11.5x greater than the "indirect effect" coming through changes in the PDV of depreciation deductions. Finally, the changes in the user cost will only be picked up if changes in the PDV of depreciation deductions change

then the response of capital to changes in taxes is analogous to changes in interest rates:

$$\frac{\partial K_t/K_t}{\partial T/T} = \Psi \tag{7}$$

Thus, the response of capital investment to changes in tax rates identifies the same parameter as Equation 4, estimated in this project. This is because in partial equilibrium, both tax rates and monetary policy affect capital investment through their effect on the user cost. I thus compare the estimates from this project to recent estimates from Zwick and Mahon (2017), who estimate the effect of temporary changes in ζ on investment.

The pink line in Figure 7 shows that, while economically significant, the implied semi-elasticities estimated from monetary shocks are much smaller than the corresponding estimates from temporary changes in tax policy.[14] In an annual panel regression, the estimates in Zwick and Mahon (2017) imply an elasticity of approximately -10. This is more than three times larger than the effect of interest rate policy at a one-year horizon. Even combining the total growth in investment over more than two years, the maximum response of investment is less than half of the annual effect of bonus depreciation in Zwick and Mahon (2017), and the Zwick and Mahon (2017) estimate lies well outside the implied elasticity from the upper-bound of the 95% confidence interval in Figure 3.

The results imply that while interest rates have a meaningful effect on investment, they are substantially smaller than the corresponding effect of temporary changes in tax rates. Since monetary and fiscal policy have very different effects on investment behavior, using estimates from tax policy to discipline or extrapolate the interest rate elasticity will likely lead to an over-estimate of the impact of monetary policy on investment. These results also present a puzzle for traditional neoclassical models, which suggest that the exact same parameter determines tax rate elasticities and interest rate elasticities.

4.7 Robustness of Baseline Investment Results

I conduct a number of robustness checks to assess the stability of the baseline results. One significant concern is that this project uses the quarterly Compustat panel, while Zwick and Mahon (2017) use annual IRS data, which includes a broader sample of firms, including small, private firms. Zwick and Mahon (2017) show evidence that smaller firms have larger investment elas-

more for long-duration industries when compared with short-duration industries. In practice, the relationship is unclear ex-ante, and potentially non-linear: in my baseline calibration, the PDV increases more for short-duration industries, which would not be picked up by my empirical strategy and biases me against finding a direct effect.

[14] The estimated user cost elasticity at a one-year horizon is -0.48. The maximum value of the user cost elasticity is eight quarters after the shock, at -0.6. In comparison, the baseline Zwick and Mahon (2017) elasticity is -1.6, which can be found in Table 3, Panel 3, Column 1.

ticities. If these firms are underrepresented in Compustat relative to the IRS panel, it could bias my estimates downward relative to Zwick and Mahon (2017). To address this concern, I estimate the effect of both bonus depreciation and interest rate policy simultaneously in a broader dataset covering investment for the entire U.S. economy at the capital good level. This allows me to compare the effects of tax and monetary policy in the same dataset and time period. I use data on aggregate investment by capital good type from BEA, as well as data from House and Shapiro (2008) and Zwick and Mahon (2017), to create a panel of nominal investment spending combined with data on rates of economic and tax depreciation

I estimate the following regression specification:

$$\log(I_{i,t}) = \beta \epsilon_t \delta_i + \alpha_i + \alpha_{c,t} + \eta \frac{1 - \tau z_{i,t}}{1 - \tau} + e_{i,t} \tag{8}$$

In this specification, $i \subseteq c$ indexes a capital good that is part of an investment good class: $c \in \{\text{structure}, \text{equipment}\}$. The dependent variable is aggregate, gross nominal investment spending for capital good i in time t. The primary coefficient of interest is β, which is the coefficient on the interaction of the monetary policy shock ϵ_t, and the capital good's standardized rate of economic depreciation. The specification also includes α_i, a capital good fixed effect, and $\alpha_{c,t}$ a capital good class by time fixed effect. This estimator thus restricts comparisons to goods that are either equipment or structures but face different economic depreciation rates and, thus, differing investment responses to monetary policy. Finally, $\frac{1-\tau z_{i,t}}{1-\tau}$ is the tax term that estimates the effect of bonus depreciation policies on nominal investment during this time period. Because relatively few capital goods are covered in this quarterly BEA dataset, I cluster standard errors at the time level only.

Table 3 shows the effect of monetary policy and tax policy on investment in the BEA dataset. The bottom row converts the β coefficient into a user cost elasticity that can be directly compared to the tax term elasticity. Reassuringly, the results show that monetary policy has significant effects on investment. The results are insignificant prior to the shock quarter, after which investment is persistently higher for capital goods with lower rates of economic depreciation compared with higher rates of economic depreciation. The results also show a significant effect of bonus depreciation.[15]

However, across all time periods, the effect of bonus depreciation is at least twice as large as that of monetary policy. The tax term elasticities for bonus depreciation are approximately -4, while the corresponding elasticities for monetary policy lie between -1 and -2. After the shock, across all horizons, we can reject that the bonus and monetary policy elasticities are

[15] The fact that the pre-period coefficients are significant for the tax term coefficient likely reflects the fact that bonus depreciation policies are autocorrelated over time, unlike monetary shocks.

Table 3: The Effect of Bonus Depreciation and Monetary Shocks on Gross Investment

	Gross Investment					Cumulative Investment	
	t=-4	t=-2	t=0	t=2	t=4	t=4	t=8
Exposure x Shock	-0.016	0.014	0.039*	0.048**	0.080***	0.056***	0.043**
	(0.025)	(0.021)	(0.020)	(0.022)	(0.027)	(0.020)	(0.020)
Tax Rate UCE	-4.46***	-4.35***	-4.25***	-4.17***	-4.03***	-4.10***	-3.91***
	(0.44)	(0.47)	(0.42)	(0.42)	(0.39)	(0.38)	(0.35)
N	3132	3204	3276	3204	3132	3276	3276
R^2	0.92	0.92	0.92	0.92	0.92	0.93	0.93
Capital FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Date-Class FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Interest Rate UCE	0.38	-0.34	-0.93	-1.15	-1.92	-1.35	-1.04

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Notes: This table shows the effect of interest rate and bonus depreciation shocks in BEA capital goods data. The first row shows the effect on the main coefficient of interest, the depreciation rate interacted with the monetary policy shock. The second row shows the effect on the tax term user cost elasticity. The bottom row converts the monetary shock interaction term into an interest rate user cost elasticity that can be compared to the tax term user cost elasticity. The first five columns show the effect of the shocks on gross investment (in logs) at different horizons. The last two columns show the effect on cumulated gross investment (in logs) at two different horizons. Standard errors clustered by time in parentheses.

equal with $p < 0.01$. This bolsters the baseline results, which found interest rate elasticities that were between one-quarter and one-half as large as tax rate elasticities. Overall, the BEA data provide additional evidence that monetary policy has significant effects on investment and that tax policy has substantially larger effects than monetary policy.

Appendix Tables A3 and A4 also show limited heterogeneity in the investment response by firm size. Zwick and Mahon (2017) show in both IRS data and Compustat that the large response of smaller firms is responsible for the substantial tax rate elasticities. I first split each firm-quarter observation into quintiles based on one year of lagged sales after residualizing on industry and date fixed effects. I then estimate a flexible specification allowing heterogeneous interest rate elasticities by the firm-size quintiles. Appendix Table A3 shows that all interaction terms are statistically insignificant, indicating limited heterogeneity by firm size. In addition, the coefficients do not move monotonically with firm size.

The specification in Appendix Table A4 more closely follows the methodology in Zwick and Mahon (2017) and splits the sample into small and large firms based on their average, residualized sales over the entire sample. At both the one- and two-year horizon, the coefficient for large firms is bigger than for small firms. Overall, I find limited evidence of significant heterogeneity by firm size, implying that differences in the sample of firms is unlikely to drive differences in tax and interest rate elasticities. If anything, the results from Appendix Table A4 suggest that reweighting the estimates from monetary shocks to match the sample in Zwick and Mahon (2017) would lead to even smaller interest rate responses, and wider discrepancies between the tax rate and interest rate elasticities.

Appendix Table A5 tests whether the larger investment response for low depreciation firms translates into higher prices for capital goods. This would be consistent with upward-sloping capital supply curves functioning as an external adjustment cost offsetting lower interest rates.[16] To test this, I reestimate Equation 8, but use the log nominal price of each good as the dependent variable. Appendix Table A5 shows no significant effect of monetary shocks on the prices of capital goods at any horizon. The results suggest that monetary shocks do not increase prices, implying that external adjustment costs are not significant factors affecting the responsiveness of investment.

Appendix C shows additional results that confirm the robustness of the baseline estimates. Appendix Figure A6 re-estimates the baseline specification, using cumulated capital expenditures normalized by the lagged capital stock as the dependent variable. Despite using a completely different variable for investment, the results are quantitatively very similar and statistically significant. Appendix Figure A7 also shows the coefficients are essentially unchanged when weighting by the lagged capital stock.

Appendix Figures A8, A9, and A10 show that the baseline results are not sensitive to the choice of controls used in estimating the impulse response. The results are qualitatively unchanged when dropping the baseline controls, allowing for more flexible interactions between the baseline controls, or adding additional controls for firm size or estimates of investment irreversibility interacted with the monetary shock (Kermani and Ma, 2022).[17] Appendix Figure A11 also shows that the results are robust to excluding periods with significant changes to other policies that might differentially affect industries with different types of capital goods. Appendix Figure A11, Panel (A) shows robustness to dropping periods around significant announcements related to Bonus Depreciation. Appendix Figure A11, Panel (B) shows that quantitative easing does not confound the baseline estimates (Hubert de Fraisse, 2023). Finally, Appendix Figures A12 and A13 show that the baseline results are minimally affected by changes in risk that might occur due to Fed announcements. The results are similar when allowing the response of investment to changes in the term premia to vary with the depreciation rate, or for flexible interactions of monetary shocks with firm-level beta. Overall, the robustness tests confirm the

[16]External adjustment costs in the form of upward-sloping capital supply curves are common features of macroeconomic models (Ottonello and Winberry, 2020) and underly other important macroeconomic channels, including the financial accelerator channel (Bernanke, Gertler and Gilchrist, 1999).

[17]Note that not all industries have sufficient data on recovery rates, and thus the specification with the recovery rate control includes fewer observations.

baseline finding that interest rates have a significant effect on firm-level investment, but the magnitude of the response is significantly smaller than the response to changes in tax rates.

5 Model

Empirically, this paper provides a new estimate of the interest rate elasticity of investment and shows that it is substantially smaller than the elasticity of investment to changes in corporate taxes. This poses a challenge for standard neoclassical models, where the same parameter governs the response to both types of policies. In this section, I build a quantitative model of capital investment with heterogeneous firms to highlight how the empirical estimates from this paper can be used as moments to discipline quantitative magnitudes and adjudicate between different macroeconomic models. The model builds closely on the heterogeneous firm blocks of Ottonello and Winberry (2020), Fang (2021), and Koby and Wolf (2020), but augments these models by including a corporate tax system that allows me to study the effects of both monetary and tax policy.

The model is a dynamic extension of the model presented in Section 2, but includes a second factor of production, a corporate tax code, and more flexible financial frictions and adjustment costs. A fixed mass of firms indexed by the unit interval produces a homogeneous good using a decreasing returns to scale production technology. Firms vary both in their idiosyncratic productivity and in the rate of capital depreciation. Firms have idiosyncratic productivity draws (z), which follow an AR(1) process. In addition, firms draw a constant depreciation rate (δ), which is taken as given. Thus, the model is designed to match the assumption underlying the empirical strategy: firms are endowed with a production process based on their industry, which determines the nature of the capital they use in production.

Firms face an infinite horizon and solve a capital accumulation problem. Because I find empirically that firms do not use debt financing to increase investment spending after monetary shocks, I do not allow firms to use debt to fund investment. However, in the baseline model, firms can pay out negative dividends to fund higher investment (equity issuance). As a result, the firm's state variables are its productivity, capital stock, and depreciation rate. In each period, the firm takes its productivity as given, chooses its capital stock, hires labor in a spot market, and then produces. Firms maximize a stream of (net-of-tax) dividends discounted by the interest rate. Formally, the firm problem is:

$$\begin{aligned} V_t(k,z,\delta) = \max_{k',n} & \, p_t f(k,z,n_{f,t}) - w_t n - q_t * (k' - (1-\delta) * k) \\ & - \mathrm{AC}(k',k,I_{f,t}) - T(\pi,\tau_t,\theta_t) + \mathbb{E}_t[\frac{1}{1+r_t} V_{t+1}(z,k',\delta)] \end{aligned} \tag{9}$$

where $\text{AC}(k', k, I_{f,t})$ is a capital adjustment cost and $\frac{1}{1+r_t}$ is the firm's discount factor, q_t is the price of capital, and p_t is the price of the goods produced by the heterogeneous firm. I assume firms produce according to the following production function:

$$f(k,z,n) = e^z k^\alpha n^\nu$$

T is a function that captures the flow of corporate taxes owed by the firm in each period. The firm's corporate tax bill is a function of two potentially time-varying parameters: the corporate tax rate τ_t and a parameter θ_t, which captures the generosity of tax depreciation. Modeling a realistic tax depreciation system requires keeping track of the tax benefits owed to firms by the government in future periods, which are a function of investment choices made in past years. This would require many state variables representing the investment choices made by firms in prior periods. Traditionally, researchers have used the fact that since previous investment decisions are sunk, they should not influence current investment choices that firms make beyond their effect on the current capital stock (Winberry, 2021; Chen et al., 2022).[18] However, in the presence of external-financing constraints, this is no longer true because the timing of payments affects whether and how quickly firms hit their financial constraint. As a result, I study a stylized form of bonus depreciation, where firms are either not entitled to depreciate their capital investments for tax purposes ($\theta_t = 0$) or can fully expense their investment up until the point at which they have zero taxable income ($\theta_t = 1$).

The empirical estimator in Section 4 includes sector-by-time fixed effects, thus differencing out general equilibrium factors that affect all firms. Thus, I initially solve the model in partial equilibrium and match the empirical response of investment to shocks estimated in this paper and Zwick and Mahon (2017). Appendix F shows how to insert the heterogeneous firm problem in a full, general equilibrium New Keynesian model.

Taking initial prices $\{p_t, w_t, q_t\}$, policy parameters $\{r_t, \tau_t, \theta_t\}$, and an initial firm-size distribution $\mu_0(k,z,\delta)$ as given, an equilibrium of the model is a set of value functions $V_t(k,z,\delta)$, policy functions $k_t(z,k,\delta)$, and a firm-size distribution $\mu(k,z,\delta)$, such that all firms optimize and the distribution of firms is consistent with the decision rules. I then introduce temporary shocks to fiscal and monetary policy parameters in the model to study investment dynamics in response to monetary and fiscal policy shocks, while holding fixed other prices ($\{p_t, w_t, q_t\}$). I study the response of investment and other firm-level variables to these shocks and the transition back to steady state.

To study monetary policy, I solve for the transition path after a series of shocks to the real interest rate r_t that matches the path of nominal interest rates estimated in Figure 2. To study

[18]Both Winberry (2021) and Chen et al. (2022) provide formal proofs of this argument.

bonus depreciation, I solve for the transition path after a policy change realized at time zero, where the expensing parameter θ_t changes from zero to one. I assume this change lasts for 8 quarters. For both shocks, I assume all agents have exact knowledge of the sequence of shocks when the first shock is realized. As a result, I study a perfect-foresight transition path back to the steady state, solving the model using the methodology described in Boppart, Krusell and Mitman (2018). As a result, the transition path in my model is fully nonlinear.

6 Quantitative Results

In this section, I bring the empirical estimates of the investment response to interest rates from Section 4 to the model. I consider two distinct types of models with frictions that can be calibrated to match the empirical impulse response of investment. First, I consider a model with adjustment costs, calibrating the strength of the adjustment costs to match the investment response. Then, I consider a model without any adjustment costs, but including a particular type of financial friction: a dividend constraint. In practice, this limits the amount of equity the firm can issue each period, thus requiring the firm to finance their investment out of their existing cash flows.

6.1 Calibration

Table 4 shows the externally calibrated parameters that remain consistent across all calibrations of the model. The model is at the quarterly frequency. I set the discount factor $\beta = 0.994$ to match the low real interest rates during the period. This also implies that the monetary shock temporarily brings the interest rate to the zero lower bound. The coefficients on capital (α) and labor (ν) in the production function are equal to 0.28 and 0.57, respectively. This matches a 33% capital share and a decreasing returns to scale parameter of approximately 0.85. I set the persistence and dispersion of the idiosyncratic TFP process to match the estimates in Winberry (2021).

The baseline model has two possible depreciation rates equal to 1.7% or 3% per quarter. Finally, the baseline corporate tax rate is $\tau = 0.04$ and the baseline expensing parameter is $\theta = 0$. While the corporate tax rate during this period is much higher than 4%, in practice, this matches the approximate distortion from the corporate tax system in terms of the cost of capital during this sample period.[19] This also ensures that the tax policy shock I consider matches the magnitude of the tax rate change experienced during actual periods of bonus depreciation.

[19]Equation 7 shows how corporate taxes affect the cost of capital.

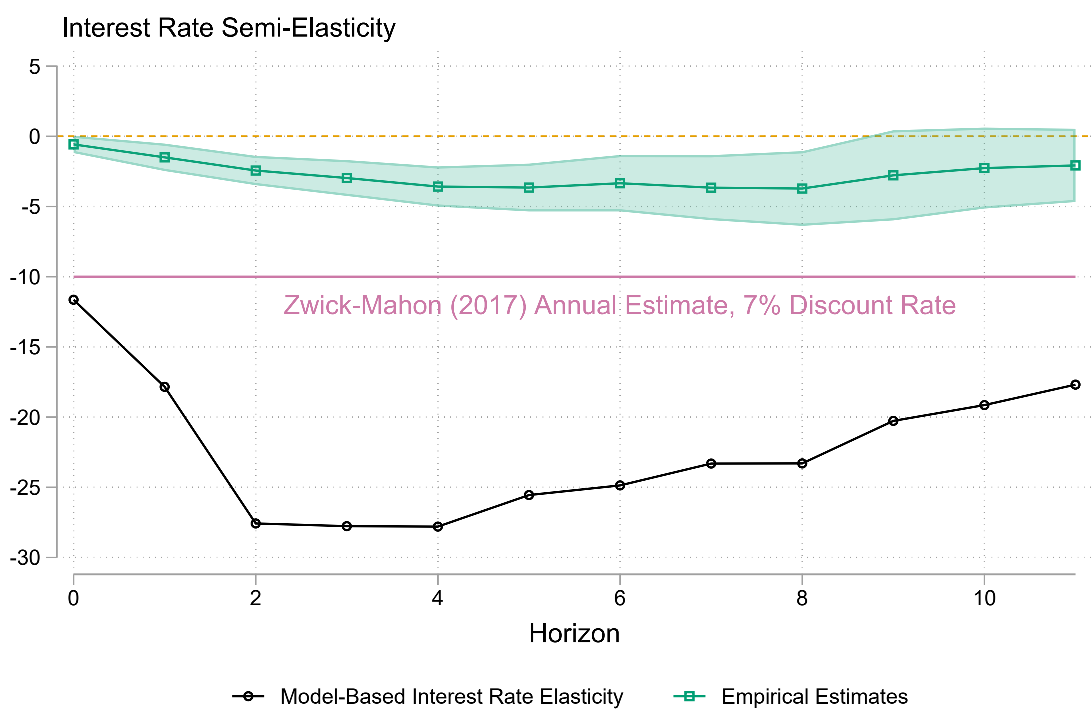
Table 4: Externally Calibrated Parameters

Parameter	Description	Value	Source
β	Discount Factor	0.994	Data
ν	Labor Coefficient	0.57	Labor Share
α	Capital Coefficient	0.28	Capital Share
ρ	Persistence of TFP	0.9	Winberry (2021)
σ_j	S.D. of TFP Innovations	0.053	Winberry (2021)
τ	Baseline Corp. Tax Rate	0.04	U.S. Corp. Tax Distortion
θ	Baseline Expensing Parameter	0	U.S. Corp. Tax Distortion

6.2 The Effect of Interest Rate Shocks in a Quantitative Model

First, I investigate how investment responds to interest rate shocks in the quantitative model. I mimic the estimate from the data in the model by taking the average investment response to a monetary policy shock across firms with different depreciation rates. I then rescale the investment response using Equations 3 and 4, just as I do in the data.

Figure 8: The Effect of an Interest Rate Shock in a Frictionless Model



Notes: This figure plots the model-based interest rate elasticity after a monetary shock in black. The line in gray shows the effect of bonus depreciation converted into an interest rate elasticity using the derivation in Section 2. The green line and shading show the empirical estimates from this paper.

First, Figure 8 confirms that frictionless models, without adjustment costs or financial frictions, generate investment responses that are too large relative to the empirical estimates. The black line shows the estimated interest rate semi-elasticities from the frictionless model. The model-implied estimates suggest that one year after the shock, a 1 p.p. fall in the interest rate would increase the capital stock by around 28%. This is nearly 3 times larger than the baseline parameterization from Zwick and Mahon (2017), and almost an order of magnitude larger than the estimates from Section 4. These results confirm that frictionless models cannot generate realistic investment elasticities and that partial equilibrium estimates can be used to discipline the magnitudes in quantitative models (Winberry, 2021; Koby and Wolf, 2020).

Next, I calibrate two types of models to the empirical estimates from the paper. I first consider the model with adjustment costs. I include both fixed and convex adjustment costs, which have both been argued to be crucial in determining investment dynamics. I adopt the following specification for the adjustment costs.

$$AC(k', k, I_{f,t}) = \frac{\eta}{2}(\frac{k'-k}{k})^2 k + \zeta \mathbb{1}\{I_{f,t} \neq 0\} w_t$$

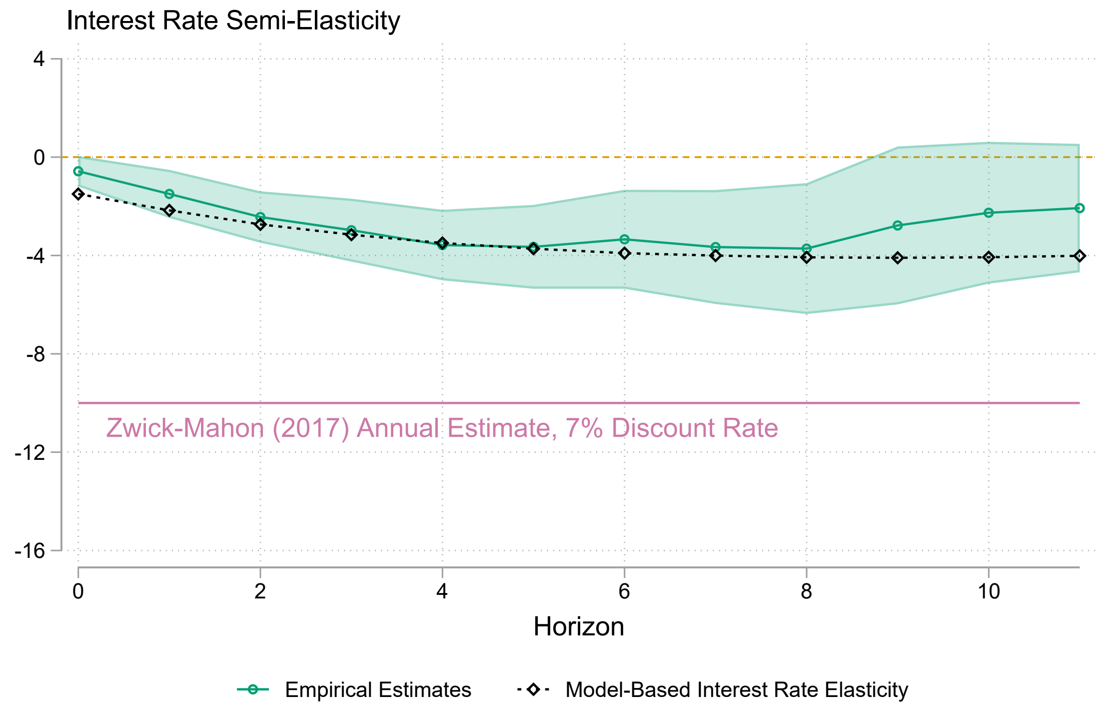
In this formulation, the parameter η determines the strength of the convex adjustment costs and ζ is a uniform random variable that parameterizes the strength of the fixed cost. Winberry (2021) calibrates fixed adjustment costs to microdata on investment spikes in the United States. I follow Winberry (2021) and set the maximum value of ζ to be 0.703. I allow for maintenance investment by allowing firms to invest up to 1% of the capital stock each quarter without paying the fixed cost. In addition, I have the convex adjustment cost scale with the firm's capital stock relative to the average, steady-state capital stock in the firm's industry. This implies that adjustment costs are similar across industries, even if firms in one industry have larger capital stocks. This is required because the model generates very different steady-state capital levels across industries due to the persistent differences in depreciation rates. Though I find that capital stocks are slightly larger in low-depreciation industries, Appendix Figure A5 shows that the data strongly rejects the heterogeneity implied by the model. As a result, higher adjustment costs in low depreciation industries are not a plausible mechanism for explaining the results.[20]

Figure 9 shows the fit from the adjustment costs model when the magnitude of the convex cost is picked to match the empirical interest rate semi-elasticity. Figure 9 shows that the model-based interest rate elasticity of investment closely matches the interest rate elasticity estimated from the data.

Table 5 shows that matching the empirical interest rate elasticity requires very strong con-

[20]Higher adjustment costs by industry would also imply a less dispersed firm-size distribution. This implication is also rejected by the data, as shown in Figure A5.

Figure 9: The Effect of an Interest Rate Shock in the Estimated Model with Adjustment Costs



Notes: This figure plots the model-based interest rate elasticity after a monetary shock in black. The green line and shading show the empirical estimates from this paper.

vex adjustment costs. Thus, the findings from the adjustment cost estimates suggest that very strong convex and fixed costs can together generate plausible investment responses to interest rate shocks, consistent with Winberry (2021) and Koby and Wolf (2020). However, one feature of the impulse response does not closely match the data: the strong convex adjustment costs necessary to reduce the investment elasticity make the model-based, interest rate elasticity much smoother and more persistent than the data. In the data, the interest rate elasticity begins to decline nine quarters after the shock. In contrast, eleven quarters after the shock, the model-based elasticity is still plateauing near its maximum value. The empirical impulse response is around -2 three years after the shock; in contrast, the model-based impulse response does not reach this level until more than eight years after the shock. More than twelve years after the shock, the model-based coefficient is still below -1. This finding of "excess smoothness" is similar to a point made in Bayas-Erazo and Hanks (2023), who argue that models with substantial adjustment costs are unrealistically persistent. Overall, the results suggest that very strong adjustment costs can generate realistic investment elasticities, although at the cost of producing excessively smooth and persistent impulse responses.

Table 5: Estimated Adjustment Costs Parameterization

Parameter	Description	Value	Source
η	Convex Cost	2.950	Estimated
$\bar{\zeta}$	Upper Bound on Fixed Cost	0.703	Winberry (2021)

Next, I consider a variant of the model without adjustment costs but with financial frictions. In particular, I consider a version of a cash-flow-based constraint in which firms' equity and dividend issuance are constrained to be a function of their flow profits. In particular, I impose the following constraint on all firms in the model:

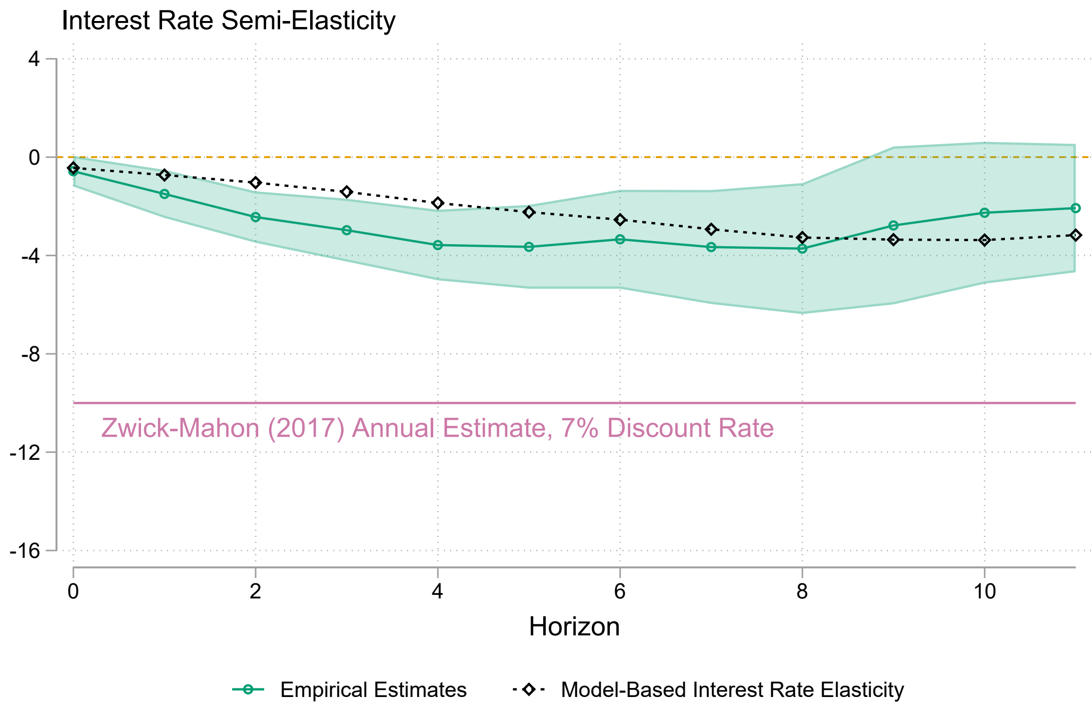
$$D \geq \omega\pi$$

Where $D = \pi - q_t * (k' - (1-\delta) * k) - \text{AC}(k', k, I_{f,t}) - T(\pi, \tau_t, \theta_t)$ are the dividends the firm remits back to its shareholders and π are the firm's cash flows net of payments to its workers. Note that D and ω can potentially be negative, meaning the firm can issue equity, which it can use to fund investment. Under this model, a firm's cash flows are a primary determinant of the amount of investment they can undertake because (1) constrained firms can only use their cash flows to pay for investment and (2) higher cash flows can directly relax the firm's constraint.

Figure 10 shows the estimated impulse response from the model when I choose ω to match the empirical estimates from the data. The model with the dividend constraints matches the ultimate quantitative magnitude of the interest rate elasticity nearly perfectly. However, the dynamics of the investment response do not match the dynamics of the empirical estimates. Early on, the estimated interest rate elasticity is too small relative to the data and peaks too late. The empirical estimates are at their peak between four and eight quarters after the shock, while the model-implied elasticities are at their peak between eight and ten quarters after the shock. This is because of how coarse the cash-flow constraint in the model is: early on, both low- and high-depreciation firms invest until they hit the constraint, making the difference between them too small relative to the data. A more flexible model, where firms can pay a cost to violate their dividend constraint, may be able to fit the dynamics of the model instead of just the magnitude. However, after the peak effect, the interest rate elasticity begins to decline toward zero, implying the model with financial frictions does not face the same excessive persistence as the model with adjustment costs.

Table 6 shows that very strong financial frictions are necessary to match the data. In particular, the estimated dividend constraint not only does not let firms issue equity but also requires them to pay out a fraction of their cash flow as dividends. Overall, both the adjustment costs

Figure 10: The Effect of an Interest Rate Shock in the Estimated Model with Financial Frictions



Notes: This figure plots the model-based interest rate elasticity after a monetary shock in black. The green line and shading show the empirical estimates from this paper.

and financial friction parameterizations suggest that very strong frictions are needed to generate realistic investment elasticities. This highlights how the empirical estimates from this project can be used to discipline models with capital investment and ensure models generate realistic quantitative magnitudes.[21] These results also highlight how financial frictions alone can lead to realistic investment elasticities without relying on arbitrary adjustment costs. However, both models can match the magnitudes, suggesting that the investment response to one shock alone is not enough to determine which mechanism better describes the frictions that firms face.

6.3 The Response of Investment to Tax Rate Shocks

Next, I study the response of investment to tax rate shocks in both models calibrated to match the interest rate elasticity. The response of investment to a tax rate shock functions as an over-

[21] Appendix Figure A4 also compares the estimated interest rate elasticities in the model with the actual aggregate investment response. Across all models, the estimator remains very informative about the actual investment response, confirming the underlying usefulness of the empirical estimator even for disciplining models with very strong frictions.

Table 6: Estimated Financial Frictions Parameterization

Parameter	Description	Value	Source
η	Convex Cost	0.0	Restricted
$\bar{\zeta}$	Upper Bound on Fixed Cost	0.0	Restricted
ω	Dividend Constraint	0.10	Estimated

identifying test. Since both models can approximately match the magnitudes and timing of the interest rate shock, I use the investment response to tax rate changes as an untargeted moment to discriminate between the two models of firm behavior. I study an eight-quarter shock to the expensing parameter θ, which is meant to approximately match the countercyclical, temporary bonus depreciation policies implemented during the 2001 and 2008 recessions.

Table 7: Untargeted Moment: Implied Interest Rate Elasticity from Tax Rate Shock

	Data	Adjustment Costs Model	Financial Frictions Model
Tax Rate Elasticity	-10.00	-1.55	-8.05

Table 7 shows the implied interest rate elasticities from the bonus depreciation shock in the two models and the implied estimates from Zwick and Mahon (2017). Table 7 shows that only the financial frictions model generates a tax rate elasticity that is close to the acutal empirical data from Zwick and Mahon (2017). The adjustment costs model generates a low semi-elasticity of around -2, which is close to the interest rate elasticity from a monetary shock, but far from the actual tax rate elasticity which should be much larger (in magnitude).

In contrast, the model with the external financing friction generates elasticities that are both much closer to the empirical estimates and also much larger than the estimated interest rate elasticities. Only the model with financial frictions can generate elasticities that are both relatively close to the actual empirical elasticities and qualitatively reflect the fact that interest rate elasticities tend to be substantially smaller than tax rate elasticities. Overall, these results provide evidence in favor of models where financial frictions generate smaller investment elasticities and against models where strong arbitrary adjustment costs are used to slow the investment response. This also shows how evidence from both tax and interest rate shocks can be used to discriminate between different models. While calibrations of either model can directly match the estimates from one type of shock, only the financial frictions model can generate heterogeneity in the interest rate and tax rate elasticities highlighted by the empirical estimates in this paper.

6.4 Underlying Mechanisms

Why can't the model with adjustment costs fit the data? Recall that in the frictionless, neoclassical model, tax and monetary policy operate through the exact same channel in partial equilibrium: both affect firms' investment decisions by changing firms' user cost of capital. This is why the investment response to both policy shocks is governed by the same simple parameters, and why they should generate identical elasticities. Models with adjustment costs do not change this underlying logic. This is because adjustment costs slow the investment response with the exact same force regardless of which policy instrument is used to change the cost of capital. Thus, adjustment costs alone are not able to generate large differences between the monetary and tax elasticities. This is confirmed in the quantitative model, where the tax and monetary elasticities are quite similar to each other.

In contrast, in the presence of financial frictions, interest rates and tax rates do not operate through the exact same channels. In particular, while both tax rates and interest rates still have an effect on the cost of capital, in the presence of financial frictions, tax policy has a second effect on investment choices. Lower tax payments also generate extra cash flow for the firm because it reduces the firm's immediate tax bill. In a frictionless model, this cash-flow effect is irrelevant because the firm can *costlessly* borrow to pay for its desired investment. However, if borrowing is costly or undesirable, then this extra cash flow can be very valuable because the firm can use that money to fund its higher desired investment. Because tax policy has this additional channel, the model with financial frictions can generate tax elasticities that are significantly larger than the monetary elasticities, consistent with the empirical estimates.

Because there was no significant debt response, the model abstracted from firms' debt choices. In the presence of debt financing, monetary policy can also generate free cash flow by reducing interest expenses. However, the benefits are smaller and less immediate than those for tax financing. Consider a firm that purchases $1000 of computers, financed with floating-rate debt. If interest rates are reduced by 1 p.p., this reduces the firm's interest payments by 1 p.p., or around $10 per period. In contrast, moving to 50% bonus depreciation increases the firm's free cash flows by $140 in the year of purchase relative to the no bonus depreciation benchmark, an order of magnitude larger than the effect of monetary policy (Zwick and Mahon, 2017). In addition, because 50% bonus depreciation has a smaller effect on the cost of capital than the 1 p.p. drop in interest rates, and because the majority of corporate debt is fixed rather than floating rate, this example, if anything, understates the differences between tax and monetary policy at generating immediate cash flows. For example, Bräuning, Joaquim and Stein (2023) estimates that a 1 p.p. increase in interest rates only increases interest expense ratios by around 0.5 p.p., with the peak effect occurring more than 1 year after the change in the Fed. Funds rate.

The empirical estimates and quantitative model provide new evidence in support of models with financial frictions where firms' cash flows are a key determinant of investment financing. This adds new quasi-experimental evidence bolstering a significant literature in economics that has posited an important role for cash flows and retained earnings on investment (Fazzari, Hubbard and Petersen, 1988). This result validates the finding in Zwick and Mahon (2017) that the large elasticities they estimate are driven by taxable firms that receive immediate cash flows as a result of bonus depreciation. It is also consistent with the evidence in Section 4 on the financial responses to monetary shocks: I find that firms do not respond to interest rate changes by issuing debt but instead increase cash holdings before increasing investment. This mechanism is also consistent with financial frictions endogenously generating higher firm-level discount rates (Gormsen and Huber, 2023). Gormsen and Huber (2023) quote a CFO who directly ties investment responses and higher discount rates to a cash-flow-based investment constraint that exactly mimics the constraint in the financial frictions model, stating:

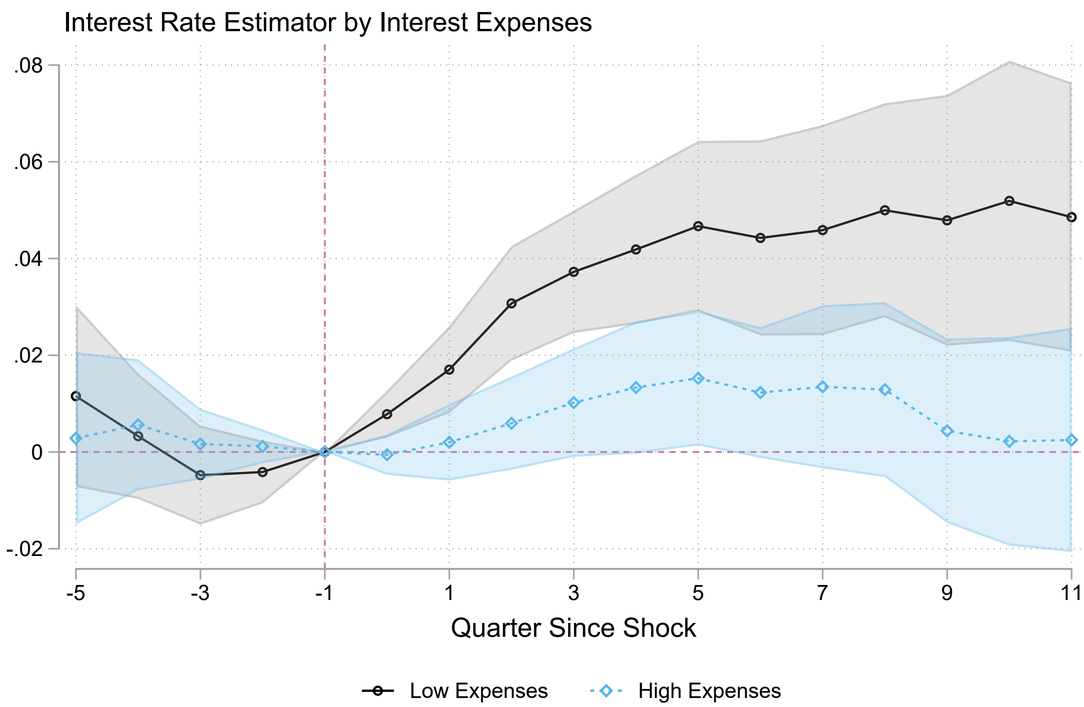
> "We are living within our cash flow, meaning that we want to be able to fund our CapEx and our dividend from our cash flow. And so that is the constraint, and so, because we have a limited amount of capital, that is why we have the hurdle rate set at 15 percent IRR for projects."

7 Heterogeneous Responses

The existing empirical results, when analyzed through the quantitative model, suggested that financial frictions are important in slowing the investment response to interest rate shocks. In this section, I examine heterogeneity in the interest rate elasticity to test this channel in the data more explicitly. I test whether firms that are more likely to be borrowing constrained exhibit smaller interest rate elasticities from those that are less likely to be constrained, consistent with the findings from the quantitative model. In particular, I focus on a specific type of cash-flow-based constraint: interest-coverage covenants, which are the most common debt covenant (Greenwald, 2019). Note that this constraint does not precisely map to the financial friction in the model: that friction placed limits on firms' ability to issue equity, while interest-coverage ratios limit firms' debt issuance. However, both limit a firm's ability to borrow and fund investment and thus make cash flows inside the firm particularly valuable.

I use a firm's interest expenses as a proxy for whether or not firms are likely to be bound by this financial constraint. In particular, I regress firms' interest expenses on industry and date fixed effects, as well as on splines of total firm assets. I then take residuals from that regression to split the sample into firms with high or low interest expenses.[22] I then re-estimate the baseline regression specification, allowing for an interaction between the primary variable of interest: the depreciation rate interacted with the monetary shock, and an indicator for whether or not a firm has high vs. low interest expenses.

Figure 11: The Effect of Monetary Policy Shocks for Low and High Interest Expense Firms



Notes: This figure plots the β_h coefficients from Equation 6, separately for firms with low vs. high interest expenses. The coefficients represent the Jordà (2005)-style impulse response for the effect of monetary policy shocks on net investment, comparing low vs. high depreciation firms. 95% confidence intervals are plotted, and standard errors are two-way clustered at the industry and date level.

Figure 11 documents striking heterogeneity by firms' interest expenses. For firms with high interest expenses relative to their assets and industry, the estimated impulse response is close to the baseline but rarely statistically significant. However, for firms with low interest expenses, the effect is large and very significant. The coefficients for firms with low interest expenses are more than twice as large as the baseline, implying much larger interest rate elasticities.

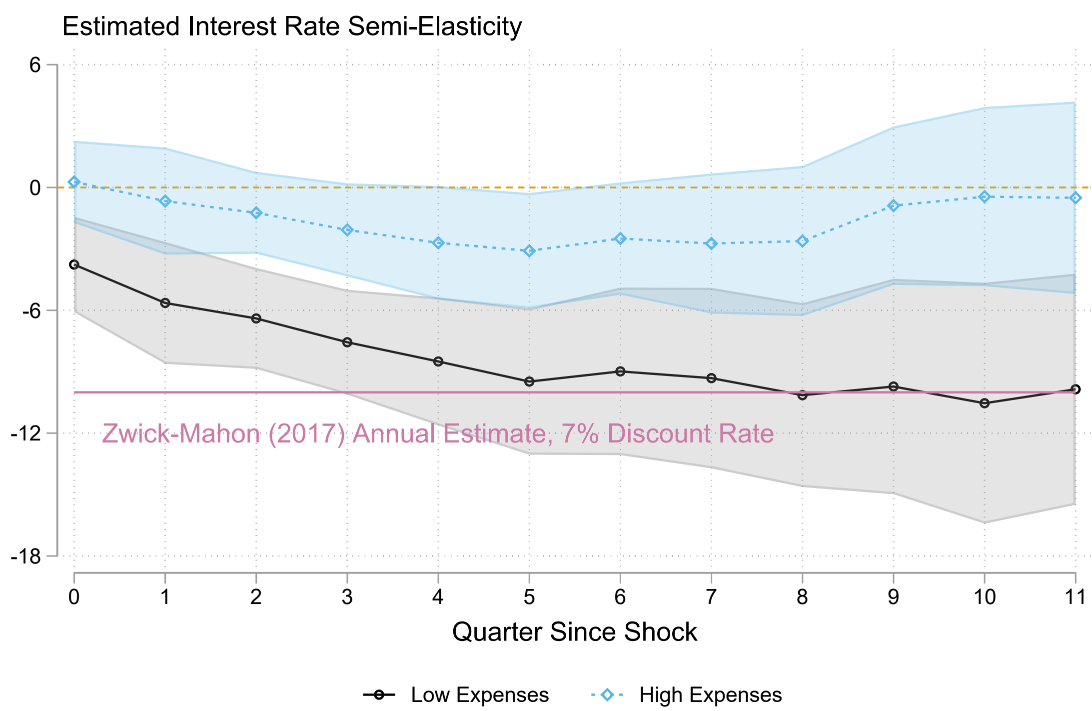
Overall, these results suggest that interest expenses, and thus interest-coverage ratios, are an important constraint on investment. This implies that tighter financial constraints are the key constraint limiting firms' investment response to interest rate shocks, consistent with the findings of the quantitative model. The results contrast with those from Cao et al. (2024),

[22] I also remove the middle 20% of firms.

who estimated limited heterogeneity by interest expenses in Norway using a different empirical strategy. Finally, this strong pattern of heterogeneity provides evidence that the muted baseline results are not driven by sticky discount rates (Fukui, Gormsen and Huber, 2024) or firm inattention to monetary shocks.

Figure 12 converts these impulse responses into semi-elasticities. Surprisingly, for low-interest-expense firms, the interest rate elasticities are nearly identical in magnitude to the implied elasticities from Zwick and Mahon (2017). For firms that are likely to be unconstrained, interest rate elasticities are nearly identical to tax rate elasticities. It is only the firms that are likely to be close to borrowing constraints for whom interest rate elasticities are much smaller than tax rate elasticities. This provides additional support for the mechanism implied by the quantitative model: financial frictions that limit firms' ability to use external funds for new investment lead to smaller interest rate elasticities.

Figure 12: Interest Rate Elasticities for Low and High Interest Expense Firms



Notes: This figure plots the estimated interest rate semi-elasticities based on the estimates in Figure 11. The graph also features lines indicating the interest rate semi-elasticity derived from Zwick and Mahon (2017).

I also examine other frictions hypothesized to affect firms' responses to interest rate shocks. In particular, I focus on firms' existing leverage (Ottonello and Winberry, 2020), liquidity (Jeenas, 2019), and fixed costs. I follow the same methodology used to study interest ex-

Table 8: Heterogeneous Responses to Interest Rate Shocks

	Baseline	Fin. Constraint		Fixed Cost	Cash Flow
		Leverage	Liquidity	Spike	Int. Expenses
1-Year Effect	0.015***	0.019**	-0.002	0.012**	0.037***
	(0.003)	(0.006)	(0.005)	(0.004)	(0.006)
x Characteristic		-0.005	0.021	0.011	-0.027**
		(0.007)	(0.011)	(0.020)	(0.008)
Observations	199960	161857	165191	175847	133775
R^2	0.221	0.236	0.230	0.241	0.247

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

penses for leverage and liquidity. For fixed costs, I split firms by whether or not they had an investment spike in the year prior to the monetary shock.

Table 8 shows results for the heterogeneity tests for these three factors. I only show estimated coefficients one year out from the shock. Column (1) shows the baseline estimates. Column (2) shows the heterogeneous effects of firm leverage. I find the coefficient on the main term is nearly unchanged from the baseline, and the interaction effect is very close to zero and statistically insignificant. This provides more evidence in favor of a cash-flow-based constraint against a more traditional financial friction based on firm leverage. It also provides validation that the split by interest expenses is not driven by the closeness of firms to default.

Column (3) also estimates a statistically insignificant effect of firm liquidity on the interest rate elasticity. Though statistically insignificant, the interaction term is positive. This implies that, in contrast to a story where firm liquidity is an important constraint on firm investment, firms with low liquidity actually drive the underlying interest rate response. One possible explanation for this finding is that these estimates reflect the endogenous nature of firms' liquidity choices. In particular, if firms accumulate liquidity exactly because they have few profitable investment opportunities, this might also lead these firms to be *less* responsive to changing interest rates. Note that these results do not suggest that liquidity and leverage have no effect on firm investment. Rather, these estimates suggest that they do not mediate the responsiveness of firms to changes in the cost of capital induced by movements in interest rates. However, they may be important for understanding general equilibrium channels that are differenced out by my empirical strategy.

Column (4) also shows that fixed costs play a limited role in shaping the investment response to monetary shocks. The main coefficient is close to the baseline estimate, and the interaction term is an imprecise zero. Column (5) shows that interest expenses are the only characteristic along which there is important heterogeneity in the investment response. These heterogeneous responses provide broad evidence for the mechanism uncovered by the quantitative model: financial frictions that constrain firms when they cannot fund investment out of their cash flows can explain both the quantitative magnitude of the investment response estimated in Section 4, as well as the differences between the tax rate elasticity and interest rate elasticity.

8 Discussion

This project makes four primary contributions. First, I use a novel empirical strategy to estimate how investment responds to interest rate changes caused by monetary policy, using high-frequency shocks and quasi-experimental techniques. My empirical strategy isolates the partial equilibrium effect of interest rates on investment due to changes in the cost of capital. These results provide a newly identified, empirical moment based on monetary shocks that can discipline empirical models of investment (Nakamura and Steinsson, 2018*a*). Second, I show that these effects are substantially smaller than prominent estimates of the effect of corporate taxes on investment. This poses a puzzle for standard neoclassical models, which suggest that the same parameters should govern the investment response to interest rates and tax rates.

Third, I build a quantitative model of heterogeneous firms making corporate investment decisions to highlight how my estimates of the interest rate elasticity of investment can be used to discipline and discriminate between different macroeconomic models. I find that neoclassical models require strong frictions that slow the investment response to interest rates to generate elasticities that match the estimated elasticities. In addition, only models with external financing constraints can jointly match the investment response to interest and tax rate shocks. Tax policy generates free cash flow for firms by reducing their contemporaneous tax liability. In models without costly external financing, these free cash flows are irrelevant. However, when cash flows inside the firm are valuable for funding investments, these cash flows magnify the neoclassical effect of tax rates on investment, generating larger investment elasticities than those from changes in interest rates. Finally, I provide evidence that cash-flow-based borrowing constraints, like those in the quantitative model, have large effects on the estimated elasticity. Firms more likely to be constrained have much smaller investment responses than those less likely to be constrained.

My research has several significant implications for the design of public policy. First, a rigorous understanding of monetary policy requires knowledge of how monetary policy transmits to the real economy. This study adds crucial empirical evidence that changes in interest rates lead to substantive changes in investment, validating a key channel of monetary transmission. However, the estimated elasticities are significantly smaller than implied by the investment response to tax rates, suggesting that the investment response is more limited than would be implied by the existing estimates. Second, I provide novel evidence for the importance of a particular type of financial friction that slows the investment response to interest rate changes. This contrasts with other financial frictions prominent in the literature, such as the financial accelerator channel (Bernanke, Gertler and Gilchrist, 1999), that amplify the investment response to interest rate changes.

Third, I provide new evidence that suggests countercyclical tax policies will be more effective at stimulating investment than interest rate changes. This suggests that corporate tax policy changes can act as a very effective substitute for monetary policy at the ZLB or when monetary policy is constrained (Wolf, 2021). In addition, policy rules that generate countercyclical corporate tax rates may be a particularly effective automatic stabilizer (McKay and Reis, 2021). I leave a full quantification of optimal policy for future work.

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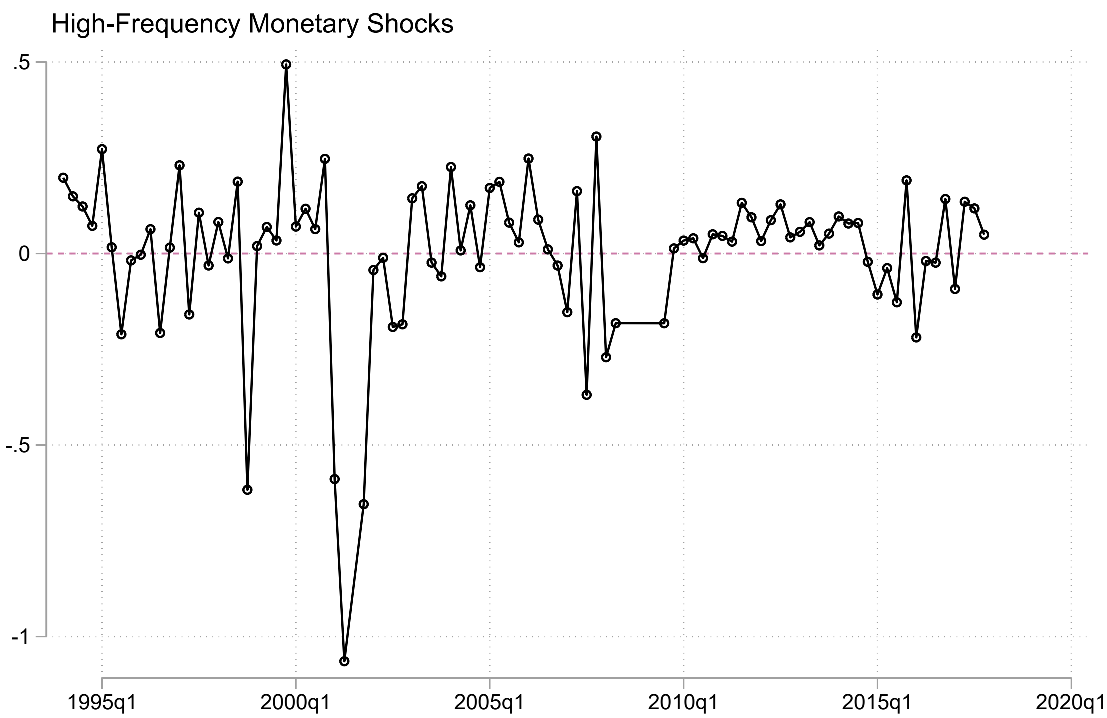
Appendices Contents

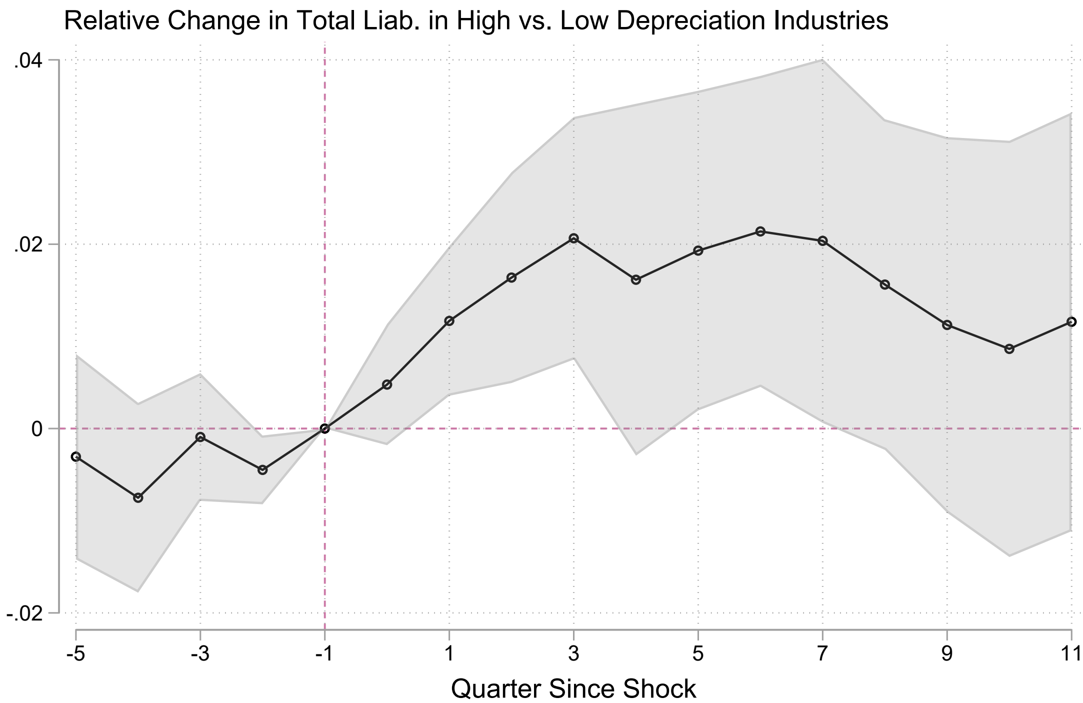
A Additional Figures

Figure A1: Time Series of Monetary Shocks



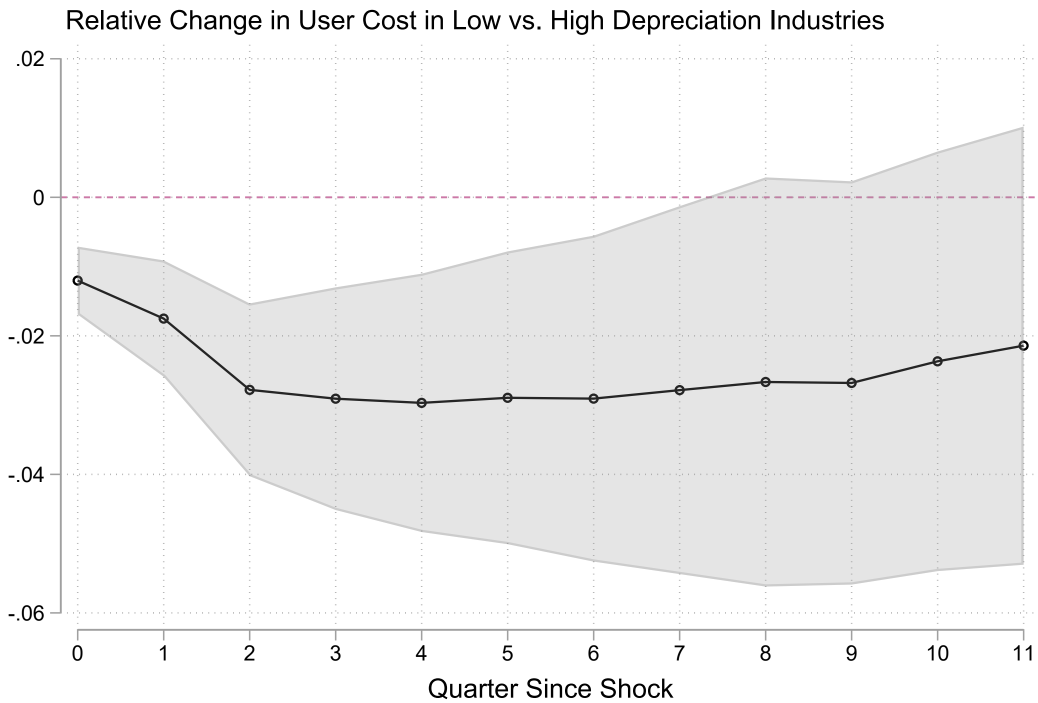
Notes: This figure shows the time series of high-frequency monetary shocks used in this paper.

Figure A2: Firm-Level Impulse Response: Effect on Total Liabilities



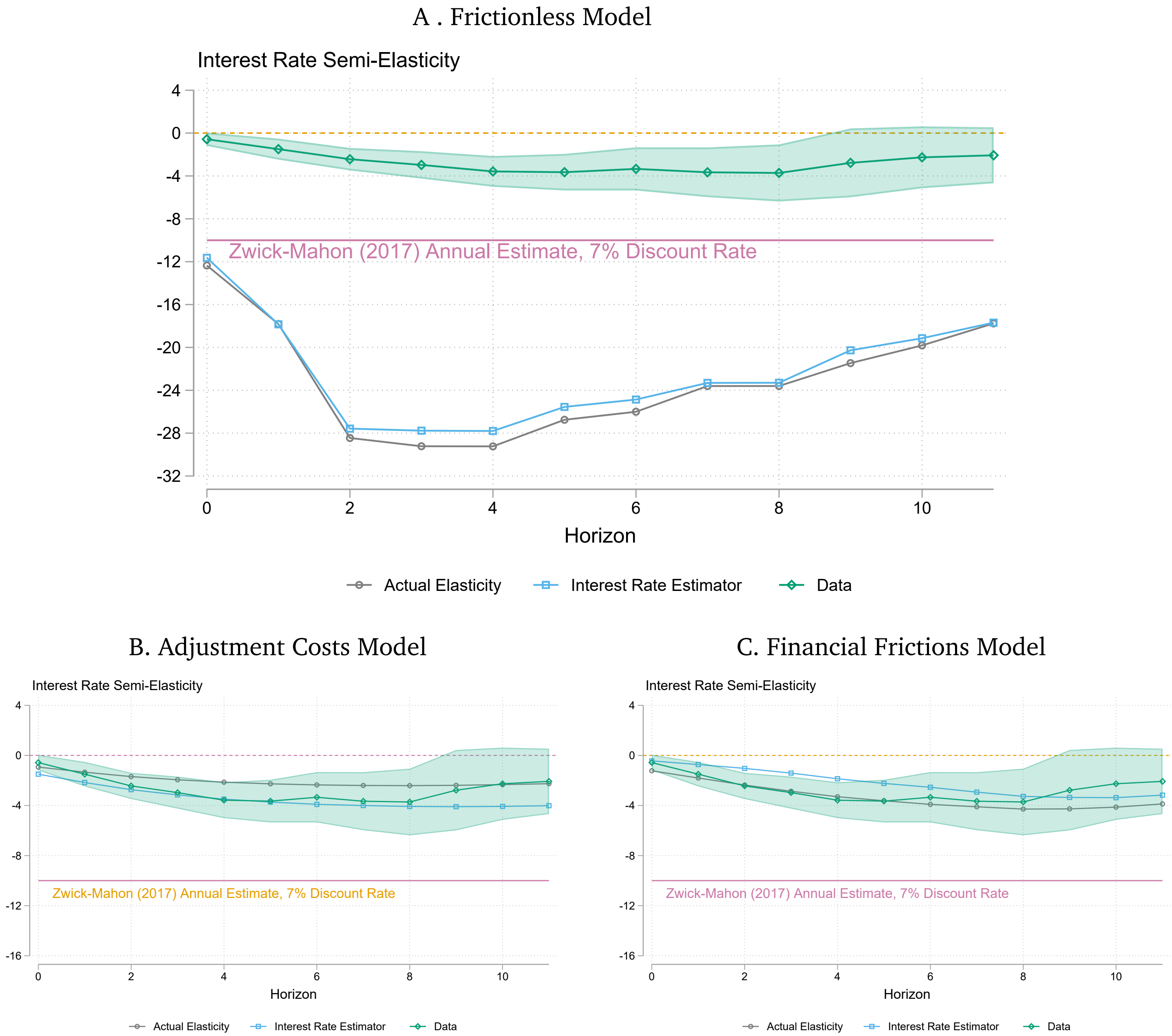
Notes: This figure plots the Jordà (2005)-style impulse response of the effect of monetary policy shocks on firm-level outcomes. The outcome variable is the change in log total liabilities. 95% confidence intervals are plotted, and standard errors are two-way clustered at the industry and date level.

Figure A3: Firm-Level Impulse Response: Effect on Log User Cost of Capital



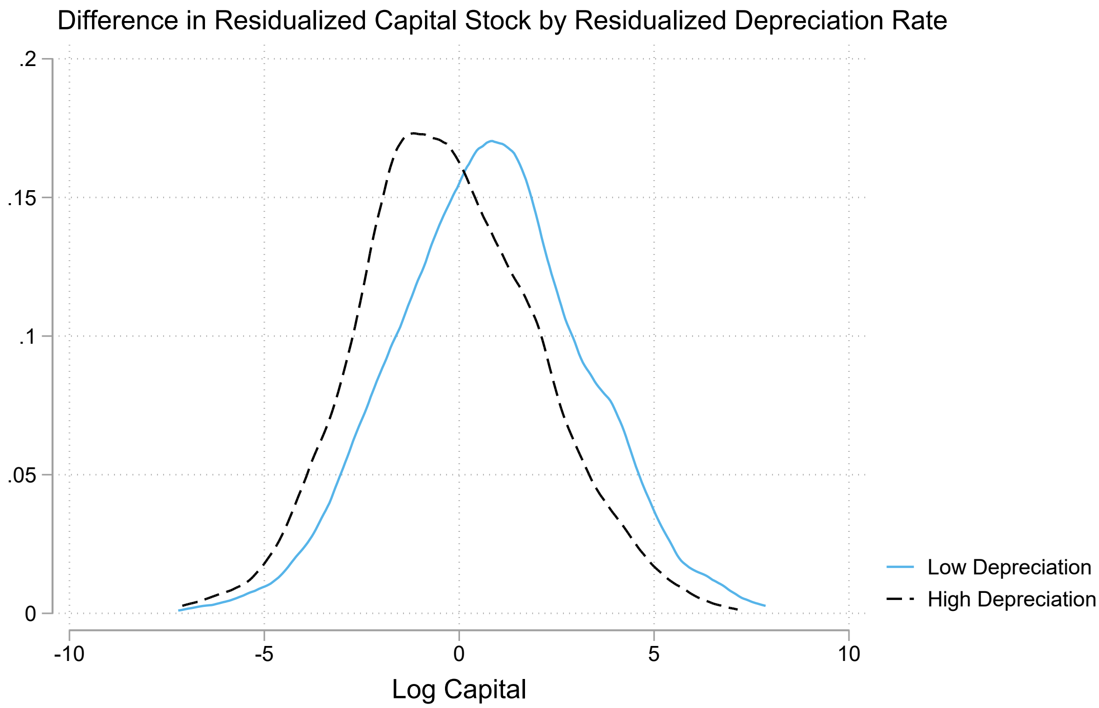
Notes: This figure plots the Jordà (2005)-style impulse response of the effect of monetary policy shocks interacted with the depreciation rate. The outcome variable is the change in the log user cost. The regression includes sector-by-time fixed effects. 95% confidence intervals are plotted, and standard errors are two-way clustered at the industry and date level.

Figure A4: The Effect of Monetary and Fiscal Policy in Models with Frictions



Notes: This figure plots the interest rate elasticity estimated in the model using the methodology from Section 4 and the actual aggregate interest rate elasticity taken from the aggregate investment response in the model. Panel (A) shows a frictionless model without adjustment costs. Panel (B) shows the model with adjustment costs and Panel (C) shows the model with financial frictions. All figures also show the empirical interest rate elasticities from the data.

Figure A5: Residualized Firm-Size Distribution in the Data



Notes: This figure plots kernal density estimates of the amount of capital held at the firm level in the data after residualizing on sector fixed effects.

B Appendix Tables

Table A1: Residualized Depreciation Rates

Industry	Residualized Depreciation
Funds, Trusts, Oth. Finance	-6.0%
Rail Transportation	-3.5%
Education Services	-3.4%
Primary Metal Manufacturing	-3.4%
Utilities	-3.3%
Broadcasting	-3.2%
Petrol. and Coal Manufacturing	3.7%
Performing Arts	3.7%
Misc. Professional Services	5.3%
Car Manufacturing	6.8%
Computer Systems Design	7.0%
Truck Transportation	8.8%

Notes: This table shows the highest and lowest depreciation industries after residualizing the depreciation rates on major-industry fixed effects.

Table A2: The Response of Inflation to Monetary Shocks

	CPI	F1. CPI	F2. CPI	F3.CPI	F4.CPI	F5.CPI
Monetary Shock	-0.0013	-0.0012	-0.0035	-0.0036	0.0014	-0.0019
	(0.0026)	(0.0023)	(0.0031)	(0.0034)	(0.0033)	(0.0040)
N	91	90	89	88	87	86
R^2	0.0026	0.0025	0.013	0.014	0.0021	0.0039

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A3: Heterogeneous Responses to Interest Rate Shocks by Firm Size

	1-Year Effect		2-Year Effect	
Baseline Coefficient	0.015***	0.022**	0.018**	0.035
	(0.003)	(0.007)	(0.006)	(0.018)
x Quintile 2		-0.013		-0.043
		(0.010)		(0.024)
x Quintile 3		-0.011		-0.017
		(0.007)		(0.022)
x Quintile 4		-0.005		-0.017
		(0.013)		(0.020)
x Quintile 5		-0.003		-0.003
		(0.010)		(0.019)
Observations	199960	199540	184608	184208
R^2	0.221	0.222	0.314	0.315

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A4: Heterogeneous Responses to Interest Rate Shocks by Firm Size

	1-Year Effect			2-Year Effect		
	All Firms	Small Firms	Big Firms	All Firms	Small Firms	Big Firms
Main Coefficient	0.015***	0.011*	0.015**	0.018**	0.009	0.023*
	(0.003)	(0.005)	(0.005)	(0.006)	(0.004)	(0.009)
Observations	199960	107096	92121	184608	99358	84573
R^2	0.221	0.213	0.248	0.314	0.298	0.355

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A5: The Effect of Monetary Shocks on Investment Prices

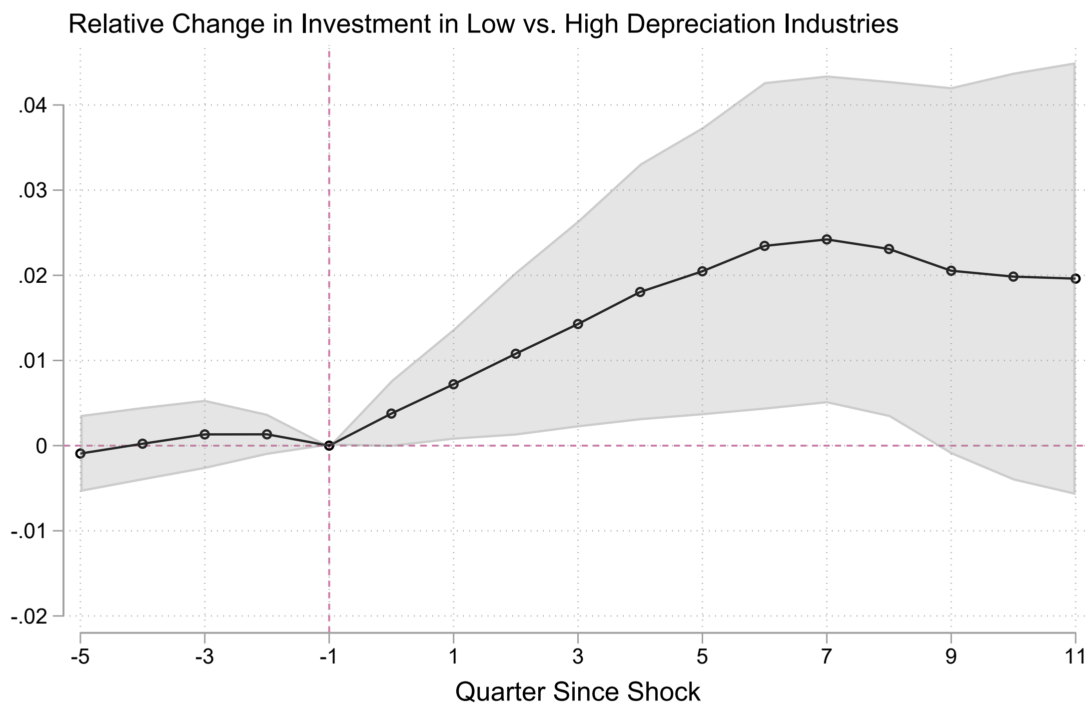
	L4. Ln(P)	L2.Ln(P)	Ln(P)	F1. Ln(P)	F2. Ln(P)	F4. Ln(P)	F8. Ln(P)
Exposure x Shock	-0.086	-0.065	-0.028	-0.024	-0.015	-0.015	-0.022
	(0.075)	(0.073)	(0.076)	(0.075)	(0.075)	(0.073)	(0.065)
N	3132	3204	3276	3240	3204	3132	2988
R^2	0.75	0.74	0.73	0.73	0.73	0.74	0.74
Capital FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Date-Class FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

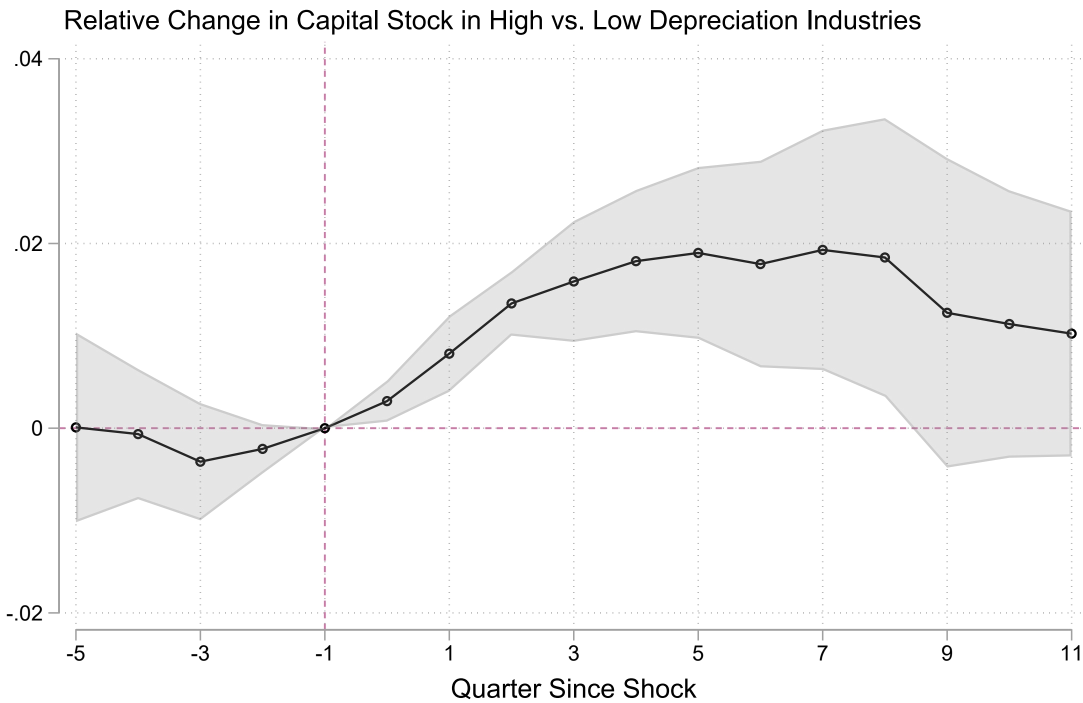
C Robustness Appendix

Figure A6: Firm-Level Impulse Response: Using Cumulated Investment As Dependent Variable



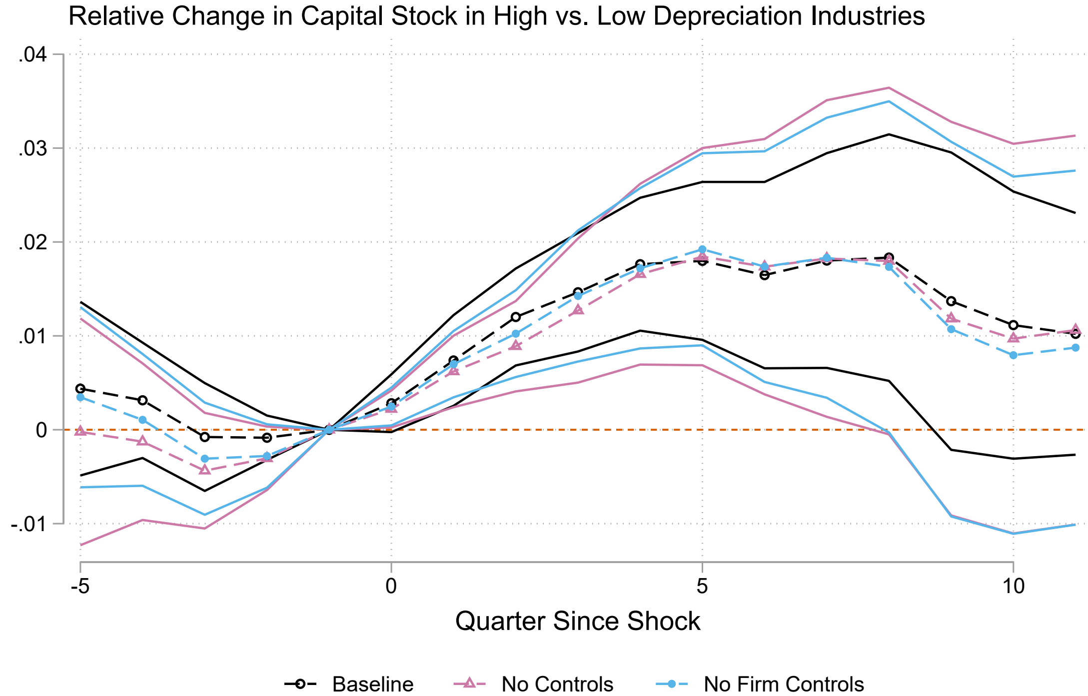
Notes: This figure plots the Jordà (2005)-style impulse response of the effect of monetary policy shocks on firm-level outcomes. The outcome variable is cumulated gross investment, normalized by the lagged capital stock. 95% confidence intervals are plotted, and standard errors are two-way clustered at the industry and date level.

Figure A7: Firm-Level Impulse Response: Weighted Regression



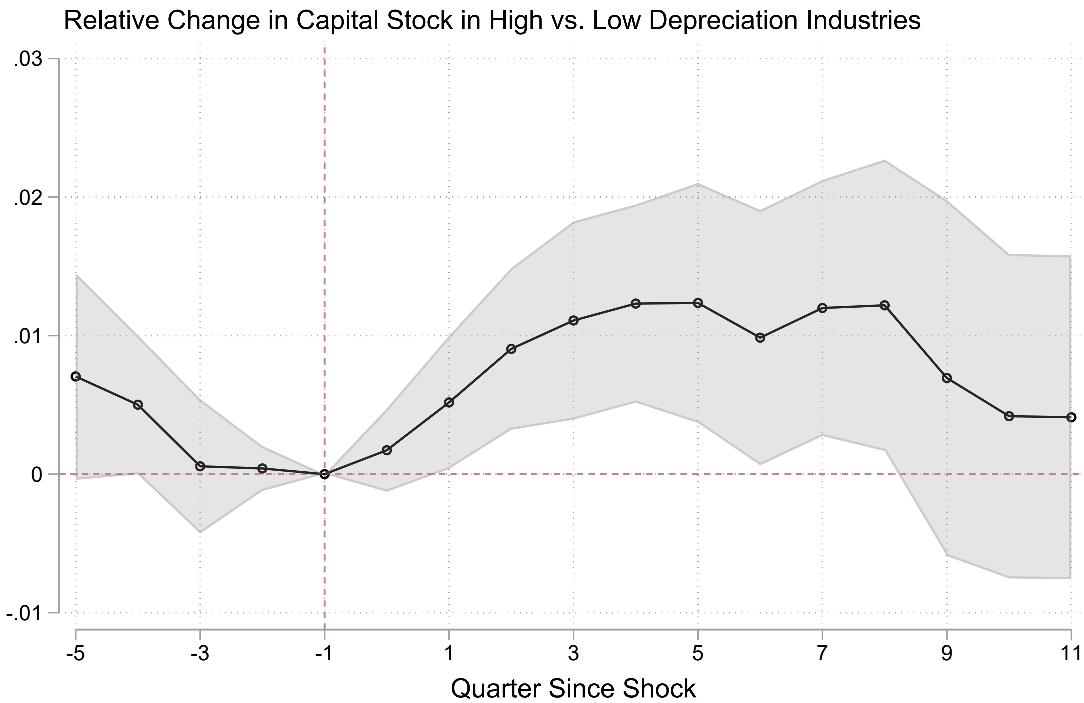
Notes: This figure plots the Jordà (2005)-style impulse response of the effect of monetary policy shocks on firm-level outcomes. The outcome variable is net investment, and the regression is weighted by the normalized (within-quarter) lagged capital stock. 95% confidence intervals are plotted, and standard errors are two-way clustered at the industry and date level.

Figure A8: Firm-Level Impulse Response: Robustness to Control Set



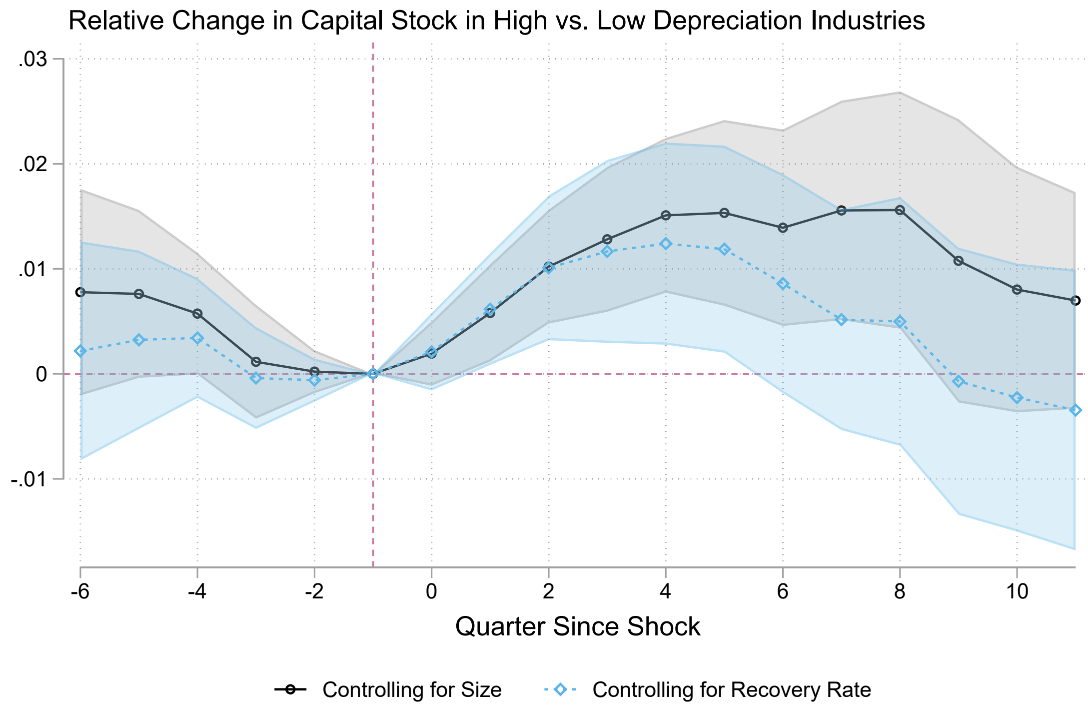
Notes: This figure plots the Jordà (2005)-style impulse response of the effect of monetary policy shocks on firm-level outcomes. The outcome variable is the change in net investment. 95% confidence intervals are plotted, and standard errors are two-way clustered at the industry and date level.

Figure A9: Firm-Level Impulse Response: Robustness to Control Set



Notes: This figure plots the Jordà (2005)-style impulse response of the effect of monetary policy shocks on firm-level outcomes. The outcome variable is the change in net investment. 95% confidence intervals are plotted, and standard errors are two-way clustered at the industry and date level.

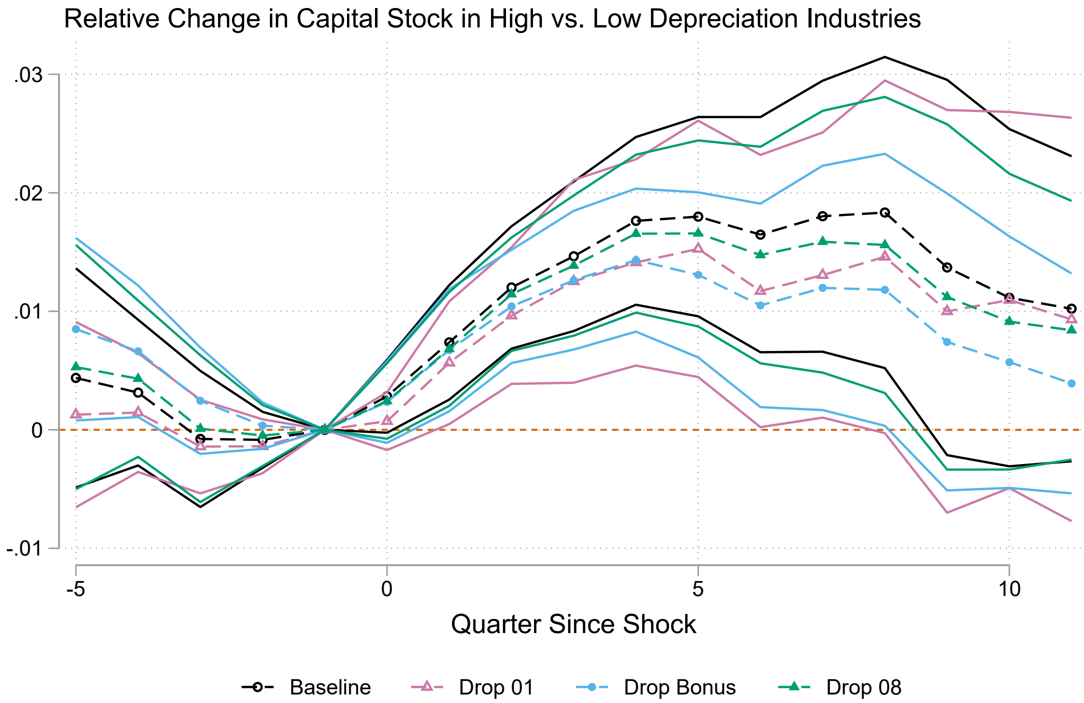
Figure A10: Firm-Level Impulse Response: Robustness to Control Set



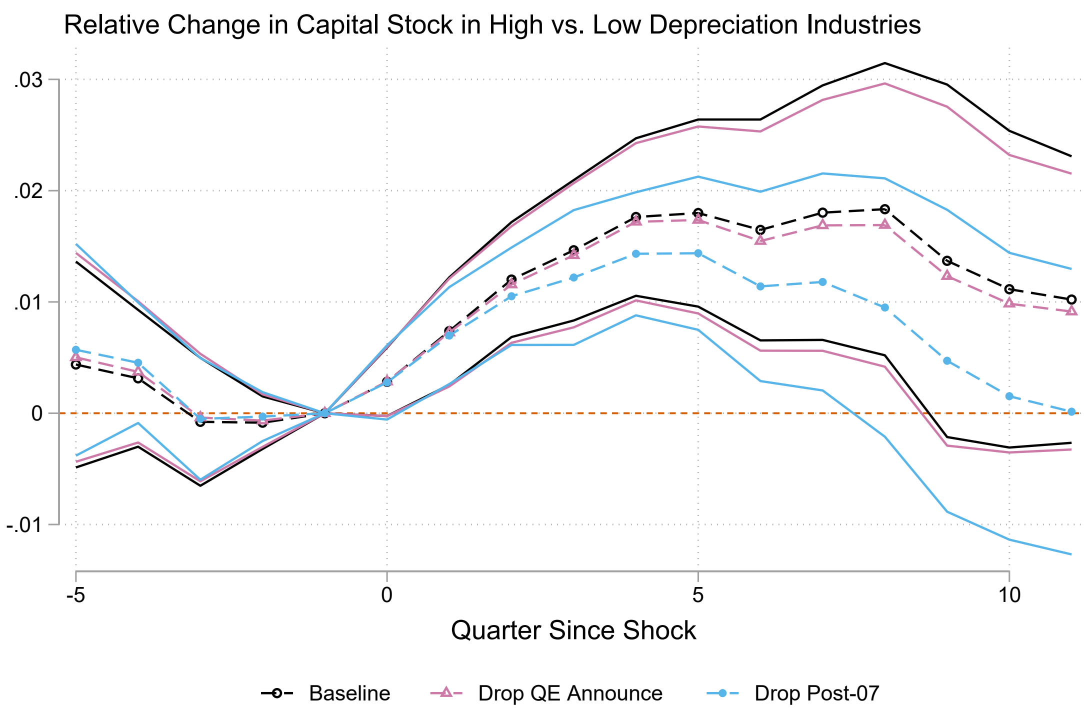
Notes: This figure plots the Jordà (2005)-style impulse response of the effect of monetary policy shocks on firm-level outcomes. The outcome variable is the change in net investment. 95% confidence intervals are plotted, and standard errors are two-way clustered at the industry and date level.

Figure A11: Firm-Level Impulse Response: Robustness to Restricting Time Dimension

A. Dropping Periods Around Bonus Announcements

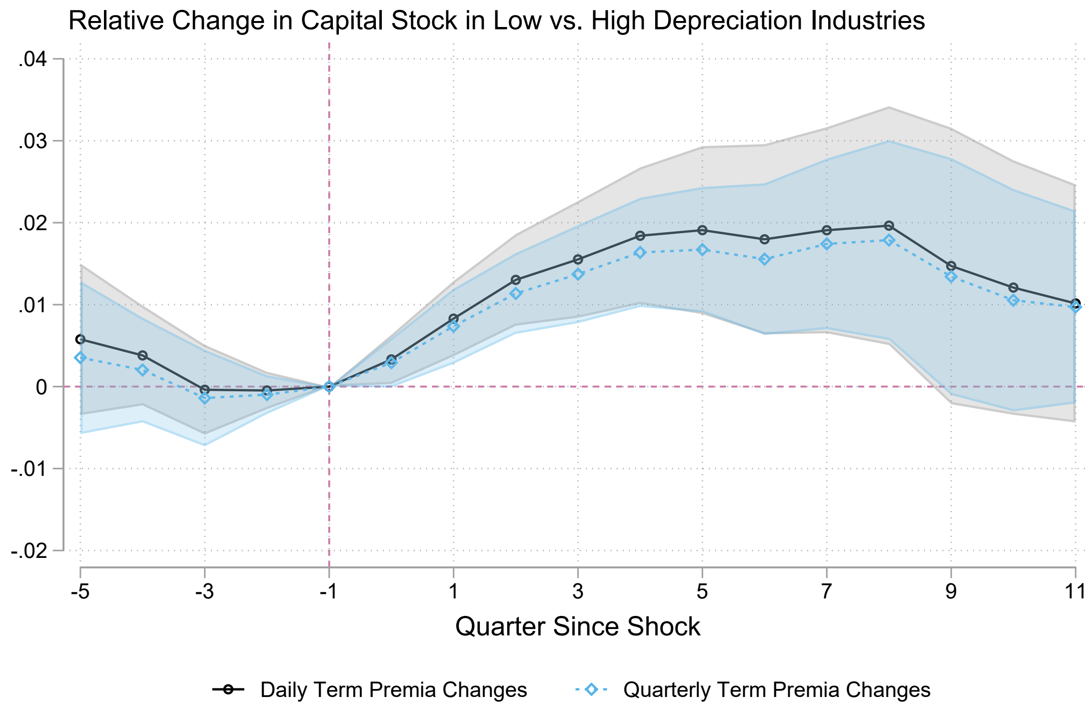


B. Dropping Periods Around QE Announcements



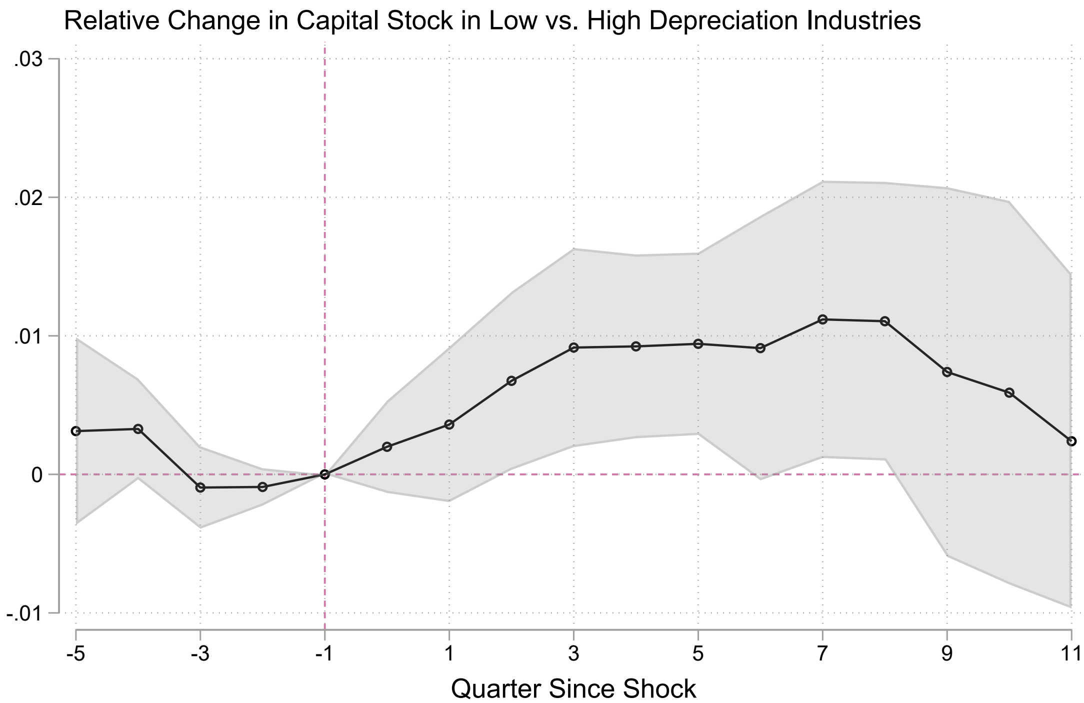
Notes: This figure plots the Jordà (2005)-style impulse response of the effect of monetary policy shocks on firm-level outcomes. Panel (A) shows impulse responses excluding quarters around the announcement of the first two rounds of bonus depreciation. Panel (B) shows impulse responses excluding quarters around the announcement of QE policies. 95% confidence intervals are plotted, and standard errors are two-way clustered at the industry and date level.

Figure A12: Firm-Level Impulse Response: Allowing for Flexible Term-Premia Interactions



Notes: This figure plots the Jordà (2005)-style impulse response of the effect of monetary policy shocks on firm-level outcomes. The outcome variable is the change in net investment. 95% confidence intervals are plotted, and standard errors are two-way clustered at the industry and date level. The impulse response in black shows the results controlling for daily changes in the term premia on Fed announcement days interacted with the depreciation rate, while the impulse response in blue controls for overall, quarterly changes in the term premia interacted with the depreciation rate. Estimates from the term premium come from Adrian, Crump and Moench (2013)

Figure A13: Firm-Level Impulse Response: Allowing for Flexible Firm-Level Beta Interactions



Notes: This figure plots the Jordà (2005)-style impulse response of the effect of monetary policy shocks on firm-level outcomes. The outcome variable is the change in net investment. 95% confidence intervals are plotted, and standard errors are two-way clustered at the industry and date level.

D Alternative Derivation of Estimator

In this section, I derive a similar alternative estimator that does not rely on the assumption of no adjustment costs. The model builds heavily on the model presented in House and Shapiro (2008).

I use a similar model to the one presented in Section 2. To simplify the algebra, I assume no heterogeneous productivity shocks. Firms choose investment to maximize a discounted stream of dividend payments. As with the primary model, firms differ in their capital depreciation rate δ_f. Firms also face **external adjustment costs**: the marginal cost of investment is increasing in the amount that investment firms do. Formally, firms choose investment each period to maximize the following expression:

$$\max_{I_t} \sum_t (\Pi_{s=1}(1+R_s+\Theta))^{-1}(K_t^{\alpha} - I_t * (\frac{I_t}{I^*})^{\frac{1}{\xi}})$$

Firms are subject to the standard flow budget constraint: $K_t = I_t + (1-\delta_f)K_{t-1}$. In this formulation, ξ is the parameter that governs the strength of the adjustment costs. In this model, this parameter is the elasticity of the investment supply curve. I^* is the steady-state level of investment. As noted by House and Shapiro (2008), though this differs from the traditional **internal adjustment costs** standard in the literature, there is a direct mapping from the elasticity of investment supply in this model to the parameter that governs the strength of the internal adjustment costs in Hayashi (1982). Then, the first-order conditions for investment are given by the following expressions:

$$\frac{\partial L}{\partial I} = -\frac{(\xi+1)\frac{I_t}{I^*}^{\frac{1}{\xi}}}{\xi} + q_t = 0$$

and

$$\frac{\partial L}{\partial K} = -q_t + \frac{1}{1+R_t+\Theta}(\alpha K_t^{\alpha-1} + q_{t+1}(1-\delta_f)$$

Where q represents the Lagrange multiplier on the budget constraint. House and Shapiro (2008) show that under the assumption that capital is sufficiently durable and the policy shock is sufficiently transitory, you can approximate q and K with their steady-state values. Under these assumptions, we get the following expression, where stars indicate steady state values:

$$\alpha K^{*\alpha-1} \approx q^*(1+R_t+\Theta) - q^*(1-\delta_f)$$

This implies:

$$\alpha K^{*\alpha-1} \approx -\frac{(\xi+1)\frac{I_t}{I^*}^{\frac{1}{\xi}}}{\xi}(\delta_f + R_t + \Theta)$$

Implicitly differentiating with respect to R_t results in the following expression for the interest rate elasticity of investment:

$$\frac{\partial \log(I_t)}{\partial R_t} \approx -\frac{\xi}{\delta_f + R_t + \Theta}$$

This expression is exactly analogous to Equation 3 in the main text, only replacing the change in the **capital stock** with the **log change in net investment**. In addition, while in Equation 3, the overall change in the capital stock is driven by the curvature of the revenue function, in this expression the change in the investment rate is given by ξ, or the degree of adjustment costs.

As in the main text, define $\mu_{f,t} = \delta_f + R_t + \Theta$, and then from the firms' first-order conditions, we can derive an estimator for the ξ adjustment cost parameter, comparing a low depreciation firm ($f = l$) to a high depreciation firm ($f = h$) before an after a monetary shock. In that case, the regression equation is:

$$\Delta \log(I_{l,t}) - \Delta \log(I_{h,t}) \approx \xi\{\Delta \log(\mu_{l,t}) - \Delta \log(\mu_{h,t})\} + \epsilon_{f,t}$$

Once again, this regression equation is directly analogous to Equation 4 in the main text, but now the dependent variable is the change in *gross* investment, instead of the differences in **net** investment. Similarly, now the regression coefficient identifies ξ, the adjustment costs parameter, instead of Ψ in the main text.

E Macro Counterfactual

Orchard, Ramey and Wieland (2023*a*,*b*) suggest assessing the plausibility of micro estimates by constructing "macro counterfactuals": calibrating macroeconomic models to microeconomic estimates and applying the models to historical periods. Orchard, Ramey and Wieland (2023*a*,*b*) calibrate models of consumption to micro estimates of the effect of rebate checks on consumption. They then use these models to argue that existing estimates of the MPC are too high because they imply that consumption would have collapsed to implausibly low levels without the rebate checks. In this section, I use the empirical estimates of the interest rate elasticity estimated in this paper, as well as the implied partial equilibrium elasticity from Zwick and Mahon (2017) applied to the 2001 recession to illustrate the magnitude of the empirical results and assess the plausibility of differing estimates of the interest rate elasticity.

E.1 Investment During the 2001 Recession

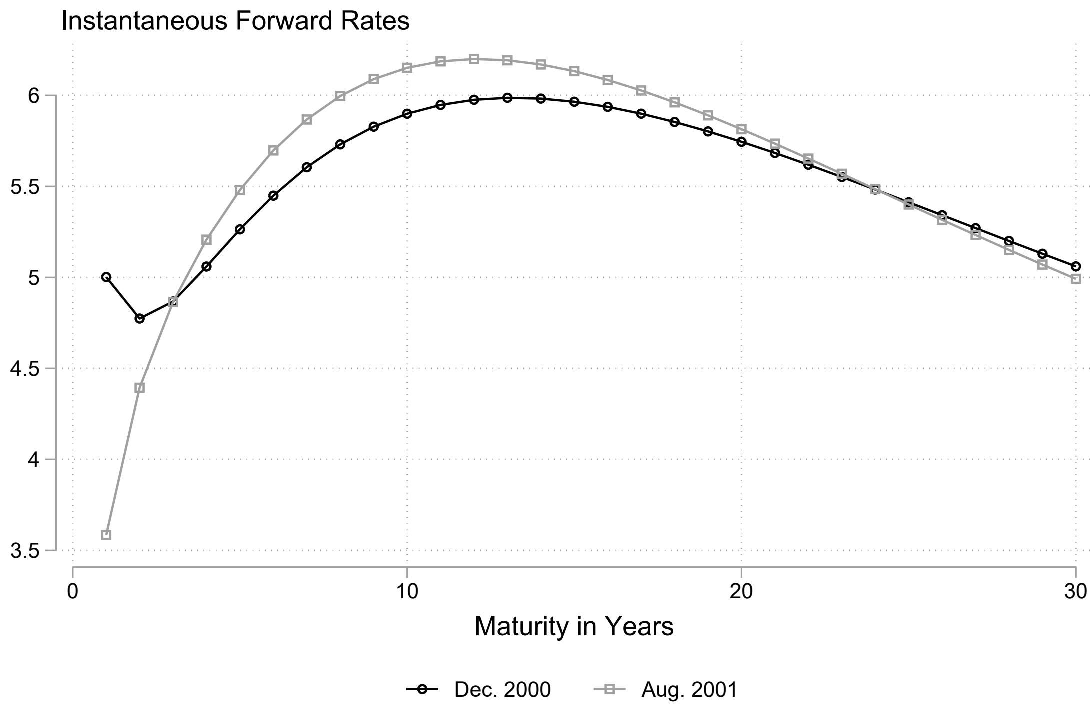
At the outset of the 2001 Recession, the Federal Reserve moved aggressively to lower interest rates, routinely surprising the market with larger-than-expected rate cuts. The largest quarterly interest rate shock (in absolute value) across the sample period occurs in the second quarter of 2001. In addition, both the first and fourth quarters of 2001 also feature surprise interest rate cuts.[23] Figure A14 plots instantaneous, nominal forward rates separately for the end of December 2000 and the end of August 2001. At the end of December 2000, markets expected rates one year ahead to be around 5%. However, by the end of August 2001, nominal rates had fallen by around 1.5 p.p., and markets expected interest rates to stay at 3.5% for another year. This fall matches the fall in interest rates implied by monetary shocks. Combining all monetary shocks across the first two quarters of 2001 implies that short-term rates fell by around 1.7 p.p. due to Fed surprises.[24]

I use both the estimates from this paper and Zwick and Mahon (2017) to construct an implied counterfactual series for investment had the Fed not moved so aggressively to cut rates in the first half of 2001. To construct the counterfactual series for investment, I take the 1.7 p.p. fall in short-term interest rates due to surprise Fed policy. Because Figure A14 implies that markets did not expect further decreases in interest rates, I assume that the effect of the shocks on short-term rates is fully accounted for by the contemporaneous 1.7 p.p. change that occurred in those first two quarters. I then use the impulse response of investment from Figure 7 to calculate the implied effect of those interest rate changes on investment and subtract that

[23] Following Nakamura and Steinsson (2018*a*), I drop the third quarter of 2001, which included surprise Fed meetings related to September 11th

[24] I focus on the first two quarters of 2001 to avoid any effects of September 11th

Figure A14: Nominal Forward Rates Fell in The First Half of 2001



Notes: This figure plots instantaneous forward rates at the ends of December 2000 and August 2001. Data are drawn from Gürkaynak, Sack and Wright (2007)

from the **realized path of investment** during that period.

This results in a counterfactual series for investment that represents the implied path of investment **if the Fed had not lowered rates by 1.7 p.p. during this period**.[25] Similarly, for the Zwick and Mahon (2017) counterfactual, I use the baseline estimates in that paper to construct a counterfactual level of investment for 2001.[26] Importantly, both estimates result in partial equilibrium counterfactuals. Thus, they do not represent forecasts for aggregate investment. Instead, they provide intuition for whether or not the partial equilibrium effects are of a reasonable magnitude relative to aggregate movements in investment. They can also help assess the strength of general equilibrium effects necessary to generate realistic aggregate values for investment.

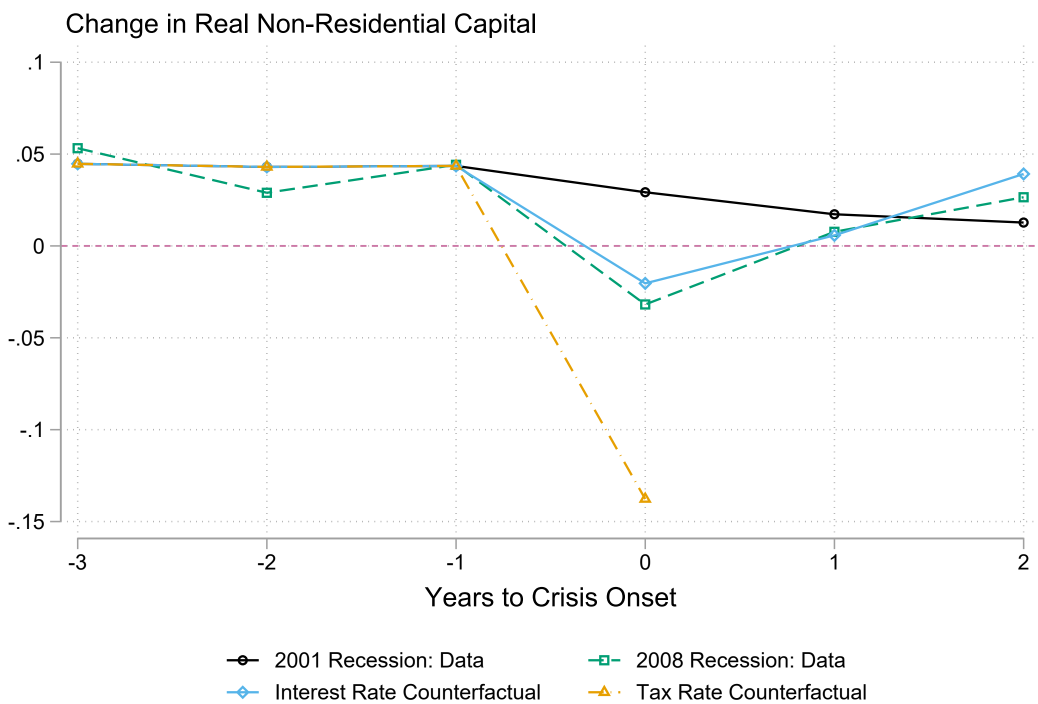
Figure A15 shows the macro counterfactual based on the 1.7 p.p. drop in interest rates in the first half of 2001. The line in black shows the actual path of net, nonresidential investment during this period. During the 2001 recession, net investment fell moderately relative to its

[25]To simplify the calculation, I assume all shocks occur in the first quarter of 2001 and use a 7% real rate.

[26]Because the baseline estimate in Zwick and Mahon (2017) is an annual panel regression, as opposed to an impulse response, I only construct the counterfactual for 2001, the year of the monetary shocks.

pre-recession trend. Before the onset of the recession in 2001, net investment was stable at 3-4 log points each year. After the onset of the recession, net investment was still positive but grew at a lower rate, falling to around 1.5 log points in the 2 years after the crisis began before recovering to its pre-crisis level. As a point of comparison, the line in green shows the path of net investment during the Great Recession. During the Great Recession, the collapse in investment was much larger than in the 2001 recession. In 2008, the first year of the crisis, net investment was negative, decreasing to -3 log points. The recovery was also much weaker: 3 years after the onset of the crisis, net investment only grew by 1 log point, well below the pre-recession level of 3-5 log points each year.

Figure A15: Macro Counterfactuals: The Effect of 2001 Interest Rate Surprises



Notes: This figure plots estimated counterfactuals for net investment based on estimates from Section 4 and Zwick and Mahon (2017).

The blue line in Figure A15 shows the counterfactual path of net investment without the Fed's 1.7 p.p. surprise interest rate decreases based on estimates from this paper. The blue line shows that without the change in the cost of capital induced by the Fed's surprise interest rate cuts, investment in 2001 would have followed a similar path as during the Great Recession. The estimates suggest that investment would have been about 4 log points lower in 2001 and slightly lower in 2002 without the Fed's surprise rate cuts. In contrast, 2 years after the onset of the crisis, the counterfactual level of investment is higher than the actual data. Overall, the counterfactual shows that by cutting interest rates in 2001 by 1.7 p.p., the Fed avoided a collapse in non-residential investment spending similar to the fall seen in the Great Recession by accelerating investment that otherwise would have occurred in 2003 and 2004. The magnitude of the effects highlights the substantial impact of interest rates on investment. However, the implied counterfactual series are comparable in magnitude to investment behavior during other recessions in this period.

The yellow line in Figure A15 shows the counterfactual path of investment in 2008 based on the estimates in Zwick and Mahon (2017).[27] The yellow line shows that using Zwick and Mahon (2017) to construct the macro counterfactual implies an implausibly large drop in investment without Fed interest rate surprises. The Zwick and Mahon (2017) estimate implies that net investment would have fallen by almost 14 log points, which is more than 2.5 times larger than the fall in net investment in the Great Recession. Given the historic magnitude of the Great Recession, as well as the fact that these estimates do not capture the effect of additional Fed policies that occurred after the first half of 2001, the Zwick and Mahon (2017) counterfactual implies an implausibly large effect of interest rates on investment.

Alternatively, the Zwick and Mahon (2017) counterfactual implies very large, offsetting general equilibrium effects that slow the investment response. Ex-ante, general equilibrium effects of the magnitude are implausible because general equilibrium effects could either magnify or slow the investment response. For example, both large intertemporal Keynesian MPCs that increase aggregate demand increases and loosening financial frictions or credit constraints could magnify the PE effects I estimate. In contrast, the estimates from this paper, estimated directly from interest rate changes, suggest that the effect of interest rates on investment spending is substantially more muted and more realistic. These estimates do not require sizeable general equilibrium smoothing to bring them in line with historical norms, making them significantly more plausible.

[27] I also follow Zwick and Mahon (2017) and assume a 7% discount rate when constructing this counterfactual.

F General Equilibrium New Keynesian Model

This section integrates the partial equilibrium firm block from Section 5. The New Keynesian closure closely follows the models in Ottonello and Winberry (2020) and Fang (2021). The heterogeneous firm problem is nearly identical to the baseline model. The one difference is that in GE, the household discounts firms' continuation value not using the real interest rate directly, but rather using the household's stochastic discount factor Δ_t. Thus, the firm problem is:

$$\begin{aligned} V_t(k,z,\delta) = \max_{k',n} & \, p_t f(k,z,n_{f,t}) - w_t n_{f,t} - q_t * (k' - (1-\delta) * k) \\ & - \mathrm{AC}(k',k,I_{f,t}) - T(\pi_{f,t},\tau_t,\theta_t) + \mathbb{E}_t[\Delta_t V_{t+1}(z,k',\delta)] \end{aligned} \tag{10}$$

F.1 New Keynesian Block

Heterogeneous firms produce a series of identical goods, indexed by the unit interval, and sell them (at a price that can perfectly adjust) to a mass of retailers also indexed by the unit interval. These retailers take the undifferentiated goods given by the production firms and differentiate them into different varieties using a one-to-one transformation. These retailers then sell their differentiated goods to a final goods firm, which aggregates them up using a CES production function into the final good consumed by the household, generating a demand curve faced by the retailers. Retailers face a Rotemberg price adjustment cost $\frac{\phi}{2}(\frac{\tilde{p_t}}{\tilde{p_{t-1}}} - 1)^2 Y_t$, where Y_t is the final good and $\tilde{p}$ is the retailers price. The retailers' profit maximization problem generates a (linearized) New-Keynesian Phillips Curve:

$$\log\Pi_t = \frac{\gamma - 1}{\phi} \log\frac{p_t}{p*} + \beta\mathbb{E}_t[\log\Pi_{t+1}]$$

Where γ is an elasticity of substitution over intermediate goods, ϕ is a coefficient on the price adjustment cost, and $p^* = \frac{\gamma-1}{\gamma}$ is the steady-state price of output of the heterogeneous production firms.

In this economy, the nominal interest rate is set by the central bank, which follows a Taylor Rule in logs:

$$\log r_t = \log\frac{1}{\beta} + \sigma\log\Pi_t + \epsilon_t^m$$

Where e_t is a shock and σ is the weight on inflation in the central-bank reaction function

$$\mathbb{E}_0 \sum_t \beta^t (\log C_t - \Upsilon L_t)$$

subject to the following budget constraint:

$$P_t C_t + \frac{1}{r_t} B_t \leq B_{t-1} + w_t n_t + D_t$$

where D_t is dividends and B_t is bonds. Household optimization gives the labor-supply decision and the following equation for the SDF:

$$\Delta_t = \frac{\Pi_{t+1}}{r_t}$$

Relative to the partial equilibrium model, there are also two crucial market clearing conditions. In particular, total output Y_t has to equal consumption from the households plus investment from the firms, net of adjustment costs. Labor supplied by the representative household has to equal labor demanded by the intermediate goods firms. Thus, aggregate inflation and p_t are determined by the New Keynesian Phillips Curve, and w_t is the endogenous price from the household's and firms' first-order conditions that ensures the labor market clears.

In the baseline New Keynesian model, I hold q_t fixed, following the evidence in Section 4 that capital goods prices do not respond to monetary shocks. However, one can easily endogenize q_t following Ottonello and Winberry (2020). In particular, we now require a capital goods producer to produce the investment technology. Ottonello and Winberry (2020) use a production technology for capital, which generates the following equilibrium price of capital:

$$q_t = \left(\frac{\frac{I_t}{K_t}}{I^*}\right)^{\frac{1}{\sigma}}$$

where I^* is the steady-state investment rate and σ represents the investment supply elasticity, as in Appendix Section D. This adds another equilibrium condition, where investment supply from the capital goods firm equals investment demand from the intermediate goods firm. q_t is the price that clears this market.

In this case, an equilibrium takes the initial firm-size distribution $\mu_0(k, z, \delta)$ as given, as well as a sequence of policy parameters $\{\tau_t, \theta_t\}$. Now an equilibrium of the model is a set of value functions $V_t(k, z, \delta)$, policy functions $k_t(z, k, \delta)$, and a firm-size distribution $\mu(k, z, \delta)$, such that all firms optimize and the distribution of firms is consistent with the decision rules. In addition, $\{p_t, w_t, q_t, \Pi_t, \Delta_t\}$ must satisfy the New Keynesian equilibrium relationships such that, households optimize and all markets clear.