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ABSTRACT

We consider a DSGE model in which firms follow one of four price-setting regimes: sticky prices, sticky-information, rule-of-thumb, or full-information flexible prices. The parameters of the model, including the fractions of each type of firm, are estimated by matching the moments of the observed variables of the model to those found in the data. We find that sticky-price firms and sticky-information firms jointly account for over 95% of firms in the model, with the two receiving approximately equal shares. We compare the performance of our hybrid model to pure sticky-price and sticky-information models along various dimensions, including monetary policy implications.

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1 Introduction

The nature of price-setting decisions made by firms has long played a pivotal role underlying controversies in macroeconomics. Whereas real business cycle (RBC) models assume that firms with full information are free to set prices optimally at all times, New Keynesian models are typically defined by departures from the assumption of flexible prices.[1] Recent work has also emphasized the implications of deviating from the assumption of full-information in price setting.[2] This paper is motivated by the idea that a single assumption about firms' price-setting decision process may be insufficient to adequately capture macroeconomic dynamics by missing potentially important interactions among heterogeneous firms. Indeed, firm-level evidence indicates striking heterogeneity in price setting as well as significant information costs.[3] We develop and estimate a dynamic stochastic general equilibrium model that allows for four commonly assumed price-setting sectors to coexist and interact via their price-setting decisions. Our results indicate that 1) sticky-price and sticky-information firms account for more than 95% of all firms; 2) neither rule-of-thumb nor flexible-price full-information firms are important to match the moments of the data; 3) strategic interaction of different price setting practices is qualitatively and quantitatively important.

To assess the relative importance of heterogeneity in the price-setting behavior of firms, we consider a continuum of monopolistic producers of intermediate goods, divided into four segments, each of which uses a different price-setting approach. These include sticky-prices, sticky-information, rule-of-thumb, and full-information flexible-price firms.[4] This setup is nested in an otherwise standard New Keynesian model with a representative consumer and a central bank. The model also allows for a stochastic trend in technology and non-zero trend inflation.[5] The parameters

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[1] See Kydland and Prescott (1982) for the seminal presentation of a classical RBC model and Woodford (2003) for an in-depth presentation of New Keynesian models.

[2] Sims' (2003) rational inattention model, Woodford's (2001) imperfect common knowledge, and Mankiw and Reis' (2002) sticky-information models are prime examples.

[3] Empirical work typically finds a large amount of heterogeneity in the frequency of price changes by firms, as well as in the source of costs to changing prices (information vs menu costs). Bils and Klenow (2004) and Dhyne et al (2005), for example, find that there are large differences in durations between price changes across sectors. Taylor (1999) cites the example of frozen orange juice prices changing every two weeks while magazine prices change every three years. Zbaracki et al (2004) and Fabiani et al (2005) report significant information costs.

[4] Sticky-price firms are modeled a la Calvo (1983), sticky-information firms are as in Mankiw and Reis (2002), and rule-of-thumb firms always update prices by last period's inflation rate, as in Barsky and Kilian (2004).

[5] We allow for trend inflation because it has non-trivial effects on the dynamics of the sticky price model (Ascari 2004, Coibion and Gorodnichenko 2008). In addition, we show in section 2.5 that trend inflation has interesting steady state effects on the relative price levels of different price setting sectors and therefore plays an important role in our model.

of the model, including the share of each type of firm, are estimated jointly using a method of moments approach. This delivers a set of predicted moments for the observable variables that can be directly compared to those of the data.

Because we allow for these four types of firms to coexist, our model nests many price-setting models considered in the literature. First, sticky-price models are frequently augmented with rule-of-thumb firms to better match the inflation inertia observed in the data, but the relative importance of forward-looking versus backward-looking behavior has been much debated.[6] Our result that sticky-price firms account for approximately fifty percent of firms is consistent with the findings of much of this literature, but the fact that rule-of-thumb firms are ruled out in favor of sticky-information firms implies that the role previously assigned to rule-of-thumb firms in explaining backward-looking behavior in the New Keynesian Phillips Curve (NKPC) is instead likely due to the presence of sticky-information firms.

Flexible-price full-information firms are included to capture the potential importance of heterogeneity in rates at which prices and information are updated. Bouakez et al (2006), Carvalho (2006) and Aoki (2001) demonstrate that heterogeneity in price stickiness across sectors affects the dynamics and optimal monetary policy of a sticky price model respectively. By including flexible price firms, our model nests a simple case of such heterogeneity. The fact that these types of firms receive an estimated share of less than 5% indicates that heterogeneity of this sort is relatively unimportant to match the moments of the data.

The presence of sticky-price, sticky-information, and rule-of-thumb firms also nests empirical work to assess the empirical support for the NKPC versus the Sticky Information Phillips Curve (SIPC). While results have been either ambiguous or favored the NKPC (Korenok (2004), Kiley (2007) and Coibion (forthcoming)), most of this literature has assumed that either the NKPC or SIPC (or their weighted average) form the true models without allowing for coexistence of different price setting mechanisms.[7] We build on this approach by allowing for both sticky-price and sticky-information firms to coexist and interact via strategic complementarities in price-setting. Our finding that both types of firms are required to best match the data thus calls into question much of this previous work focused only on one model or the other.

[6] Gali and Gertler (1999), Linde (2005), and Rudd and Whelan (2006) are examples.
[7] Andres et al (2005) is an exception by finding that the sticky-information model is statistically preferred to a sticky-price model.

By considering a hybrid model with sticky-prices and sticky-information, this paper is most closely related to recent work by Dupor et al (forthcoming) and Knotek (2008), both of which append delayed information updating as in Mankiw and Reis (2002) upon firms already facing nominal rigidities: menu costs in Knotek (2008) and time-dependent updating in Dupor et al (forthcoming).[8] Both Knotek and Dupor et al provide empirical evidence for sticky-prices and sticky-information. Thus, our results complement their findings. However, our approach differs from theirs in three important aspects. First, whereas Knotek and Dupor et al each consider models in which all firms are subject to both sticky prices and sticky information, our model allows for sticky-price and sticky-information firms to coexist and interact via strategic complementarities in price-setting, but does not allow for any firm to have both sticky-prices and sticky-information. While we view our approach as a better approximation to the fact that the relative importance of pricing and informational rigidities varies across firms, and thus are likely to be best modeled via different pricing assumptions, whether sticky-prices and sticky-information are best integrated vertically (as in Knotek (2008) and Dupor et al (forthcoming)) or horizontally is an as-of-yet unexplored empirical question. Second, our model is more general since it nests sticky-price, sticky-information, and rule-of-thumb firms as well as flexible-price full-information firms, whereas Knotek (2008) and Dupor et al (forthcoming) exclude either rule-of-thumb or flexible-price full-information firms. Third, neither Knotek (2008) nor Dupor et al (forthcoming) use fully-specified DSGE models for their empirical results and thus are not able to explore the implications of heterogeneous price-setting for sources of business cycles, optimal policy and so on.

To estimate our DSGE model, we make use of the dynamic auto- and cross-covariances of observable variables. These moments provide important insights about the lead-lag structure of economic relationships. By comparing the ability of the estimated hybrid model and estimated pure models to match these moments of the data, one contribution of the paper is being able to assess *why* the data prefer our hybrid model over pure sticky-price or sticky-information models. For example, because the estimated sticky-price model over-predicts by how much inflation leads output growth, we argue that the sticky-price model yields inflation that is too forward-looking, a point closely related to Gali and Gertler (1999). On the other hand, we argue that the sticky-information model is rejected primarily due to the fact that inflation in such a model tends to be too inertial.

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[8] In Knotek (2008), information updates follow a Poisson process as in Mankiw and Reis (2002), but subject to a maximum number of periods after which information is automatically updated.

We also consider the implications of our results for optimal monetary policy. While much work has been devoted to studying optimal monetary policy for sticky-price models, and some work has extended this type of analysis to sticky-information, Kitamura (2008) is the only other paper which considers optimal monetary policy in a hybrid sticky-price and sticky-information model and does so using the vertically integrated hybrid model of Dupor et al (forthcoming).[9] Based on our estimated DSGE model, we find that there could be significant gains in welfare if the central bank used policy rules different from the estimated Taylor rule. In particular, our simulations indicate dramatic improvements when the central banker has a more aggressive response to inflation or incorporates an element of price level targeting in his or her reaction function. Second, we show that using pure sticky-price or sticky-information models can greatly mislead the central banker about potential gains from using alternative policy rules in the presence of heterogeneous price setting. The fact that Kitamura (2008) reaches a similar conclusion using an alternative integration of price and informational rigidities supports the notion that accounting for both types of rigidities has important monetary policy implications which are not adequately addressed in either pure sticky-price or pure sticky-information models. Finally, there is little penalty from using a policy with a response to inflation uniform across sectors relative to policy rules with differential responses.

The structure of the paper is as follows. In section 2, we present the model. Section 3 discusses the empirical methodology. Our benchmark estimates, discussion, and robustness analysis are in section 4. Section 5 considers the implications of our results for optimal monetary policy while section 6 concludes.

2 Model

The model has three principal sectors: consumers, firms, and the central bank. The consumer's problem is modeled as a representative agent with internal habit formation.[10] Production is broken into final goods and intermediate goods. The final goods sector is perfectly competitive whereas the intermediate goods sector consists of a continuum of monopolistic producers. The latter follow different price-setting rules. Finally, the central bank sets interest rates according to a Taylor (1993) rule.

[9] See Woodford (2003) for optimal monetary policy based on sticky-prices and Ball et al (2005) for the sticky-information model.

[10] Ravina (2004) and Grishchenko (2005) provide empirical evidence supporting internal habit formation over external habit formation.

2.1 Consumer's Problem

The representative agent seeks to maximize the present discounted value of current and future utility levels

$$\max_{\{C_{t+j},N_{t+j}(i),H_{t+j}\}_{j=0}^{\infty}} E_t \sum_{j=0}^{\infty} \beta^j \left[e^{g_{t+j}} \ln(C_{t+j} - hC_{t+j-1}) - \frac{1}{1+1/\eta} \int_0^1 N_{t+j}^{1+1/\eta}(i) di \right],$$

where C_t is time-t consumption, $N_t(i)$ is labor supplied to intermediate goods sector i, h is the degree of internal habit formation, η is the Frisch labor supply elasticity, β is the discount factor, and g_t is a shock to the marginal utility of consumption. We allow for labor to be supplied individually to specific industries to generate stronger strategic complementarity in price setting.[11] Because consumption and labor are separable in the utility function, we impose that consumption enters in a logarithmic form to be consistent with a balanced growth path. Each period, the consumer faces the following budget constraint

$$C_{t+j} + \frac{H_{t+j}}{P_{t+j}} \leq \int_0^1 N_{t+j}(i) \left(1 - \tau_{N,t+j}\right) \frac{W_{t+j}(i)}{P_{t+j}} di + \frac{H_{t+j-1}}{P_{t+j}} R_{t+j-1} + T_{t+j} ,$$

where H_t is the stock of risk-free bonds held at time t, with the gross nominal interest rate R_t in the following period. $W_t(i)$ is the nominal wage earned from labor supplied to intermediate goods sector i, T_t consists of transfers and profits returned to the consumer, and $\tau_{N,t}$ is an exogenous time-varying labor income tax. Finally, P_t is the price of the consumption good at time t.

Defining Λ_t to be the shadow value of wealth, the first-order conditions with respect to each control variable are

Consumption $$\Lambda_t = \frac{e^{g_t}}{C_t - hC_{t-1}} - \beta h E_t \frac{e^{g_{t+1}}}{C_{t+1} - hC_t} , \quad (1)$$

Labor Supply $$N_t^{1/\eta}(i) = \Lambda_t \left(1 - \tau_{N,t}\right) \frac{W_t(i)}{P_t} , \quad (2)$$

Bonds $$\Lambda_t = \beta E_t \left[\Lambda_{t+1} R_t \frac{P_t}{P_{t+1}} \right]. \quad (3)$$

[11] See Woodford (2003, Chapter 3) for a discussion of why strategic complementarity is needed in New Keynesian models.

2.2 Production

The final good is produced by a perfectly competitive industry using a continuum of intermediate goods through a Dixit-Stiglitz aggregator

$$Y_t = \left(\int_0^1 Y_t(j)^{\frac{\theta-1}{\theta}} dj \right)^{\frac{\theta}{\theta-1}}.$$

This yields the following price level

$$P_t = \left(\int_0^1 P_j(j)^{1-\theta} dj \right)^{\frac{1}{1-\theta}}.$$

The demand facing an intermediate producer j is then given by

$$Y_t(j) = \left(\frac{P_t(j)}{P_t} \right)^{-\theta} Y_t.$$

We assume that intermediate goods producers have a production function that is linear in labor $Y_t(j) = A_t N_t(j)$.[12] Despite the presence of firm-specific labor supply, we assume that firms treat wages as exogenously determined. The optimal frictionless price ($P_t^{\#}$) is a markup $\mu \equiv \theta/(\theta-1)$ over firm-specific nominal marginal costs, where the latter are given by $MC_t(j) = W_t(j)/A_t$. Eliminating the firm-specific elements of marginal cost by substituting in the labor supply condition and the firm-level demand yields the following relationship between real firm-specific marginal costs and aggregate marginal costs

$$\frac{MC_t(j)}{P_t} = \frac{\left(P_t(j)/P_t\right)^{-\omega\theta}}{D_t} \frac{MC_t}{P_t},$$

where $\omega \equiv \eta^{-1}$, $MC_t/P_t \equiv \frac{(Y_t/A_t)^{\omega}}{\alpha \Lambda_t A_t (1-\tau_{N,t})} \int_0^1 \left(P_t(i)/P_t\right)^{-\omega\theta} di$, and $D_t = \int_0^1 \left(P_t(i)/P_t\right)^{-\omega\theta} di$ is a measure of the dispersion of prices across firms. We can then write a firm's instantaneous optimal desired relative price as

$$\left(\frac{P_t^{\#}}{P_t}\right)^{1+\omega\theta} = \left(\frac{\mu}{D_t}\right) \frac{MC_t}{P_t}, \tag{4}$$

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[12] We omit capital from the model for tractability. Woodford (2003, p. 372-378) argues that the dynamics of the standard pricing model without capital is very similar to the dynamics of the model with capital.

Since there is no capital in the model, the goods market clearing condition is simply $Y_t = C_t$.

2.3 Price-Setting Behavior

Intermediate good producing firms are assumed to be in one of four price-setting sectors: sticky prices, sticky-information, rule-of-thumb, or flexible prices. We assume, without loss of generality, that firms of the same pricing sector are grouped into segments so that the price level can be written as

$$P_t = \left[\int_0^{s_1} P_t^{sp}(j)^{1-\theta} dj + \int_{s_1}^{s_2+s_1} P_t^{si}(j)^{1-\theta} dj + \int_{s_2+s_1}^{s_3+s_2+s_1} P_t^{rot}(j)^{1-\theta} dj + \int_{s_3+s_2+s_1}^{1} P_t^{flex}(j)^{1-\theta} dj \right]^{1/(1-\theta)},$$

where *sp, si, rot*, and *flex* are indices for sticky-price, sticky-information, rule-of-thumb, and flexible price firms respectively. Importantly, firms are otherwise identical in the sense that a firm in a given sector is the same competitor to all other firms symmetrically irrespective of whether they are in the same sector or not. The weighting parameters s_1, s_2, and s_3 are the fractions of firms that belong to the sticky-price, sticky-information, and rule-of-thumb sectors respectively. Flexible-price firms are assigned the remaining mass of $s_4=1-s_1-s_2-s_3$. Firms cannot switch sectors. Defining the price level specific to sector x as $P_t^x \equiv \left[\int_0^1 P_t^x(j)^{1-\theta} dj \right]^{1/(1-\theta)}$, we can rewrite the aggregate price level as

$$P_t = \left[s_1 P_t^{sp^{1-\theta}} + s_2 P_t^{si^{1-\theta}} + s_3 P_t^{rot^{1-\theta}} + s_4 P_t^{flex^{1-\theta}} \right]^{1/(1-\theta)}. \tag{5}$$

<u>*Sticky price firms*</u>: These firms face a constant probability $1-\delta_{sp}$ of being able to change their price each period. A firm with the ability to change its price at time t will choose a reset price B_t to maximize the expected present discounted value of future profits

$$B_t(j) = \arg\max \sum_{j=0}^{\infty} \delta_{sp}^j E_t \left\{ Q_{t,t+j} \left(B_t(j) - MC_{t+j}(j) \right) Y_{t+j}(j) \right\}$$

where $Q_{t,t+j}$ is the nominal stochastic discount factor between times t and $t+j$ and firm-specific marginal costs and output are as before. Taking the first-order condition and replacing firm-specific marginal costs and output with their corresponding aggregate terms yields the optimality condition

$$\sum_{j=0}^{\infty} \delta_{sp}^j E_t \left\{ Q_{t,t+j} Y_{t+j} P_{t+j}^{\theta} \left[B_t^{1+\omega\theta} - \mu MC_{t+j} P_{t+j}^{\theta\omega} / D_{t+j} \right] \right\} = 0 \tag{6}$$

so that all firms with the opportunity to reset prices choose the same value of B_t. The price level for sticky price firms obeys

$$P_t^{sp} = \left[(1-\delta_{sp})B_t^{1-\theta} + \delta_{sp} P_{t-1}^{sp^{1-\theta}}\right]^{1/(1-\theta)}. \tag{7}$$

Sticky-Information Firms: These firms face a Poisson process for updating their information sets, with the probability of getting new information in each period given by $1-\delta_{si}$. In every period, firms set prices freely given their information set. Thus, a firm j that updated its information at time k periods ago sets its time-t price equal to $P_{t|t-k}^{si}(j) = E_{t-k} P_t^{\#}$. Hence, the price level for sticky information firms is

$$P_t^{si} = \left[(1-\delta_{si})\sum_{j=0}^{\infty} \delta_{si}^{j} (E_{t-j} P_t^{\#})^{1-\theta}\right]^{1/(1-\theta)}. \tag{8}$$

Rule-of-Thumb Firms: These firms always change their prices by the previous period's inflation rate.[13] Hence, the price level follows

$$P_t^{rot} = P_{t-1}^{rot}\left(\frac{P_{t-1}}{P_{t-2}}\right). \tag{9}$$

Flexible Price/Information Firms: These firms are always free to change prices and have complete information. They thus always set prices equal to the instantaneously optimal price. The price level for flexible price firms is then just $P_t^{flex} = P_t^{\#}$.

2.4 Shocks

We assume the following shock processes. First, technology shocks follow a random walk with drift

$$\log A_t = \log a + \log A_{t-1} + \varepsilon_{a,t},$$

[13] Technically this implies that the relative price level of rule-of-thumb firms is indeterminate in a stationary steady-state. This can be avoided by assuming a Poisson probability 1-δ_{rot} that each firm is allowed to set its price equal to $P_t^{\#}$. Taking the limit as δ_{rot} goes to one leads to a well-defined relative price level equal to $P^{\#}/P$. We omit this in the text for simplicity but assume it implicitly later when we characterize the steady-state.

where $\varepsilon_{a,t}$ are independently distributed with mean zero and variance σ_a^2. Tax and preference shocks are stationary AR(1) processes

$$g_t = \rho_g g_{t-1} + \varepsilon_{g,t} ,$$

$$\tau_t = (1-\rho_\tau)\overline{\tau} + \rho_\tau \tau_{t-1} + \varepsilon_{\tau,t} ,$$

where $\tau_t \equiv \log(1-\tau_{N,t})$, and both $\varepsilon_{g,t}$ and $\varepsilon_{\tau,t}$ are independently distributed shocks with mean zero and variances σ_g^2 and σ_τ^2 respectively.

2.5 Log-Linearizing around the Balanced-Growth Path

Because technology follows a random walk with drift, output and consumption will inherit the unit root component of technology. To ensure stationarity, we log-linearize the model around the balanced growth path in which Y/A is stationary. Note that equation (1) ensures that $\Lambda_t A_t$ is also stationary. Defining y_t and λ_t to be the log-deviations of Y_t/A_t and $\Lambda_t A_t$ from their balanced growth paths respectively, we can rewrite (1) in log-linearized form as

$$(1-h/a)(1-\beta h/a)\lambda_t =$$

$$(1-h/a)(1-\rho_g \beta h/a)g_t + (h/a)(\beta E_t y_{t+1} + y_{t-1} - \varepsilon_{a,t}) - (1+\beta(h/a)^2)y_t \qquad (10)$$

and the Euler equation as

$$\lambda_t = E_t \lambda_{t+1} + (r_t - E_t \pi_{t+1}) , \qquad (11)$$

where $\pi_t \equiv \log(P_t / P_{t-1}) - \log(\overline{\pi})$ and $\overline{\pi} = P_t / P_{t-1}$ along the balanced growth path. The log-deviation of the interest rate r_t is defined as $r_t \equiv \log(R_t / \overline{R})$.

We allow the log of steady-state inflation to differ from zero, as in Cogley and Sbordone (2008). The log-deviation of inflation from its steady-state value is a weighted average of sector specific inflation rates

$$\pi_t = \sum_j s_j \overline{p^j}^{1-\theta} \pi_t^j = \sum_j s_j^{CPI} \pi_t^j \quad \text{for } j = \{sp, si, rot, flex\} , \qquad (12)$$

where $\pi_t^j \equiv \log(P_t^j / P_{t-1}^j) - \log(\overline{\pi})$, $\overline{p^j} \equiv \overline{P^j / P}$ is the steady-state relative price level of sector *j*, and $s_j^{CPI} \equiv s_j \overline{p^j}^{1-\theta}$ is the effective share of sector *j* in the aggregate price index.[14]

Because inflation is not zero on average, sticky-price firms have to take into account the fact that prices will tend to rise on average. Hence, the reset price will generally be greater than the average price level to offset the tendency of prices to rise. From equation (6), we can find the steady-state relative reset price to be

$$\overline{\left(\frac{B}{P}\right)} = \left(\frac{1-\gamma_1}{1-\gamma_2}\right)^{1/(1+\omega\theta)} \overline{\left(\frac{P^\#}{P}\right)} > \overline{\left(\frac{P^\#}{P}\right)},$$

where $\gamma_1 \equiv \delta_{sp} a \overline{R}^{-1} \overline{\pi}^{\theta}$ and $\gamma_2 \equiv \delta_{sp} a \overline{R}^{-1} \overline{\pi}^{1+\theta(1+\omega)}$. But the non-zero rate of inflation also affects the steady-state level of the optimal relative price. Specifically, one can show that

$$\overline{\left(\frac{P^\#}{P}\right)} = \left[s_1 \left(\frac{1-\delta_{sp}}{1-\delta_{sp}\overline{\pi}^{\theta-1}}\right)\left(\frac{1-\gamma_1}{1-\gamma_2}\right)^{(1-\theta)/(1+\omega\theta)} + \left(1-s_1\right)\right]^{1/(\theta-1)}.$$

To the extent that the extra weight attached to s_1 will in general not be equal to one, the optimal relative price will also then differ from one. We can show the following result:

> ***Proposition 1:*** *When trend inflation is greater than zero, there exists a unique* $\beta^*(\theta, \omega, \delta_{sp}, \overline{\pi})$ *such that if* $\beta > \beta^*$*, the steady state average relative price level of sticky price firms is greater than one while the optimal relative price is less than one* (*and vice versa for* $\beta < \beta^*$).
> *Proof: See Appendix 1.*

When trend inflation is positive, the relative reset price chosen by sticky-price firms declines over time as the aggregate price level rises. If firms care enough about future profits, then they must choose a high reset price today to avoid the relative reset price being too low in the distant future. This will cause the average relative price level of sticky-price firms to be greater than one. However, if firms care primarily about near-term profits (β is small), then firms will choose a reset price that is close to optimal over a short time period. As this relative price declines over time with inflation, the average price level for sticky-price firms will be less than one.

[14] Note that equation (12) uses the fact that the weighted sum of the log-linearized relative price levels is zero.

If the steady-state average relative price level of a sector is greater than one, then its share in the final good will be lower than implied by its mass in the output index. The final goods price index will therefore place a smaller weight on the price of the good of this sector, that is, $s_1^{CPI} < s_1$. This implies that, upon log-linearizing around steady-state values, price changes in this sector will have a smaller effect on aggregate inflation than would be the case if it had a steady-state relative price of one, as can be seen in equation (12). Because $\beta > \beta^*$ in all of our estimates, we have $s_1^{CPI} < s_1$.

From (4) and the definition of the real marginal cost, the log-linearized deviation of the instantaneously optimal relative price is given by

$$p_t^\# \equiv \log\left(\frac{P_t^\#}{P_t}\right) - \log\overline{\left(\frac{P^\#}{P}\right)} = \left(\frac{1}{1+\omega\theta}\right)(\omega y_t - \lambda_t - \tau_t). \qquad (13)$$

To log-linearize the reset price of sticky-price firms, we first rewrite equation (6) in terms of stationary variables

$$\sum_{j=0}^{\infty}\delta_{sp}^j E_t\left\{Q_{t,t+j}\prod_{s=1}^{j}\left(\left(\frac{Y_{t+s}}{Y_{t+s-1}}\right)\left(\frac{P_{t+s}}{P_{t+s-1}}\right)^{\theta}\right)\left[\left(\frac{B_t}{P_t}\right)^{1+\theta\omega} - \left(\frac{P_{t+j}^\#}{P_{t+j}}\right)^{1+\theta\omega}\prod_{s=1}^{j}\left(\frac{P_{t+s}}{P_{t+s-1}}\right)^{1+\theta\omega}\right]\right\} = 0. \qquad (14)$$

Defining b_t as the log deviation of B_t / P_t from its stationary steady-state value and log-linearizing (14) around the balanced growth path leads to the following expression for the reset price[15]

$$b_t = (1-\gamma_2)\sum_{j=0}^{\infty}\gamma_2^j E_t p_{t+j}^\# + \frac{1}{1+\theta\omega}\sum_{j=1}^{\infty}(\gamma_2^j - \gamma_1^j)E_t[gy_{t+j} - r_{t+j-1}] + \frac{1}{1+\theta\omega}\sum_{j=1}^{\infty}[\gamma_2^j(1+\theta(1+\omega)) - \theta\gamma_1^j]E_t\pi_{t+j},$$

where $gy_t \equiv \log(Y_t / Y_{t-1}) - \log a$ is the (stationary) log-deviation of the growth rate of output from its mean.

OLI: please add the three equation system

[15] For these sums to be well-defined in the steady-state requires that $\gamma_2 < 1$. Note that we express the reset price in terms of optimal prices rather than real marginal costs. The reason is that real marginal costs are also a function of the price dispersion D_t. With non-zero trend inflation, this dispersion term has first order effects. By expressing price setting decisions in terms of desired optimal prices, we reduce the state space of the model by eliminating the need to keep track of the dynamics of price dispersion.

Denoting the log-deviation of each sector's relative price level from its steady state value as $p_t^x \equiv \log(P_t^x / P_t) - \log\left(\overline{P_t^x / P_t}\right)$, the log-linearized relative price level of sticky price firms follows

$$p_t^{sp} = (1-\delta_{sp})\overline{\left(\frac{b}{p^{sp}}\right)}^{1-\theta} b_t + \delta_{sp}\overline{\pi}^{\theta-1}(p_{t-1}^{sp} - \pi_t),$$

where the steady-state ratio of reset prices to the sticky-price level is given by[16]

$$\overline{\left(\frac{b}{p^{sp}}\right)} = \left(\frac{1-\delta_{sp}}{1-\delta_{sp}\overline{\pi}^{\theta-1}}\right)^{\frac{1}{\theta-1}}.$$

The stationary relative price level for sticky-information firms is given by

$$\frac{P_t^{si}}{P_t} = \left[(1-\delta_{si})\sum_{j=0}^{\infty}\delta_{si}^j\left(\frac{E_{t-j}P_t^{\#}}{P_t}\right)^{1-\theta}\right]^{1/(1-\theta)} = \left[(1-\delta_{si})\sum_{j=0}^{\infty}\delta_{si}^j\left(\frac{E_{t-j}(P_t^{\#}/P_t)}{(E_{t-j}P_t)/P_t}\right)^{1-\theta}\right]^{1/(1-\theta)},$$

which yields the following log-linearized expression

$$p_t^{si} = (1-\delta_{si})\sum_{j=0}^{\infty}\delta_{si}^j[E_{t-j}p_t^{\#} - CIFE_{j,t}], \tag{15}$$

where the cumulative inflation forecast error is $CIFE_{j,t} \equiv \sum_{s=1}^{j}(\pi_{t-j+s} - E_{t-j}\pi_{t-j+s})$. The latter appears because the relative price of sticky information firms depends not only on how firms set prices relative to the expected price level but also on how the expected price level differs from the actual price level. To condense the set of expectations we need to keep track of, expression (15) can be rewritten as

$$p_t^{si} = \delta_{si}p_{t-1}^{si} + (1-\delta_{si})p_t^{\#} + (1-\delta_{si})\delta_{si}\sum_{j=0}^{\infty}\delta_{si}^j\left[(E_{t-1-j}\pi_t - \pi_t) + E_{t-1-j}\Delta p_t^{\#}\right]. \tag{16}$$

Since the inflation rate for rule-of-thumb firms is

$$\pi_t^{rot} = \pi_{t-1}, \tag{17}$$

the log-linearized relative price level of rule-of-thumb firms follows

$$p_t^{rot} = p_{t-1}^{rot} + \pi_{t-1} - \pi_t = p_{t-1}^{rot} - \Delta\pi_t. \tag{18}$$

Inflation of flexible-price firms is

$$\pi_t^{flex} = p_t^{\#} - p_{t-1}^{\#} + \pi_t. \tag{19}$$

[16] For the relative reset price to be well-defined in equilibrium requires the additional condition that $\delta_{sp}\overline{\pi}^{1-\theta} < 1$.

2.6 Central Bank

To close the model, we need to describe the central bank's behavior. We follow the literature and assume that the central bank sets interest rates according to a Taylor (1993) type rule with interest smoothing such that

$$r_t = (1-\rho_1-\rho_2)[\phi_\pi \pi_t + \phi_{gy} gy_t] + \rho_1 r_{t-1} + \rho_2 r_{t-2} + \varepsilon_{r,t}, \qquad (20)$$

which allows the central bank to respond to inflation and the growth rate of output.[17] The lagged interest rate term captures the central bank's desire to smooth interest changes. The policy innovations $\varepsilon_{r,t}$ are assumed to be independently distributed with mean zero and variance σ_r^2.

3 Estimation Approach

As in Ireland (2004), our log-linearized model has three variables that directly correspond to observable macroeconomic series: the inflation rate, the growth rate of output, and the nominal interest rate. The advantage of focusing on output growth, rather than the output gap as traditionally done, is that output growth is directly observable, whereas the output gap is not. In addition, the theoretically motivated output gap would tend to be poorly approximated by standard detrending methods (see Andres et al (2005)).[18] To estimate the underlying parameters of the model, we use a method-of-moments approach that seeks to match the contemporaneous and intertemporal covariances of the observable variables from the data to those of the model. After solving our model for the unique rational expectations equilibrium and letting Ψ denote the vector of parameters in the model, we can rewrite it in reduced form as

$$X_t = A(\Psi)X_{t-1} + B(\Psi)\Phi_t + C(\Psi)\Xi_t,$$

where Φ_t is the vector of structural shocks, X_t is the vector $[Y_t' \; Q_t' \; Y_{t-1}' \; Q_{t-1}' \; \ldots \; Y_{t-p}' \; Q_{t-p}']'$, $Y_t = [gy_t \; \pi_t \; r_t]'$ is the vector of observable variables, Q_t is the vector of all unobservable variables,

[17] We follow Ireland (2004) and allow for the central bank to respond to output *growth* rather than some measure of the output gap. Our qualitative results are insensitive to the inclusion of an additional output gap term in the Taylor rule, as shown in section 4.4.

[18] Gorodnichenko and Ng (2008) also show that using growth rates of variables could lead to better statistical estimate than using levels of persistent variables.

and Ξ_t is the vector of serially uncorrelated measurement errors.[19] The value of p determines the truncation point used for the sticky information sector. Denoting the variance-covariance matrix of the structural and measurement shocks by $\Omega_\Phi = \Omega_\Phi(\Psi)$ and $\Omega_\Xi = \Omega_\Xi(\Psi)$, the variance-autocovariance matrix of X_t denoted with $\Omega_X(\Psi)$ is

$$vec(\Omega_X(\Psi)) = \left[I - A(\Psi)\otimes A(\Psi)\right]^{-1} vec\left[B(\Psi)\Omega_\Phi B(\Psi)' + C(\Psi)\Omega_\Xi C(\Psi)'\right].$$

Because measurement errors are assumed to be serially and contemporaneously uncorrelated, Ω_Ξ is a diagonal matrix whose non-zero elements consist of the variances of measurement errors of the growth rate of output ($\sigma^2_{me,gy}$), inflation ($\sigma^2_{me,\pi}$), and interest rates ($\sigma^2_{me,r}$) respectively. The variance-autocovariance matrix for observable variables is then $\Omega_Y(\Psi) = \Upsilon\Omega_X(\Psi)\Upsilon'$ where Υ is the appropriate selection matrix.

On the other hand, we can compute sample autocovariance matrix for the observed variables, $\Delta_{Y,n} \equiv [vech(\hat{\Omega}_{Y,0})' \; vec(\hat{\Omega}_{Y,1})' \; \ldots \; vec(\hat{\Omega}_{Y,n})']'$ where $\hat{\Omega}_{Y,j}$ is the sample estimate of $\mathrm{cov}(Y_t, Y_{t-j})$ in the data. We extract the corresponding moments of the model for the observable variables and denote the resulting matrix with $\Delta_{Y,n}(\Psi) \equiv [vech(\Omega_{Y,0}(\Psi))' \; vec(\Omega_{Y,1}(\Psi))' \; \ldots \; vec(\Omega_{Y,n}(\Psi))']'$. In summary, our method of moments estimator of the parameters is then given by

$$\hat{\Psi} = \arg\min\left\{(\Delta_{Y,n}(\Psi) - \Delta_{Y,n})' \times W \times (\Delta_{Y,n}(\Psi) - \Delta_{Y,n})\right\}$$

where W is a weighting matrix. The resulting $\hat{\Psi}$ is a consistent estimate, provided that $\hat{\Psi}$ is identified. Following Abowd and Card (1989), Altonji and Segal (1996) and others, we use the identity weighting matrix in the estimation of the covariance structure.[20] Note that because $\Omega_{Y,n}(\Psi)$ is highly non-linear in Ψ, it may be hard to find the global optimum. To address this problem, we use stochastic search optimizers to achieve the global optimum.

Ruge-Murcia (2003) compares method of moments estimators with other popular methods such as maximum likelihood for estimating DGSE models and finds that it performs well in simulations. An appealing feature of our method of moments approach is that the moments of the

[19] Sargent (1989) and others emphasize the importance of measurement errors in reported macroeconomic variables. We introduce measurement errors to absorb short-term fluctuations in the variables unrelated to structural shocks.

[20] These authors find that W equal to the identity matrix performs better than the optimal weighting matrix in the context of estimating covariance structures. The optimal weighting matrix, which contains high order moments, tends to correlate with the moments and this correlation undermines the performance of the method of moments estimator. We investigate the robustness of our results to the weighting matrix in section 4.4.

data have an economic interpretation. Comparing the predicted moments of the model to those of the data highlights which features of the data the model can and cannot match.

4 Results

We use data from 1954:Q4 until 2005:Q4. The growth of output is measured as $400\times log(RGDP_t/RGDP_{t-1})$ where *RGDP* is chained real gross domestic product. Inflation is measured using the CPI by $400\times log(P_t/P_{t-1})$. The interest rate is $400\times log(1+R_t)$ where R_t is the Effective Federal Funds rate (at quarterly rate). We focus on the contemporaneous covariances and the first three cross-autocovariances of these series to estimate the parameters of the model. We restrict the number of moments to the minimum sufficient for identification to minimize computational burden and to sharpen inference as the plethora of weakly informative moments tends to deteriorate the estimator's performance.[21]

Our model contains the following set of parameters $\Psi=\{a,\ \bar{R},\ \bar{\pi}\ \beta,\ \eta,\ h,\ \theta,\ \delta_{si},\ \delta_{sp},\ s_1,\ s_2,\ s_3,\ \phi_{\pi},\ \phi_{gy},\ \rho_1,\ \rho_2,\ \rho_{\tau},\ \rho_g,\ \sigma_r,\ \sigma_a,\ \sigma_{\tau},\ \sigma_{me,gy},\ \sigma_{me,\pi},\ \sigma_{me,r}\}$. We calibrate the balanced-growth inflation rate, interest rate, and growth rate of output to those observed in our sample. Following Ireland (2004), we impose $\beta = 0.99$ to guarantee that the consumer's problem is well bounded. We set $\eta = 1$, a fairly typical calibrated value for the Frisch labor supply elasticity.[22] The other parameters are estimated using Markov-Chain Monte-Carlo methods, with details provided in Appendix 2. We set the truncation of past expectations to $p = 12$.

4.1 Baseline Estimates

Table 1 presents our baseline estimates for the hybrid model, as well as estimates imposing that all firms be of the same price-setting sector.[23] We focus first on the estimates of the hybrid model and return to the estimates for the pure models in section 4.2. The estimated elasticity of substitution between intermediate goods is 17.8, implying a steady-state markup of 6 percent. The habit persistence, at 0.96, is relatively high but in the range of estimates found in other studies.[24] Our

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[21] We consider the effect of using more moments in the robustness section 4.4.
[22] See Christiano, Eichembaum, and Evans (2005), for example. We investigate the robustness of our results to η in section 4.4.
[23] We omit the case with only rule-of-thumb firms since in this model inflation is always equal to last quarter's inflation, making the dynamics of this pure model relatively uninteresting.
[24] See Fuhrer (2000), Grishchenko (2005), and Edge et al (2005).

Taylor rule estimates imply strong responses by the central bank to both inflation and the growth rate of output, with substantial inertia apparent in the interest rate. The weight assigned to sticky-price firms is 50%. Sticky-information firms are assigned almost 46%. Rule-of-thumb firms account for less than 1% of firms, while flexible price firms receive a share of less than four percent. The estimated degree of price rigidity is 0.47, which implies that sticky-price firms update their prices approximately twice a year on average. Sticky-information firms, with an estimated degree of informational rigidity of 0.62, update their information sets a little less than twice a year on average. Appendix Figure A1 displays the distribution of parameter draws over the last 100,000 draws.

Because no single firm type receives a share of 100%, the first implication of our results is that our nested model best matches the data when more than a single type of firm is present. However, rule-of-thumb and flexible price firms jointly account for less than 5% of firms. Thus, the most striking result from our estimation is that *the estimated hybrid model consists almost exclusively of sticky-price and sticky-information firms*. This result is particularly noteworthy for two reasons. First, much of the literature on sticky-prices and sticky-information has focused on testing one model against the other (Korenok (2004), Kiley (2007), Coibion (forthcoming)). Our results imply instead that both are needed to match the moments of the data. Second, sticky-price models are commonly augmented with rule-of-thumb firms to introduce more inflation inertia (Gali and Gertler (1999)). As we discuss in section 4.3, in the presence of strategic interaction across sectors rule-of-thumb firms behave similarly to sticky-information firms so that the conventional emphasis on rule-of-thumb firms could have been misplaced. Once one allows for both rule-of-thumb and sticky-information firms, the data favors sticky information as a complement to sticky-price models.

4.2 How Does The Hybrid Model Differ From The Nested Pure Models?

In this section, we study why the data prefers a hybrid sticky-price sticky-information model over the pure models. To do so, we first re-estimate the structural parameters of the model under the assumption that only one type of firm exists and use these estimates to construct variance decompositions for each model. Second, we compare the predicted moments of the hybrid and pure models to those of the data. Third, we contrast the impulse response functions of each estimated model.

4.2.1 Estimates of Pure Models

To get a sense of why the pure models are rejected in favor of a hybrid, we first re-estimate the parameters of the model while imposing that the model be entirely composed of sticky-price, sticky-information, or flexible-price full-information firms.[25] The results are presented in Table 1. Note first that the sticky-price model achieves the lowest value of the objective function after the hybrid model, the sticky-price model comes second, while the flexible-price model does much worse. Across models, the estimated degree of habit formation (h) is consistently very high, but the estimates of the elasticity of substitution θ differ across models. Interestingly, for all three pure models, the estimated level of θ is close to 8, while the hybrid model yields an estimated value of more than twice that. This high estimate introduces more strategic complementarity among firms in the hybrid model than in any of the pure models. The coefficients of the Taylor rule also differ substantially across models. The flexible price model yields almost no response to the growth rate of output, a smaller response to inflation, and little interest-rate smoothing. The sticky-price model yields estimates very similar to those of the hybrid model while the sticky information model a very large response to both inflation and output growth, as well as a substantial level of interest smoothing. The sticky-information model is close to the flexible-price model in terms of the responses to inflation and output growth, but with much more interest smoothing than in the latter. Turning to estimated shock processes, the key difference across models lies in the tax wedge shock. Whereas for the hybrid and sticky-price models the estimated standard deviation of the tax shock is not statistically different from zero, for both the sticky-information and flexible models the standard deviation is much larger and more precisely estimated. For the former, the standard deviation of tax wedge shocks is approximately eight times larger than in the hybrid model.

This has important implications for the relative importance attributed to each shock by the different models for explaining macroeconomic dynamics. Table 2 presents the one-year ahead variance decompositions of output growth, inflation, and interest rates of each model. For output growth, all the models yield the conclusion that more than ninety percent of the variance is due to preferences shocks, with the rest coming from technology shocks. For inflation, there is much more variation across models. The hybrid and sticky-price model both point to technology shocks as the primary driver of inflation volatility (around 70%), with the remaining volatility coming from policy

[25] Because the dynamic responses of each pure model are so different from each other across shocks, as well as the fact that all the parameters of the model are estimated jointly, it is misleading to take our estimated values and simply consider imposing that the model only consist of one type of firm to determine how each model fares independently.

and preference shocks. Tax wedge shocks again account for none of the volatility in these models. The sticky-information model, on the other hand, implies that forty-five percent of inflation volatility comes from the tax wedge shock, with technology and policy shocks each accounting for twenty-five percent. The flexible price model also places substantial weight on the tax wedge shock. Decomposing the variance of interest rates yields a similar result. Both the hybrid and sticky-price model find that most of the volatility in interest rates comes from policy and preference shocks but none from the tax wedge shock, while the sticky-information model yields the result that nearly twenty percent on interest rate volatility comes from the tax wedge shock. Thus, the higher estimated standard deviation of tax wedge shocks for both the sticky-information and flexible price and information models clearly yields different conclusions about which shocks drive business cycle volatility than either the sticky-price or hybrid model.

4.2.2 Comparing Predicted Moments

To further contrast the pure and hybrid models, we consider which features of the data each model can match. Figure 1 presents the autocorrelations of the observable variables implied by the models as well as those found in the data. First, the flexible price model, despite highly persistent tax shocks, is unable to reproduce the high autocorrelation of inflation observed in the data, as well as that of interest rates. Second, all models perform adequately at reproducing the autocorrelation of output growth, largely because this is driven by the high estimates of internal habit. The sticky-information model somewhat over-predicts the persistence of inflation after one quarter but underestimates it after three, whereas the sticky-price model consistently underestimates the persistence of inflation. The hybrid model comes much closer to matching the autocorrelation function of inflation than either pure model, which likely reflects the combination of sticky-price and sticky-information firms, combined with the higher estimated degree of informational rigidity in the hybrid model than in the pure sticky-information model

Figure 2 presents the cross-correlations of inflation with respect to leads and lags of output growth and interest rates, as well as that of output growth to leads and lags of interest rates. The moments of the data indicate that inflation leads output growth and interest rates, as well as that interest rates lead output growth. The fully flexible model is largely incapable of reproducing these lead-lag characteristics of the data, reflecting the fact that in this model, all variables adjust almost fully on impact. The sticky-price model, on the other hand, replicates these lead-lag patterns but tends to overstate by how much one variable leads another, a property which is particularly visible in the case of inflation leading output growth. This reflects the strong forward-lookingness embodied in the reset-price decisions of sticky-price firms, which results in an excessive amount of forward-looking behavior on the part of inflation relative to that observed in the data. While the sticky-information model is able to reproduce the dynamic cross-correlation of interest rates with respect to inflation and output growth, it does not reproduce the lead of inflation over output growth. Instead, the highest correlation between the two is contemporaneous. The hybrid model, on the other hand, yields dynamics that are very similar to the sticky-price model.

4.2.3 Impulse Responses

To understand why the sticky-information model places more weight on tax wedge shocks than either the hybrid or pure sticky-price model, it is helpful to consider the impulse responses of the observable variables to each shock from the different models. These are presented in Figures 3 through 6 for the hybrid, sticky-price and sticky-information models.[26] In each case, we use the estimated parameters from each model to derive impulse responses.

In response to a monetary policy shock, the responses to output growth and interest rates are remarkably similar across models. Even for inflation, there is very little difference. Whereas the peak response of inflation is contemporaneous for the sticky-price and hybrid models, the sticky-information model delivers a slight delay in the inflation response. In response to a preference shock, the only significant difference again lies in the inflation responses of the models, with sticky-price and hybrid models yielding a positive and hump-shaped response, while the sticky-information has a negative contemporaneous response although it quickly turns positive and hump-shaped. In response to a technology shock, all three models yield a positive effect on output growth. Interest rate decreases but differentially across models: the sticky-information model exhibits a negligible decline shortly after the shock and the trough in the response occurs after 15 quarters while the sticky-price model has a strong fall at the time of the shock and bottoms out after 6 quarters. Inflation declines in all three models, but as with policy shocks, the sticky-price model yields an immediate decline, while the sticky-information model displays a delayed response of inflation to technology shocks. The hybrid model inherits some of the delayed response of inflation from the

[26] We omit responses from the flexible price model because a) flexible price and rule-of-thumb firms account for less than 5% of firms in the hybrid model and b) the responses are very large on impact and dwarf those of the other models.

sticky-information model. Finally, in response to a tax wedge shock, all three models display a positive response of output growth and negative and instantaneous responses of inflation and interest rates.

These impulse response help clarify why the sticky-information model places more weight on tax wedge shocks than either the hybrid or sticky-price models. The key is that only technology and tax shocks simultaneously generate negative correlations between inflation and output growth, and between interest rates and output growth, while also delivering a positive correlation between interest rates and inflation, as observed in the cross-correlations of the data. In addition, technology shocks yield a rapid enough response of inflation for both the sticky-price and hybrid models to replicate the empirical finding that inflation yields output growth and interest rates. Thus, technology shocks are sufficient to match most of the cross-correlations used in the estimation for both the hybrid and sticky-price models. However, in the case of the sticky-information model, technology shocks yield only a gradual response of inflation, which fails to match the prediction that inflation leads output growth and interest rates. Instead, the sticky-information model relies on the tax wedge shock to which inflation adjusts more rapidly and which generates the same sign on cross-correlations as observed in the data. This accounts for why technology shocks appear to play such an important role for the hybrid and sticky-price models, whereas tax wedge shocks matter more for the sticky-information model.

4.3 How Important Is Strategic Interaction Among Different Price-Setting Firms?

One question that naturally arises with hybrid models is how the behavior of firms within the hybrid model compares to their behavior when they are the only type of firm. For this purpose, Figure 7 plots the response of inflation in each sector to each shock, as well as the response of aggregate inflation in a model consisting only of this type of firm. For the latter, we use the estimated parameters of the hybrid model and simply alter the share of firms to isolate the strategic interaction effect.

Focusing first on sticky-price firms, in response to monetary policy, technology, and preference shocks, inflation among sticky-price firms within a hybrid model is substantially dampened relative what it would have been had these been the only type of firm in the model. For sticky-information firms, the effect is reversed: their inflation response is more rapid within the hybrid model than in a pure sticky-information model. This is strategic complementarity at work:

the resulting inflation responses in each sector are much more similar than the inflation responses of the pure models. The effect of strategic complementarity is even more striking in the case of flexible-price full-information firms. Whereas inflation for these firms would be substantial on impact—but virtually nil in subsequent periods—within the hybrid model their inflation response is severely dampened. This reflects how much more sensitive these firms are to the behavior of other firms because they are unconstrained in their actions whereas all other firms face some kind of constraint, which is similar in spirit to Haltiwanger and Waldman (1991). If we construct an alternative set of inflation responses for the hybrid model as a weighted average of the inflation responses of each pure model, where the weights are equal to the estimated effective shares from the hybrid model, these responses would be dominated by the extreme behavior of flexible-price full-information firms.

Figure 7 also illustrates why previous work could readily have mistaken sticky-information firms for rule-of-thumb firms. Specifically, the behavior of sticky-information firms within the hybrid model is very similar to that of rule-of-thumb firms. Both commonly display delayed responses of inflation to shocks and serve to dampen inflation among sticky-price firms. However, our empirical results clearly favor sticky information over rule-of-thumb firms within the hybrid model as complements to sticky-price firms.

4.4 Robustness Analysis

In this section, we consider the robustness of our estimates to several potential issues. First, we consider the use of a larger set of moments in the estimation. Second, we discuss the use of a non-identity weighting matrix in the estimation. Third, we change the labor supply elasticity to correspond to indivisible labor. Fourth, we relax the Taylor rule to allow for the central bank to respond to the output gap. Fifth, we reproduce our estimates without allowing for the tax shock. Finally, we use only the post-1982 period in our estimation.[27]

The first issue we address is the set of moments used in the estimation. Our baseline results relied on the autocorrelations of our observable variables over three quarters and dynamic cross-correlations at maximum leads and lags of three quarters as well. The purpose of focusing on such a

[27] All robustness checks are done by using as starting values the baseline parameter estimates and associated distribution. From this starting value, we run 200,000 iterations and present results after dropping the first 100,000. This number of simulations and the length of the burn-in period are sufficient to achieve stationary distributions for estimated parameters.

restricted set of moments was to concentrate on those moments that are most precisely estimated. As a robustness check, we consider the use of a larger set of moments, specifically using autocovariances over two years, and report results in Table 3. Most of the parameters are largely unchanged, but there are some noteworthy differences which appear to primarily reflect the difficulty of matching the high autocorrelation of inflation over two years. First, the Fed's response to inflation is lower. Secondly, we find that the share of sticky-information firms rises to a little over two-thirds, while that of sticky-price firms declines to a little less than one-third. The two sets of firms account for approximately 98% of all firms in the model, so our primary contribution of ruling out rule-of-thumb firms continues to hold. In addition, the degree of price stickiness rises to 0.67 (firms update prices every three quarters on average) while the degree of informational rigidity rises to 0.75, the exact value assumed by Mankiw and Reis (2002), such that sticky-information firms updated their information sets once a year on average. All these changes increase the persistence of the inflation process, and induce a somewhat delayed response of inflation to technology shocks. As a result, the estimation yields a higher estimate of the standard deviation of tax shocks to better match the dynamic cross-correlation of the observable variables, as was the case with the pure sticky-information model. Thus, using a larger set of moments makes the hybrid model behave somewhat more like the pure sticky-information model than was the case in the baseline estimates.

An alternative approach to dealing with the precision of the moments used in the estimation is to allow for a non-identity weighting matrix. Although the optimal weighting matrix would seem an ideal candidate, many studies report poor performance of this weighting matrix in applications (e.g., Boivin and Giannoni 2006) and Monte Carlo simulations (e.g., Altonji and Segal (1996)) that involve estimation of covariance structures. A practical compromise is a diagonal weighting matrix with estimated variances of the moments on the diagonal and zeros for off-diagonal entries.[28] The primary consequence of using this alternative weighting matrix is a substantial loss in the precision of our estimates. All standard errors are several times bigger. The share of sticky-price firms is slightly smaller than in the baseline and the estimated degree of price stickiness is unchanged. Sticky-information firms, on the other hand, now account for a much smaller fraction of firms (12%) which is not statistically different from zero. Rule-of-thumb firms instead now account for nearly 30% of firms. Note that although the shares of rule-of-thumb and sticky-information firms are not

[28] Given the variance of the moment conditions in our case involves fourth moments of the data, we winsorize all observed time series at bottom and top one percent so that unusually large or small observations do not have a strong effect on the estimated fourth moments.

precisely estimated, the sum of rule-of-thumb and sticky-information shares is precisely estimated. Recall that the behavior of rule-of-thumb firms and sticky-information firms is very similar in response to structural shocks. Hence, the choice of the diagonal weight matrix may downplay some informative moments and does not allow us to clearly separate rule-of-thumb and sticky-information firms. Other estimates are broadly similar to the estimates based on the identity weight matrix.

We also consider sensitivity to the elasticity of labor supply. While most empirical work has found low elasticities of labor supply, some of the RBC literature has focused on the case with infinite labor supply (as in Hansen (1985)). In Table 3, we present estimates of the hybrid model under the assumption of indivisible labor ($\eta = \infty$), which implies that $\omega = 0$ so that there is no strategic complementarity in price setting. Note that this has little impact on most estimates. The share of sticky-price firms rises to 63%, but the estimated degree of price rigidity falls to 0.38. Sticky-price and sticky-information firms continue to account for more than 95% of all firms in the model.

Another robustness issue that we consider is allowing for the central bank to respond to the output gap. While this is often included in Taylor rules, our baseline approach instead includes only output growth. This is because output growth is directly observable to the central bank, whereas the gap is not. In addition, Ireland (2004) finds little evidence of a response to the gap once output growth is included in the Taylor rule. As a robustness check, we consider the following Taylor rule

$$r_t = (1-\rho_1-\rho_2)[\phi_\pi \pi_t + \phi_{gy} gy_t + \phi_x x_t] + \rho_1 r_{t-1} + \rho_2 r_{t-2} + \varepsilon_{r,t}$$

where x is the log-deviation between actual output and the level of output that would occur in the absence of price and informational rigidities. As can be seen in Table 3, the estimated response to the output gap is not statistically different from zero while the other parameters are largely unchanged.

According to our baseline results, we find that tax shocks have minute quantitative contribution to variation in the hybrid model. To verify that our results are not affected by the inclusion of an irrelevant shock, we reproduce our estimates with the additional assumption that $\sigma_\tau = 0$ and $\rho_\tau = 0$. The results, presented in Table 3, indicate that our baseline estimates are not influenced by including this quantitatively unimportant shock which is not surprising given that the hybrid model does not need to rely on tax wedge shocks to reproduce cross-correlations of variables at different leads and lags.

Finally, we consider estimates using the moments of the data only since 1982. Some empirical work (e.g., Clarida, Gali, and Gertler (2000)) has emphasized that the period since the Volcker disinflation has been characterized by a stronger response of the Federal Reserve to inflation. As such, it offers a natural break point to impose in the estimation. We find that monetary policy does appear to be much more responsive to both inflation and output growth since Volcker, with ϕ_π (ϕ_{gy}) rising to 3.75 (2.37). The fraction of sticky-price firms is essentially unchanged, while that of sticky-information firms declines to 38%. Rule-of-thumb firms continue to receive a tiny share which is insignificantly different from zero. We find a higher amount of price and informational rigidities, consistent with greater economic stability over this time period. Note that the estimate of informational rigidities of 0.94 is consistent with the post-82 estimates of Khan and Zhu (2006) and Knotek (2008).

5 Implications for Optimal Monetary Policy

The presence of different types of firms in the model raises the issue of what kind of monetary policy is optimal in such a setting. To assess the effect of different policies, we follow much of the literature and assume that the central banker has the following loss function

$$L_1 = \text{var}(\pi_t) + \omega_y \text{var}(x_t) + \omega_r \text{var}(r_t), \tag{21}$$

where ω_y and ω_r show the weight on output gap and interest rate volatility relative to inflation volatility. We also consider an alternative loss function which penalizes for the volatility of output growth rate instead of the volatility of output gap:

$$L_2 = \text{var}(\pi_t) + \omega_y \text{var}(gy_t) + \omega_r \text{var}(r_t), \tag{22}$$

This alternative loss function may be interesting for our analysis because, as Amato and Laubach (2004) show, habit formation introduces a concern for the volatility in the change of consumption and, hence, the loss function should include a term that captures the volatility of output growth rate.

In principle, parameter ω_y can be derived from the Phillips curve. However, because we have different interacting price-setting mechanisms as well as non-zero steady state inflation, there is no closed-form solution for the Phillips curve and ω_y. Consequently, we are agnostic about the relative weight of output gap variability and we experiment with different values of ω_y. The last term in the loss function is the penalty for the volatility of the policy instrument (interest rate).

Having ω_r greater than zero helps to keep the optimal responses to output growth and inflation bounded. We follow Woodford (2003) and calibrate $\omega_r = 0.077$.

The first question we pose is whether the central bank could have achieved lower losses by responding differently to aggregate inflation and output growth than what is implied by our estimates of the Taylor rule. Panel A in Figure 8 presents the isoloss maps for different combinations of ϕ_π and ϕ_{gy} in the Taylor rule.[29] Generally, there are substantial gains from increasing the response to inflation which reduces the volatility of the inflation, interest rate and output gap. Holding everything else constant, more aggressive response to inflation weakly increases the volatility of output growth rate (see Appendix Figure A2). In contrast, stronger response to output growth rate has the opposite effect on the volatility of relevant macroeconomic variables. Since the volatility of output growth rate is fairly insensitive to changes in ϕ_π and ϕ_{gy} in the Taylor rule, the social welfare generally improves with larger ϕ_π and somewhat smaller ϕ_{gy} irrespective of what values we use for ω_y in the loss functions (see Appendix Figure A5).

The second question we ask is whether the optimal policies in pure sticky-price and sticky-information models are similar to those found in the hybrid model. In particular, one may be concerned that using pure models to design policy rules can misguide the policymaker about his or her tradeoffs. Because scales of the social loss maps vary across models, we compute isoloss maps for pure sticky price (PSP) and pure sticky information (PSI) models and normalize these maps by the corresponding values of the loss function evaluated at the estimated Taylor rule parameters. These rescaled isoloss maps, which we call relative welfare maps, can be interpreted as losses relative to the loss incurred when the policymaker uses the estimated Taylor rule. We also scale the isoloss map for the hybrid model and then divide the relative welfare for the PSP and PSI models by the relative welfare map for the hybrid model. The resulting maps show to what extent using PSP and PSI models misinforms the policymaker about tradeoffs relative to the hybrid model.[30] Specifically, if the ratio of relative welfare maps for PSP or PSI to the relative welfare map for the hybrid model is close to one uniformly in (ϕ_π, ϕ_{gy}) space, there is no distortion in the tradeoffs. If the ratio is greater than one (smaller than one), then using the PSP or PSI model understates (overstates) the gain in welfare. Panels B and C in Figure 8 show the ratio of relative welfare maps for PSP and

[29] In this and subsequent exercises, we hold the interest rate smoothing parameters of the Taylor rule fixed at their estimated values.
[30] Alternatively, one can interpret the ratio of the relative welfare maps as the difference-in-difference estimator for the changes in the welfare changes when the policymaker considers alternative values of ϕ_π and ϕ_{gy} in the Taylor rule.

PSI models respectively. These maps demonstrate that using pure models instead of the hybrid model can greatly mislead the policymaker about potential gains from using alternative policy rules. For example, when the policymaker uses the PSP model to design policy, he or she overestimates the benefits from stronger responses to inflation relative to gains implied by the hybrid model because the ratio of relative welfare maps is substantially less than one. On the other hand, using the PSI model would understate the gains from more aggressive responses to inflation. Hence, we conclude that using pure models can provide a distorted picture of tradeoffs actually faced when price-setting is heterogeneous.

Given that PSP and PSI models have different implications for whether the central bank should target the price level or inflation, the third question we ask is whether our hybrid model predicts an important role for price level targeting. To answer this, we augment the Taylor rule with a term that corresponds to price level targeting (PLT):

$$r_t = (1-\rho_{1,r}-\rho_{2,r})\phi_\pi \pi_t + (1-\rho_{1,r}-\rho_{2,r})\phi_{PLT} p_t + (1-\rho_{1,r}-\rho_{2,r})\phi_{gy} gy_t + \rho_{1,r} r_{t-1} + \rho_{2,r} r_{t-2} + \varepsilon_{r,t},$$

where p_t is the price level linearized around $p_t^* = p_0 \bar{\pi}^t$. In this exercise, we fix ϕ_{gy} at the estimated value, vary ϕ_π and ϕ_{PLT} and plot the resulting isoloss amps in Panel D of Figure 8 and associated volatilities of output gap and growth rate, inflation and interest rate in Appendix Figure A3. In general, there are significant welfare gains from having an element of PLT in the Taylor rule. In fact, even small positive responses to deviations from the price level target dramatically reduce the volatility of output gap, interest rate and inflation. At the same time, similar to the inflation response, a more aggressive PLT response tends to weakly increase the volatility of output growth rate. However, because this increase is very small, the changes in welfare are strongly dominated by declines in $\text{var}(x_t)$, $\text{var}(\pi_t)$, and $\text{var}(i_t)$ so that PLT is generally desirable for all reasonable values of ω_y (see Appendix Figure A3). Importantly, introducing PLT in the policy reaction function eliminates a region of equilibrium indeterminacy (compare with Panel A, Figure 8) and therefore PLT could be useful in ways other than reducing the volatility of macroeconomic variables.

Finally, having the central bank respond to aggregate inflation imposes the restriction that a one percent increase in inflation in a sector leads to an increase in the interest rate proportional to that sector's effective share of inflation dynamics, as defined in equation (20). The fourth question we ask is whether there are gains to be had by responding differently to inflation in each sector. For this purpose, we compute optimal policy rules using

$$\begin{aligned} r_t &= (1-\rho_{1,r}-\rho_{2,r})\phi_\pi^{(SP)}\pi_t^{(SP)} + (1-\rho_{1,r}-\rho_{2,r})\phi_\pi^{(SI+ROT+FLEX)}\pi_t^{(SI+ROT+FLEX)} \\ &\quad +(1-\rho_{1,r}-\rho_{2,r})\phi_{gy} gy_t + \rho_{1,r} r_{t-1} + \rho_{2,r} r_{t-2} + \varepsilon_{r,t}, \end{aligned}$$

where we assume that the central banker can differentiate between sectors that have prices fixed for some time (*SP*) and that have prices changing every period (*SI*, *ROT* and *FLEX*). Here, we again fix ϕ_{gy} at the estimated value, vary $\phi_\pi^{(SP)}$ and $\phi_\pi^{(SI+ROT+FLEX)}$ and plot the resulting isoloss maps in Panel E of Figure 8 and associated volatilities of output gap and growth rate, inflation and interest rate in Appendix Figure A4.[31] We find a striking result: the isoloss maps are essentially linear in $\phi_\pi^{(SP)}$ and $\phi_\pi^{(SI+ROT+FLEX)}$. In other words, the policymaker does not face a penalty for targeting only one of the sectors. Furthermore, the slope of the isoloss lines is almost equal to one. (This result stems from the fact that the shares of the *SP* and (*SI*+*ROT*+*FLEX*) sectors are approximately equal. The slope is different from one when shares are not equal yet isoloss curves continue to be linear.) Altogether, decreasing response to (*SI*+*ROT*+*FLEX*) inflation by one and increasing response to SP inflation by one is not associated with a loss in the welfare. If the shares of *SP* and (*SI*+*ROT*+*FLEX*) are significantly different, then the policymaker could achieve a given level of social loss by having a more aggressive response to one of the sectors. This exercise suggests that the gains from the differentiated response to sector-specific inflation are probably small.

6 Conclusion

Empirical work has documented a striking amount of heterogeneity in pricing practices: both in the frequency at which firms update prices as well as in the source of costs underlying firm decision-making processes. We present a model in which four commonly used representations of how firms set prices are allowed to coexist and interact via their price-setting decisions. This model nests many specifications previously considered in the literature. We find that the two most important types of price-setting behavior are described by sticky prices and sticky information while rule-of-thumb and flexible pricing are quantitatively unimportant. Furthermore, our estimates indicate that backward-looking behavior typically assigned to rule-of-thumb firms can be driven by sticky-information firms because the two types of firms generate similar dynamics under strategic

[31] Note that moving along the 45° line in Panel E corresponds to moving along the vertical line that passes the estimated Taylor rule parameter combination in Panel A.

complementarity in price setting. This important finding suggests that sticky-information firms may be more important than previously thought.

In addition, because the dynamic cross-covariances reveal important insights about the lead-lag structure of economic relationships, we can provide intuitive explanations for how the hybrid model outperforms pure sticky-price or sticky-information models. For example, we argue that a pure sticky-price model over-predicts how forward-looking inflation is whereas a pure sticky information model tends to under-predict the degree of forward-looking behavior in inflation. In contrast, previous work that emphasized the time series representation of the data could not readily provide an economic rationale for why one model is preferred to others.

Heterogeneity in price-setting poses important issues for policymakers. We demonstrate that focusing on models with a single price-setting mechanism can misinform central bankers about trade-offs they face. Our simulations suggest that a more aggressive response to inflation, which may include an element of price level targeting, could substantially improve social welfare functions. At the same time, we do not find large benefits from targeting sectors with some particular form of price setting so that targeting aggregate inflation is a reasonable strategy for policymakers.

While we focus on the possibility of important differences in how firms set prices, this approach could be naturally extended to wage-setting decisions. Christiano, Eichembaum and Evans (2005), for example, argue that sticky wages with indexation are a particularly important element in matching macroeconomic dynamics. Yet, as with prices, allowing for indexation cannot reproduce the fact that wages often do not change for extended periods of time. A more natural approach could be to allow for heterogeneity in wage-setting assumptions for different sectors of the economy. This would capture the fact that some sectors have highly flexible wages, others have sticky wages without indexation, and some sectors, particularly those under union contracts, choose time paths for future wages infrequently. Even with relatively small sticky-wage or union-wage sectors, the behavior of the flexible-wage sector could be substantially altered if there is strategic complementarity in wage-setting decisions.

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APPENDIX 1: Proof of Proposition 1

Note first that, rewriting equation (7) in terms of relative price ratios in the steady-state yields

$$1=\left[s_1\overline{p^{sp}}^{1-\theta}+(1-s_1)\overline{p^{\#}}^{1-\theta}\right]. \tag{A1}$$

so that if the relative optimal price is less than one, the sticky-price relative price ratio must be greater than one. The steady-state relative optimal price is given by

$$\overline{p^{\#}}=\left[s_1\left(\frac{1-\delta_{sp}}{1-\theta\delta_{sp}\overline{\pi}^{\theta-1}}\right)\left(\frac{1-\gamma_1}{1-\gamma_2}\right)^{(1-\theta)/(1+\omega\theta)}+\left(1-s_1\right)\right]^{1/(1-\theta)}. \tag{A2}$$

Thus, if $\left(\frac{1-\delta_{sp}}{1-\delta_{sp}\overline{\pi}^{\theta-1}}\right)\left(\frac{1-\gamma_1}{1-\gamma_2}\right)^{(1-\theta)/(1+\omega\theta)}<1$, then $\overline{p^{\#}}<1$ and $\overline{p^{sp}}>1$.

Recall that γ_1 and γ_2 are given by $\gamma_1\equiv\delta_{sp}a\overline{R}^{-1}\overline{\pi}^{\theta}$ and $\gamma_2\equiv\delta_{sp}a\overline{R}^{-1}\overline{\pi}^{1+\theta(1+\omega)}$. The bond condition (3) evaluated in the steady-state yields $1=\beta\overline{R}/(a\overline{\pi})$ so we can rewrite γ_1 and γ_2 as $\gamma_1\equiv\delta_{sp}\beta\overline{\pi}^{\theta-1}$ and $\gamma_2\equiv\delta_{sp}\beta\overline{\pi}^{\theta(1+\omega)}$. Now define

$$X\equiv\left(\frac{1-\delta_{sp}}{1-\delta_{sp}\overline{\pi}^{\theta-1}}\right)\left(\frac{1-\gamma_1}{1-\gamma_2}\right)^{(1-\theta)/(1+\omega\theta)}=\left(\frac{1-\delta_{sp}}{1-\delta_{sp}\overline{\pi}^{\theta-1}}\right)\left(\frac{1-\delta_{sp}\beta\overline{\pi}^{\theta-1}}{1-\delta_{sp}\beta\overline{\pi}^{\theta(1+\omega)}}\right)^{(1-\theta)/(1+\omega\theta)}. \tag{A3}$$

Note first that $X\big|_{\overline{\pi}=1}=1$, so without trend inflation the average relative price of sticky-price firms is 1 in the steady-state. A well-defined steady-state requires $\gamma_1<1$, $\gamma_2<1$, and $\delta_{sp}\overline{\pi}^{1-\theta}<1$. Thus,

$$X\le 1 \iff \beta\ge\frac{1-C}{\delta_{sp}\overline{\pi}^{1-\theta}(\overline{\pi}^{1+\omega\theta}-C)}\equiv\beta^*(\theta,\omega,\delta_{sp},\overline{\pi}) \tag{A4}$$

where $C\equiv\left(\frac{1-\delta_{sp}\overline{\pi}^{\theta-1}}{1-\delta_{sp}}\right)^{(1+\omega\theta)/(\theta-1)}$. Note that for positive trend inflation $(\overline{\pi}>1)$, $C\le 1$ (with equality under zero trend inflation) and $\overline{\pi}^{1+\omega\theta}-C>0$.

APPENDIX 2: Technical Details on Estimation

To estimate the model, we use a Markov-Chain Monte-Carlo method developed in Chernozhukov and Hong (2003). This entails choosing a set of initial parameter values $\Psi^{(0)}$ and a distribution of shocks for each of the parameters. We assume a normal distribution for all shock parameters. Our choices for initial values and standard deviations are summarized in Table A1. The initial values for most variables are chosen to more rapidly approach the global minimum, while standard deviations are calibrated to about one percent of the parameter value and then adjusted on the fly to generate acceptance rates of 0.30, as proposed in Gelman et al (2004).[32] Our estimates are robust to initial starting values, but require more iterations to approach the global minimum when initial values are very different. We use the Hastings-Metropolis algorithm. Thus, for each iteration, we take previous parameter values $\Psi^{(i)}$ plus a vector of $N(0,1)$ shocks multiplied by the vector of standard deviations of shocks (i.e., parameter candidates are a random walk). If the new parameters satisfy min-max boundary conditions and yield a unique rational expectations equilibrium, we calculate the value of the objective function $J(\Psi^{(i+1)})$ at the new parameter values. We accept the new parameters $\Psi^{(i+1)}$ if $\exp\left\{J(\Psi^{(i)}) - J(\Psi^{(i+1)})\right\} > x$ where $x \sim U[0,1]$ is a random variable. We use 500,000 iterations for our baseline and robustness estimates, and drop the first 300,000. Define $\Psi^{(\min)} = \{\Psi^{(j)} : J(\Psi^{(j)}) \le J(\Psi^{(k)})\ \forall k \ne j\}$ and $J_{\min} = J(\Psi^{(\min)})$. Given the sequence of accepted parameter values, we follow Chernozhukov and Hong (2003) and calculate expected values and variances of our parameter estimates using the simulated values $\Psi^{(i)}$ and weights

$$w_i = \frac{\exp\left\{J_{\min} - J(\Psi^{(i)})\right\}}{\sum_j \exp\left\{J_{\min} - J(\Psi^{(j)})\right\}}.$$

For example, the expected value is $E(\Psi) = \sum_i w_i \Psi^{(i)}$.

[32] Estimates are very robust to initial values, as long as enough iterations are allowed for the parameters to converge to the area of the global minimum.

Table 1: Estimation Results

	Hybrid Model		Sticky-Price Model		Sticky-Info Model		Flex-Price Model	
	estimate	(s.e.)	estimate	(s.e.)	estimate	(s.e.)	estimate	(s.e.)
Fundamentals								
h	0.96	(0.0002)	0.96	(0.0002)	0.95	(0.0004)	0.95	(0.0004)
θ	17.80	(0.43)	8.28	(0.32)	7.71	(0.33)	8.82	(0.41)
Taylor Rule								
ϕ_{π}	1.98	(0.031)	1.91	(0.017)	1.58	(0.006)	1.63	(0.004)
ϕ_{gy}	1.21	(0.055)	1.10	(0.026)	0.54	(0.010)	0.00	(0.001)
ρ_1	1.395	(0.001)	1.426	(0.001)	1.472	(0.007)	0.868	(0.022)
ρ_2	-0.477	(0.003)	-0.514	(0.002)	-0.599	(0.005)	-0.426	(0.015)
Price-Setting								
s_1	0.50	(0.019)	1.00	NA	0.00	NA	0.00	NA
s_2	0.46	(0.023)	0.00	NA	1.00	NA	0.00	NA
s_3	0.005	(0.004)	0.00	NA	0.00	NA	0.00	NA
θ_{sp}	0.47	(0.012)	0.57	(0.011)	0.75	NA	0.75	NA
θ_{si}	0.62	(0.013)	0.75	NA	0.54	(0.006)	0.75	NA
Shocks								
ρ_g	0.447	(0.001)	0.447	(0.002)	0.372	(0.003)	0.225	(0.002)
ρ_{τ}	0.766	(0.002)	0.792	(0.003)	0.850	(0.004)	0.965	(0.003)
σ_r	0.53	(0.01)	0.57	(0.01)	0.68	(0.01)	0.58	(0.05)
σ_g	54.58	(0.03)	55.06	(0.09)	53.34	(0.05)	55.00	(0.10)
σ_a	5.22	(0.02)	5.68	(0.03)	4.95	(0.03)	4.64	(0.05)
σ_{τ}	1.28	(0.72)	0.87	(0.47)	9.03	(0.16)	4.92	(0.16)
Measurement Error								
$\sigma_{me,gy}$	2.087	(0.019)	2.179	(0.014)	0.899	(0.063)	0.703	(0.085)
$\sigma_{me,\pi}$	0.533	(0.034)	0.042	(0.026)	0.153	(0.028)	0.999	(0.038)
$\sigma_{me,r}$	0.421	(0.036)	0.142	(0.065)	0.050	(0.043)	0.685	(0.031)
Iterations	500K		200K		200K		200K	
Relative Objective	1.00		1.07		1.93		7.70	

Note: The table presents estimates of the baseline model, using a truncation of past expectations for sticky-information firms of 12, as well as estimates of restricted models. We use contemporaneous covariances and cross-autocovariances up to three lags. Data are from 1954:Q4 to 2005:Q4. The *s*'s correspond to the share of firms assigned to sticky-price, sticky-information, and rule-of-thumb price setting sectors respectively. The remainder are flexible-price firms. Reported value of the objective function is computed at the expected value of the estimated parameter vector, relative to that achieved by the hybrid model. See text and appendix for other parameters and details on estimation approach.

Table 2: Variance Decomposition

Model	Policy	Preference	Technology	Tax Wedge
	Source of Variance of Growth in Output			
Hybrid	0	93	7	0
Sticky-Price	0	93	7	0
Sticky-Info	0	95	5	0
Flexible	0	95	4	1
	Source of Variance of Inflation			
Model	Policy	Preference	Technology	Tax Wedge
Hybrid	18	14	68	0
Sticky-Price	19	9	71	0
Sticky-Info	25	8	23	45
Flexible	19	17	36	28
	Source of Variance of Interest Rates			
Model	Policy	Preference	Technology	Tax Wedge
Hybrid	43	49	8	0
Sticky-Price	39	45	16	0
Sticky-Info	55	23	4	18
Flexible	0	22	44	34

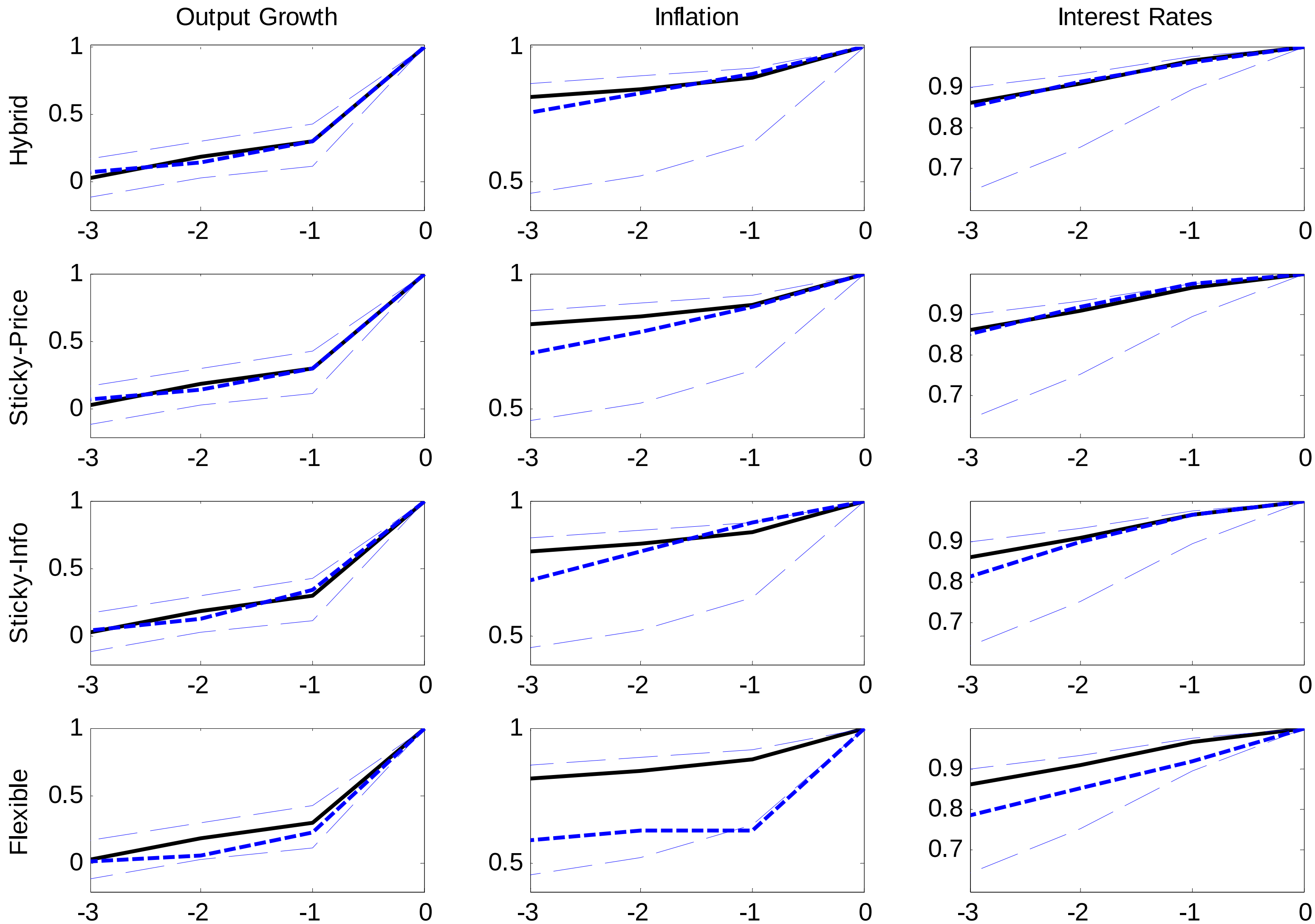
Note: Table presents variance decompositions given the parameter estimates for each model from Table 1. Horizon is four quarters.

Table 3: Robustness of Estimates

	More moments		Diagonal Weighting Matrix		Indivisible Labor		Response to Output Gap		No Tax Wedge Shock		Post-1982	
	estimate	(s.e.)	estimate	(s.e.)	estimate	(s.e.)	estimate	(s.e.)	estimate	(s.e.)	estimate	(s.e.)
Fundamentals												
η	1	NA	1	NA	∞	NA	1	NA	1	NA	1	NA
h	0.95	(0.0001)	0.96	(0.003)	0.96	(0.0002)	0.96	(0.0002)	0.96	(0.0003)	0.99	(0.0003)
θ	21.89	(0.03)	23.43	(8.60)	20.31	(0.41)	17.62	(0.06)	19.57	(0.41)	22.32	(0.97)
Taylor Rule												
ϕ_{π}	1.60	(0.005)	1.95	(0.28)	1.91	(0.02)	1.97	(0.01)	2.02	(0.02)	3.30	(0.20)
ϕ_{gy}	1.06	(0.01)	1.18	(0.44)	1.10	(0.03)	1.22	(0.003)	1.27	(0.02)	2.37	(0.16)
ϕ_{x}	0.00	NA	0.00	NA	0.00	NA	-0.01	(0.01)	0.00	NA	0.00	NA
ρ_1	1.420	(0.0003)	1.369	(0.072)	1.426	(0.002)	1.406	(0.001)	1.396	(0.005)	1.377	(0.004)
ρ_2	-0.496	(0.0004)	-0.466	(0.051)	-0.512	(0.003)	-0.486	(0.001)	-0.475	(0.004)	-0.418	(0.006)
Price-Setting												
s_1	0.308	(0.001)	0.45	(0.20)	0.63	(0.01)	0.64	(0.02)	0.62	(0.04)	0.48	(0.02)
s_2	0.673	(0.001)	0.12	(0.12)	0.33	(0.01)	0.34	(0.01)	0.32	(0.02)	0.38	(0.02)
s_3	0.018	(0.001)	0.29	(0.18)	0.02	(0.006)	0.00	(0.004)	0.01	(0.01)	0.02	(0.02)
θ_{sp}	0.67	(0.001)	0.46	(0.11)	0.38	(0.01)	0.44	(0.005)	0.41	(0.01)	0.66	(0.02)
θ_{si}	0.75	(0.001)	0.65	(0.14)	0.55	(0.01)	0.63	(0.012)	0.65	(0.010)	0.94	(0.004)
Shocks												
ρ_g	0.409	(0.001)	0.420	(0.035)	0.454	(0.002)	0.451	(0.002)	0.441	(0.004)	0.837	(0.004)
ρ_{τ}	0.763	(0.001)	0.62	(0.09)	0.77	(0.001)	0.76	(0.002)	NA	NA	0.76	(0.01)
σ_r	0.584	(0.002)	0.57	(0.20)	0.56	(0.01)	0.52	(0.01)	0.53	(0.01)	0.20	(0.05)
σ_g	53.56	(0.02)	56.34	(1.53)	55.45	(0.09)	54.71	(0.06)	55.61	(0.13)	54.74	(0.23)
σ_a	3.29	(0.02)	5.52	(0.36)	5.54	(0.03)	5.25	(0.02)	5.23	(0.03)	5.67	(0.30)
σ_{τ}	3.16	(1.08)	11.51	(10.01)	0.72	(0.32)	0.83	(0.59)	NA	NA	3.83	(3.20)
Measurement Error												
$\sigma_{me,gy}$	1.546	(0.023)	2.101	(0.267)	2.166	(0.020)	2.115	(0.014)	2.075	(0.022)	1.552	(0.024)
$\sigma_{me,\pi}$	0.735	(0.024)	0.515	(0.340)	0.081	(0.090)	0.307	(0.054)	0.337	(0.041)	0.537	(0.066)
$\sigma_{me,r}$	0.076	(0.023)	0.427	(0.306)	0.133	(0.036)	0.351	(0.036)	0.245	(0.050)	0.068	(0.047)

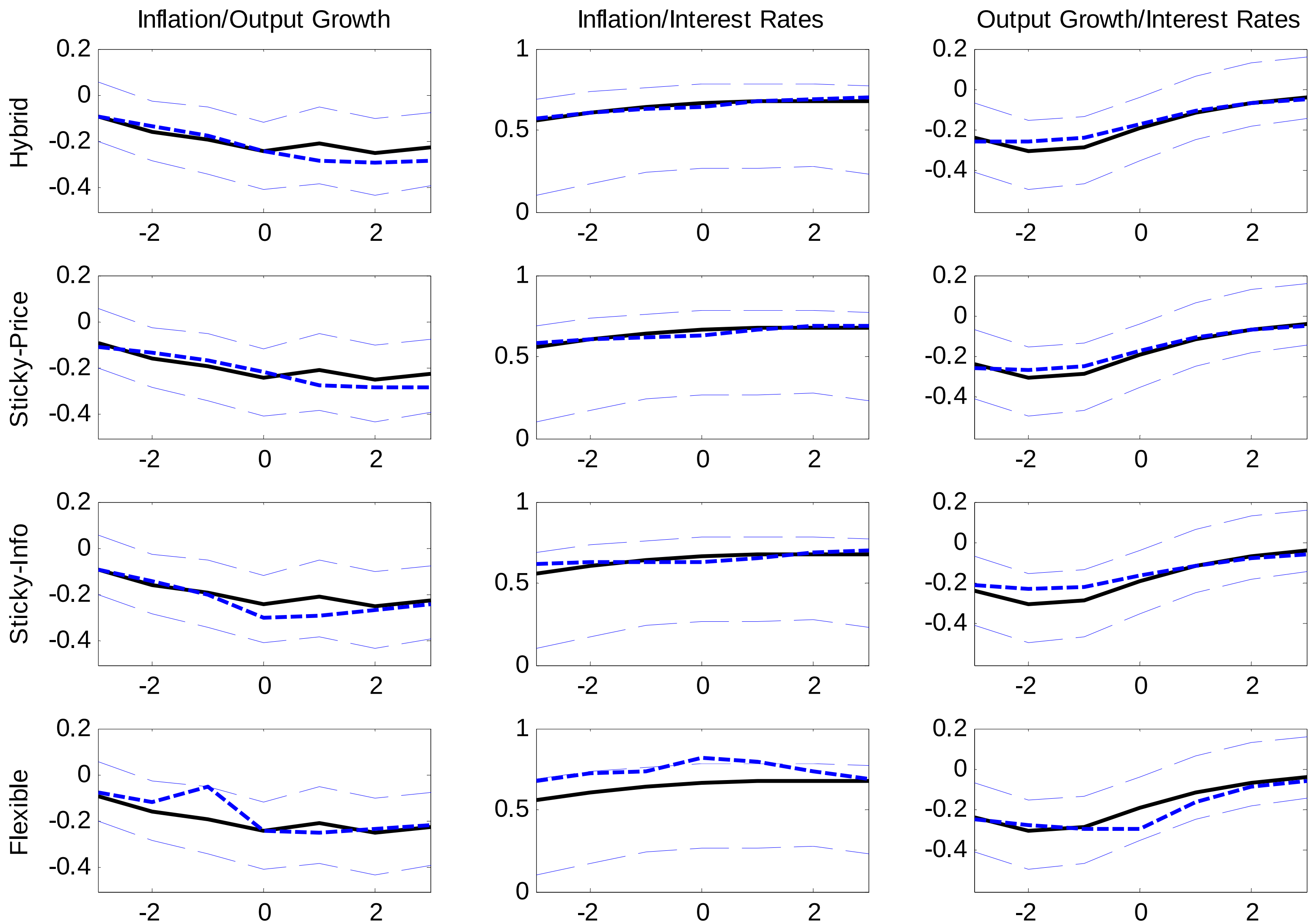
Note: The table presents robustness estimates of the baseline model. In each robustness check, initial values are the parameter estimates of the baseline model from Table 1 and associated distribution. We use 200,000 iterations for each robustness check, and presents estimates based on the last 100,000 iterations.

Figure 1: Autocorrelations of Observable Variables



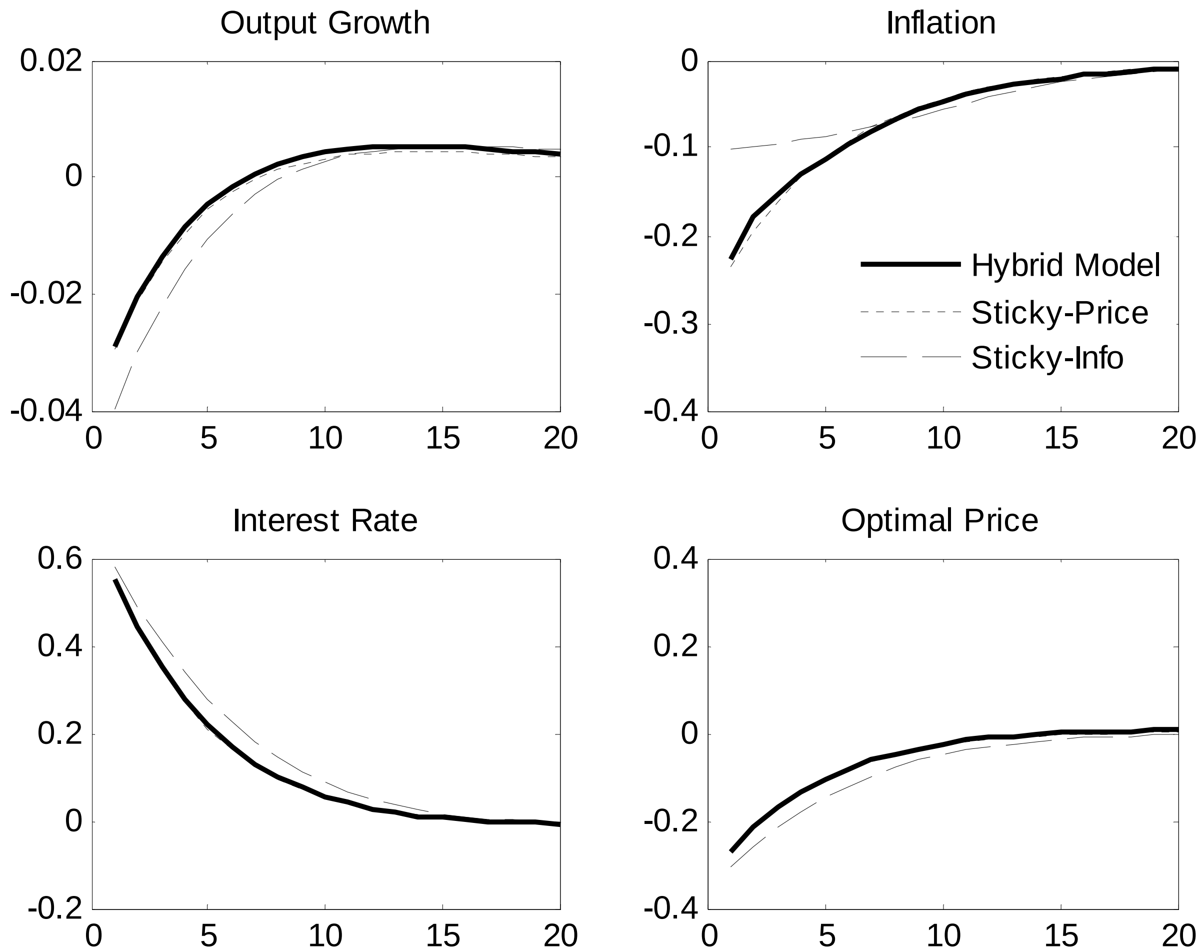
Note: The figure plots autocorrelations of observable variables in data (1954:Q4-2005:Q4), as black bold line, as well as those predicted by the hybrid model and pure models (using estimates in Table 1), as bold blue dashed line. Light dashed lines are bootstrapped 95% confidence intervals. Bootstraps are done by running a 12-lag VAR on our data, and using the VAR coefficients and residuals to generate 2000 replications of the data, from which we generate a distribution of correlations. The x-axis indicates the timing of the lagged variable used in the autocorrelation.

Figure 2: Cross-Correlations of Observable Variables



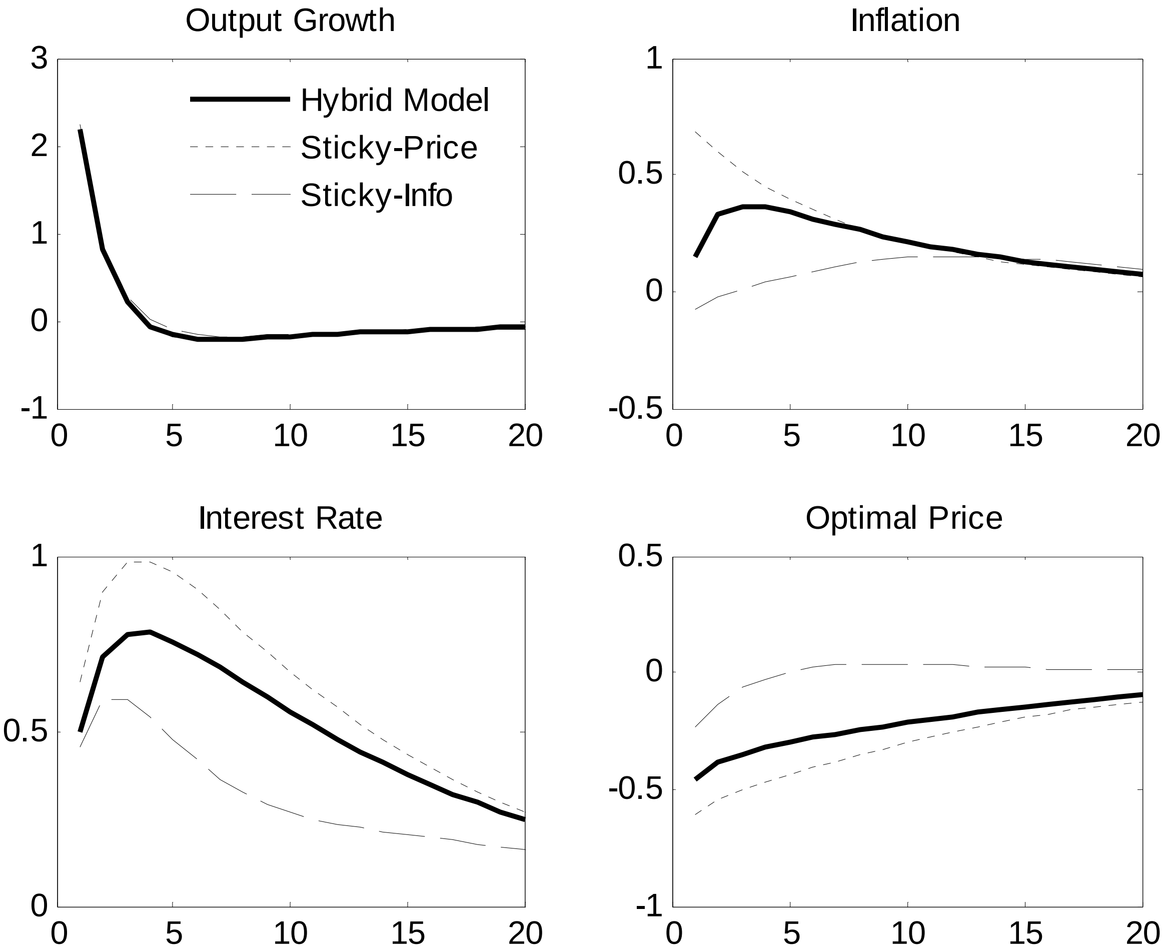
Note: The figure plots cross-autocovariances of observable variables: output growth (*gy*), inflation (π), and interest rates (*r*) in the data (1954:Q4-2005:Q4) and those predicted by the hybrid model as well as those predicted by the pure models (using estimates in Table 1). Black solid lines are from data, with light dashed lines indicating 95% bootstrap confidence intervals. Bold dashed blue lines are those of each model. Bootstraps are done by running a 12-lag VAR on our data, and using the VAR coefficients and residuals to generate 2000 replications of the data, from which we generate a distribution of correlations. The x-axis indicates the timing of the variable used in the cross-correlation (negative numbers indicate lags, positive numbers are leads).

Figure 3. Impulse responds functions: Policy Shocks



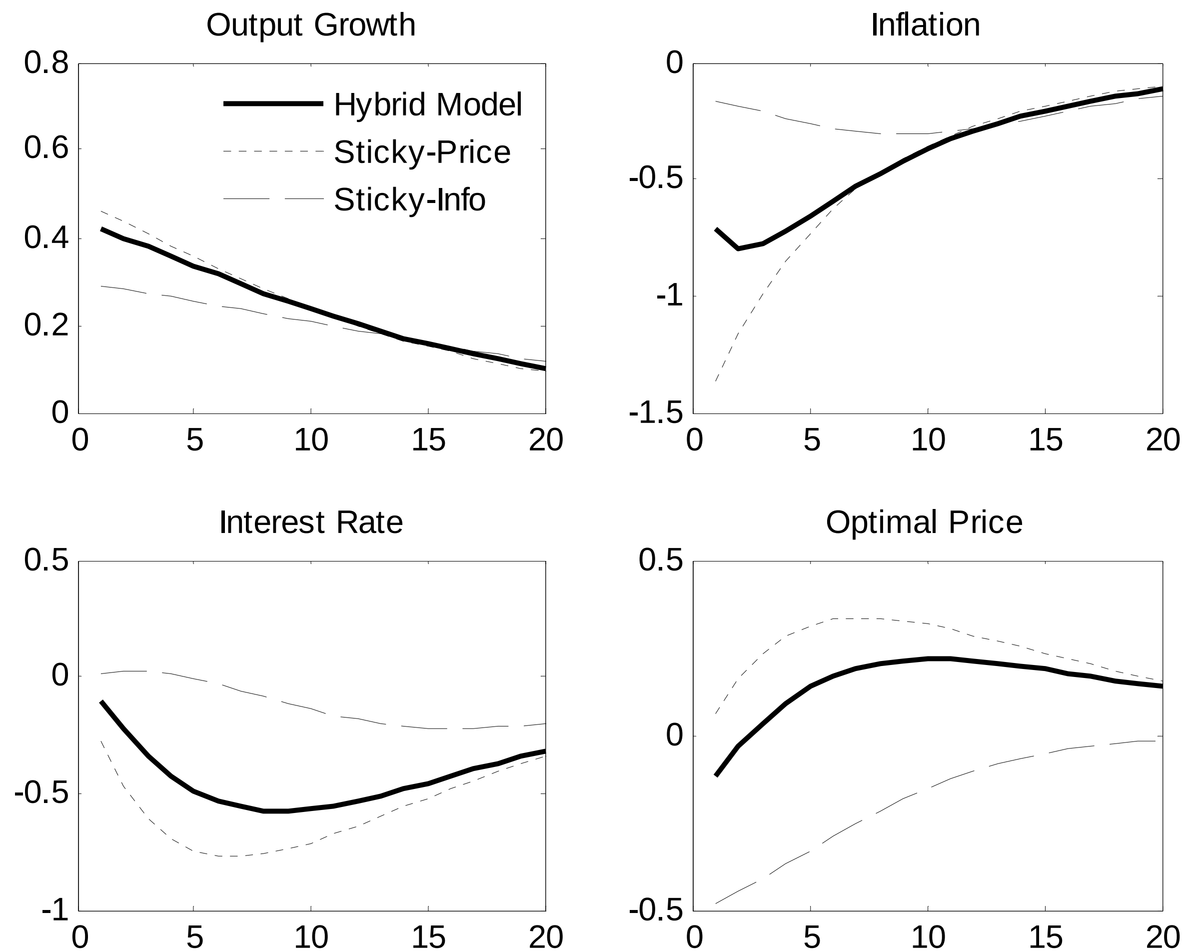
Note: The figure plots impulse responses (percent deviation from steady-state) of baseline (hybrid), pure sticky-price and pure sticky-information models (based on estimates reported in Table 1) to a positive one-standard deviation shock to the Taylor rule. Time is in quarters on the horizontal axis.

Figure 4: Impulse response functions: Preference Shocks



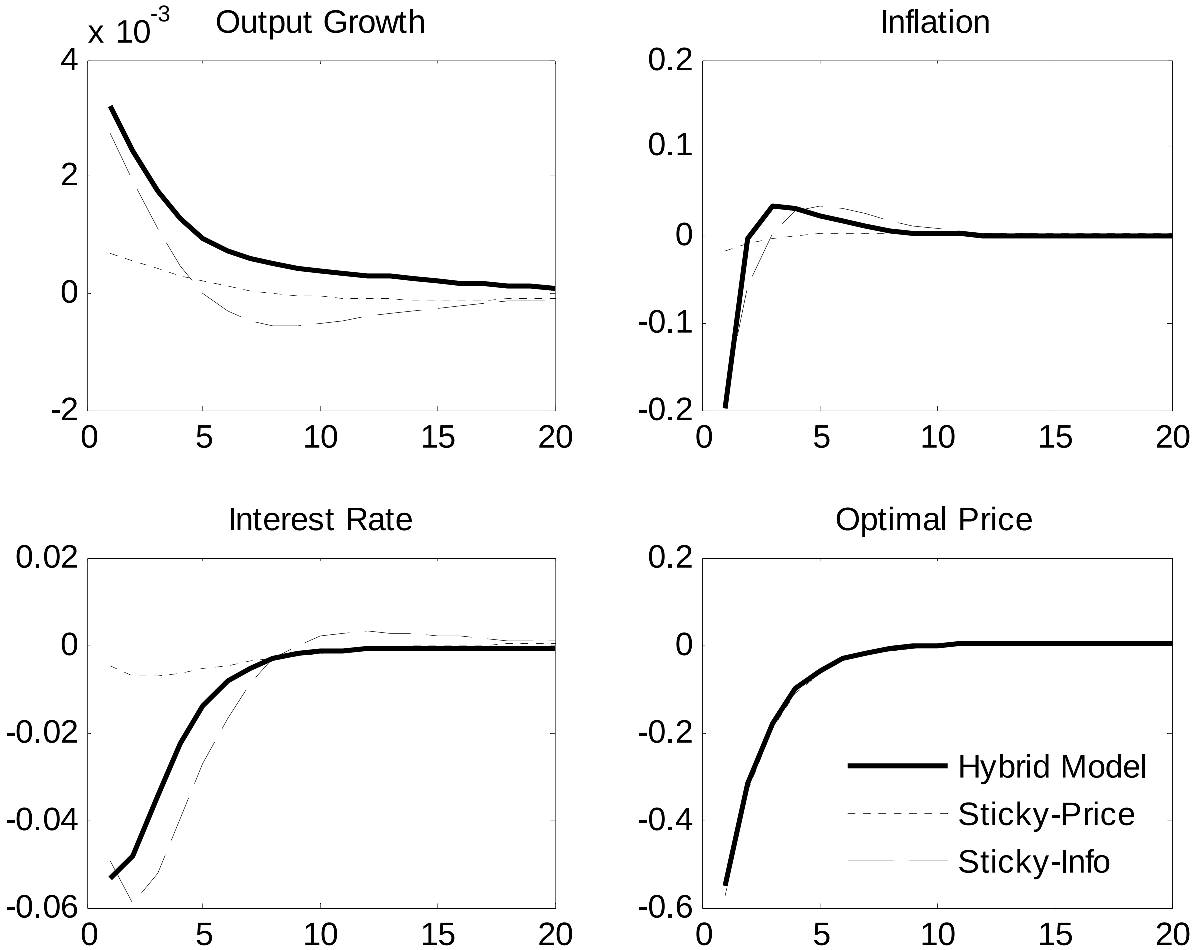
Note: The figure plots impulse responses (percent deviation from steady-state) of baseline (hybrid), pure sticky-price and pure sticky-information models (based on estimates reported in Table 1) to a positive one-standard deviation shock to preferences. Time is in quarters on the horizontal axis.

Figure 5. Impulse Response Functions: Technology Shocks



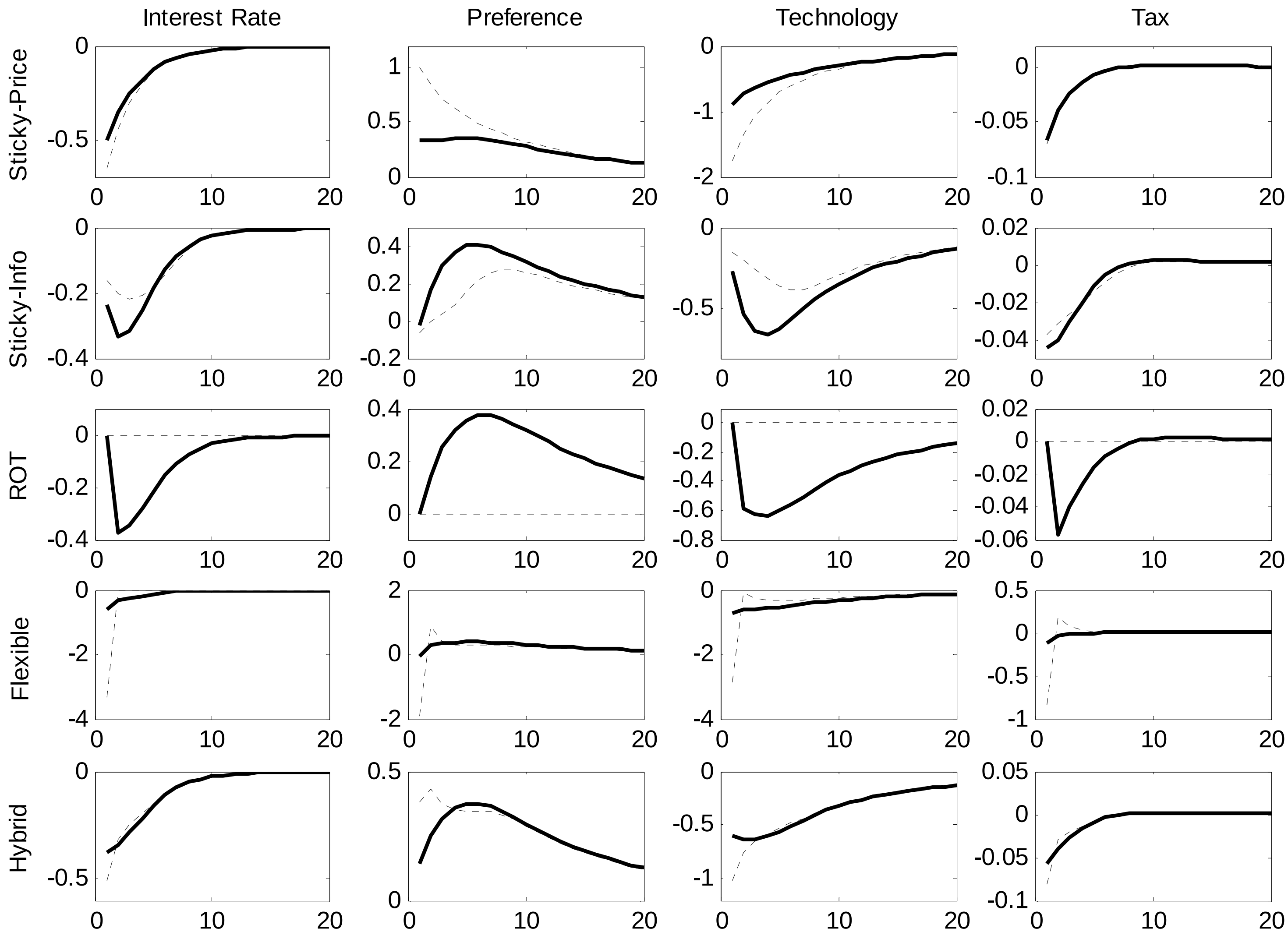
Note: The figure plots impulse responses (percent deviation from steady-state) of baseline (hybrid), pure sticky-price and pure sticky-information models (based on estimates reported in Table 1) to a positive one-standard deviation shock to technology. Time is in quarters on the horizontal axis.

Figure 6: Impulse Response Functions: Tax Shocks



Note: The figure plots impulse responses (percent deviation from steady-state) of baseline (hybrid), pure sticky-price and pure sticky-information models (based on estimates reported in Table 1) to a negative one-standard deviation shock to the labor income tax. Time is in quarters on the horizontal axis.

Figure 7: Sector-Specific vs. Pure Model Inflation

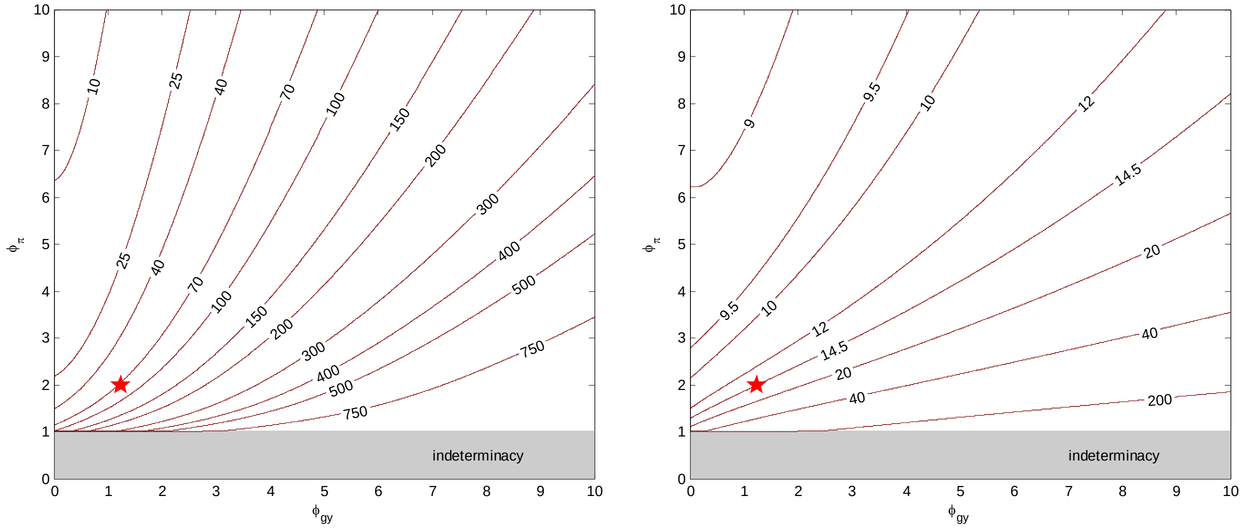


Note: The figure displays the response of inflation (percent deviation from steady-state) to shocks (labeled on top). Bold lines indicate the response of inflation of each sector (labeled at left) within the hybrid model (using estimates of Table 1) while the dash lines indicate the response of a pure model consisting only of that sector's type of firms (i.e., $s_j = 1$ for sector j). The bottom row compares the response of aggregate inflation in the hybrid model (in bold) to a weighted average of inflation rates from the pure models (in dash) where the weights are effective weights s^{CPI} of each sector from baseline estimates. Baseline parameter estimates are used in each case. Time is in quarters on the horizontal axis.

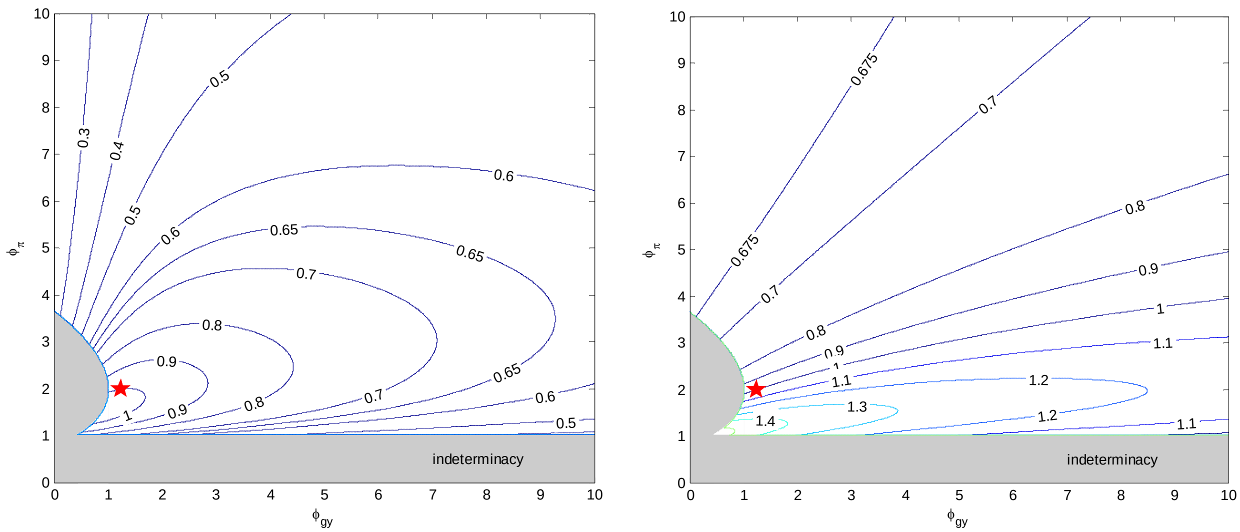
Figure 8. Welfare isoloss maps.

Loss function L_1 *Loss function L_2*

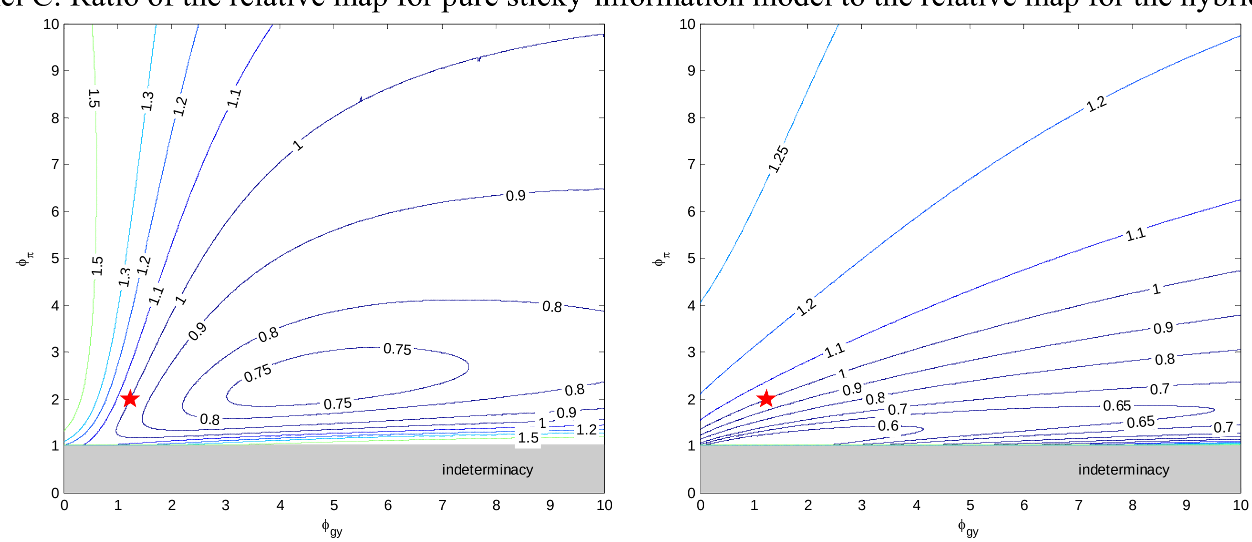
Panel A: Baseline hybrid model.



Panel B: Ratio of the relative map for pure sticky-price model to the relative map for the hybrid model.



Panel C: Ratio of the relative map for pure sticky-information model to the relative map for the hybrid model.



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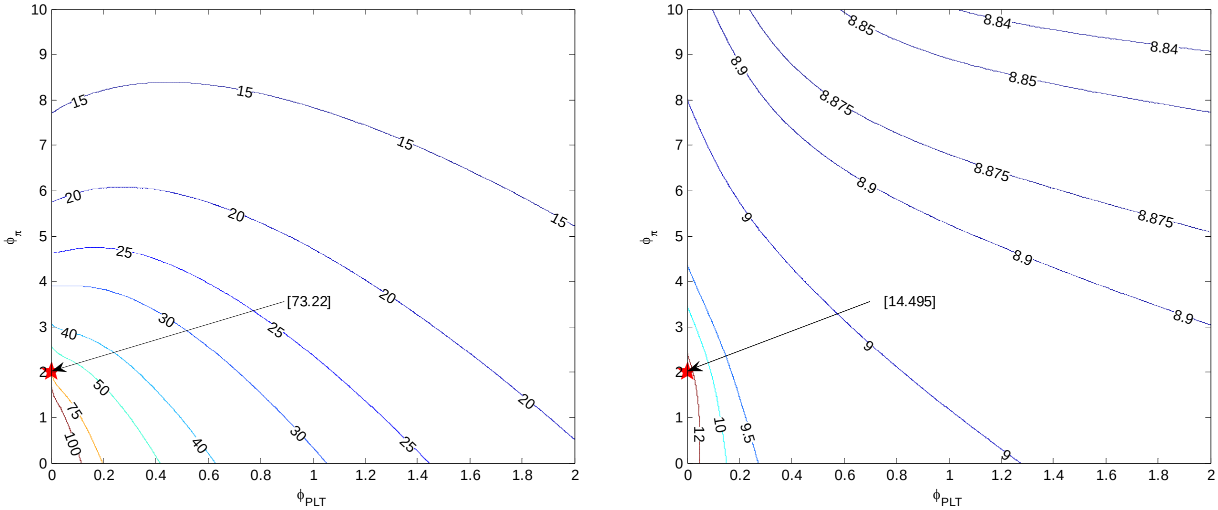
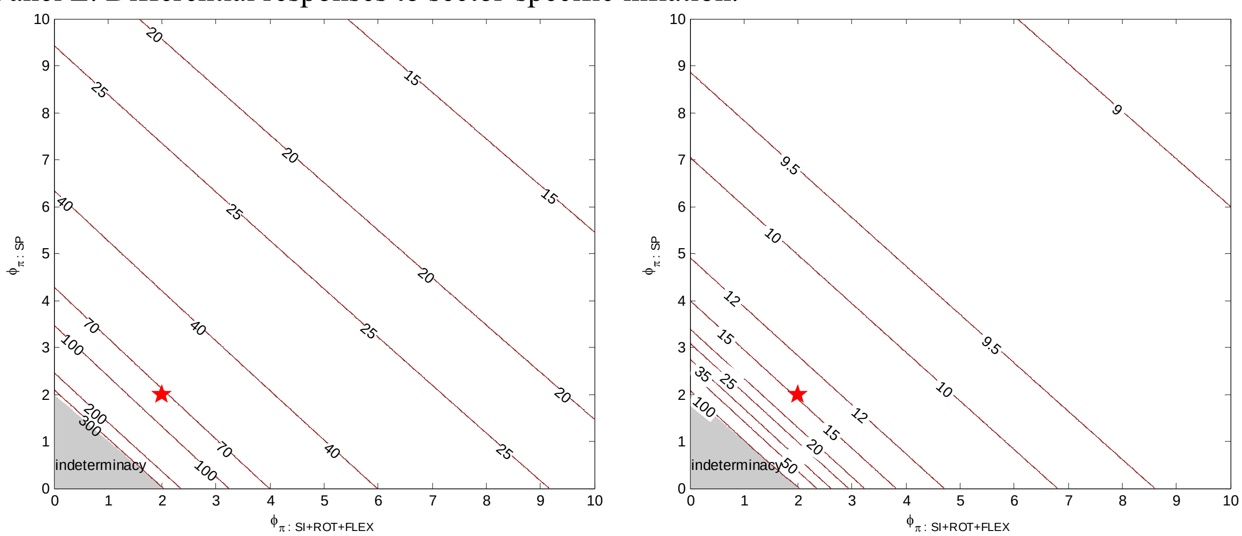
Panel D. Price level targeting.



Panel E. Differential responses to sector-specific inflation.



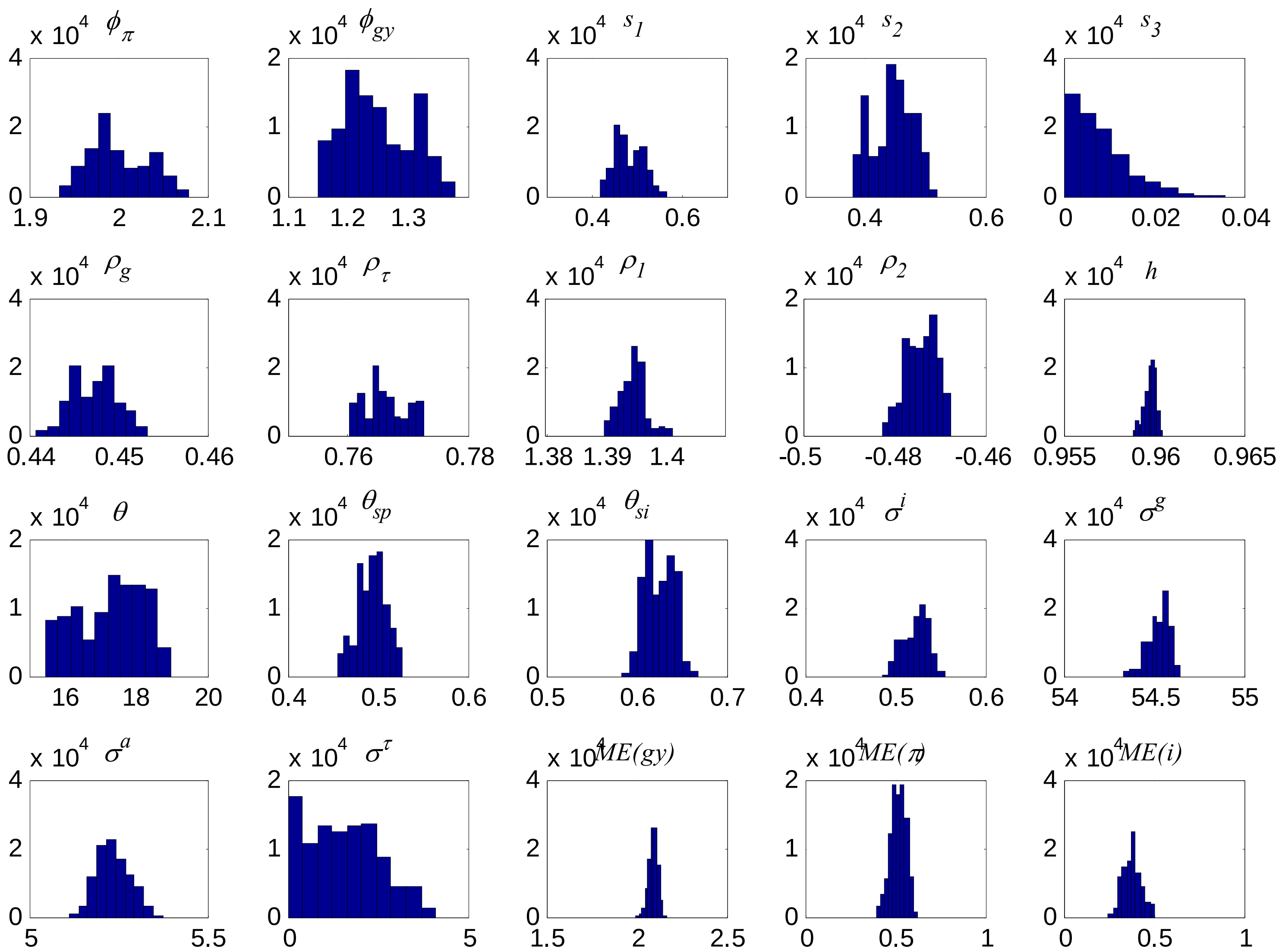
Notes: The figure plots isoloss maps for two welfare functions L_1 and L_2 for various combinations of the policy reaction function (Taylor rule). Volatilities of the variables are computed using the parameter estimates of the hybrid model. The red star indicates the position of the estimated Taylor rule. In panels A, B and C, ϕ_{gy} on the horizontal axis shows the response of the policy instrument (interest rate) to a unit increase in the output growth rate. On the vertical axis, ϕ_π shows the response of the policy instrument (interest rate) to a unit increase in the inflation. Other parameters in the Taylor rule (interest rate smoothing, volatility of the interest rate shock) are held constant. In panel D, the figures in square parentheses show the value of the social loss function evaluated at the estimated Taylor rule. On the horizontal axis, ϕ_{PLT} shows the response of the policy instrument (interest rate) to a unit increase in the deviation of the price level from its target. On the vertical axis, ϕ_π shows the response of the policy instrument (interest rate) to a unit increase in the inflation. Other parameters in the Taylor rule (interest rate smoothing, volatility of the interest rate shock, output growth rate response) are held constant. In panel E, $\phi_{\pi:\mathrm{SP+ROT+FLEX}}$ on the horizontal axis shows the response of the policy instrument (interest rate) to a unit increase in the aggregate inflation in the sticky-information, rule-of-thumb and flexible price sectors. On the vertical axis, $\phi_{\pi:\mathrm{SP}}$ shows the response of the policy instrument (interest rate) to a unit increase in the inflation in the sticky-price sector. Other parameters in the Taylor rule (interest rate smoothing, volatility of the interest rate shock, output growth rate response) are held constant. The shaded region shows the Taylor rule parameter combinations associated with equilibrium indeterminacy.

Appendix Table A1: Initial Parameter Values and Standard Deviations of Shocks

	θ	h	ϕ_{π}	ϕ_{gy}	ρ_1	ρ_2
Initial Value	10	0.9	2	1	1.3	-0.4
St.D. Shocks	0.1	0.001	0.02	0.01	0.003	0.014
	s_1	s_2	s_3	δ_{sp}	δ_{si}	
Initial Value	0.25	0.25	0.25	0.75	0.75	
St.D. Shocks	0.01	0.01	0.01	0.01	0.01	
	ρ_g	ρ_{τ}	σ_r	σ_g	σ_a	σ_{τ}
Initial Value	0.6	0.75	0.5	55.0	4.0	10.0
St.D. Shocks	0.004	0.0025	0.005	0.55	0.04	0.10
	$\sigma_{me,gy}$	$\sigma_{me,\pi}$	$\sigma_{me,r}$			
Initial Value	2.5	0.5	0.5			
St.D. Shocks	0.025	0.005	0.005			

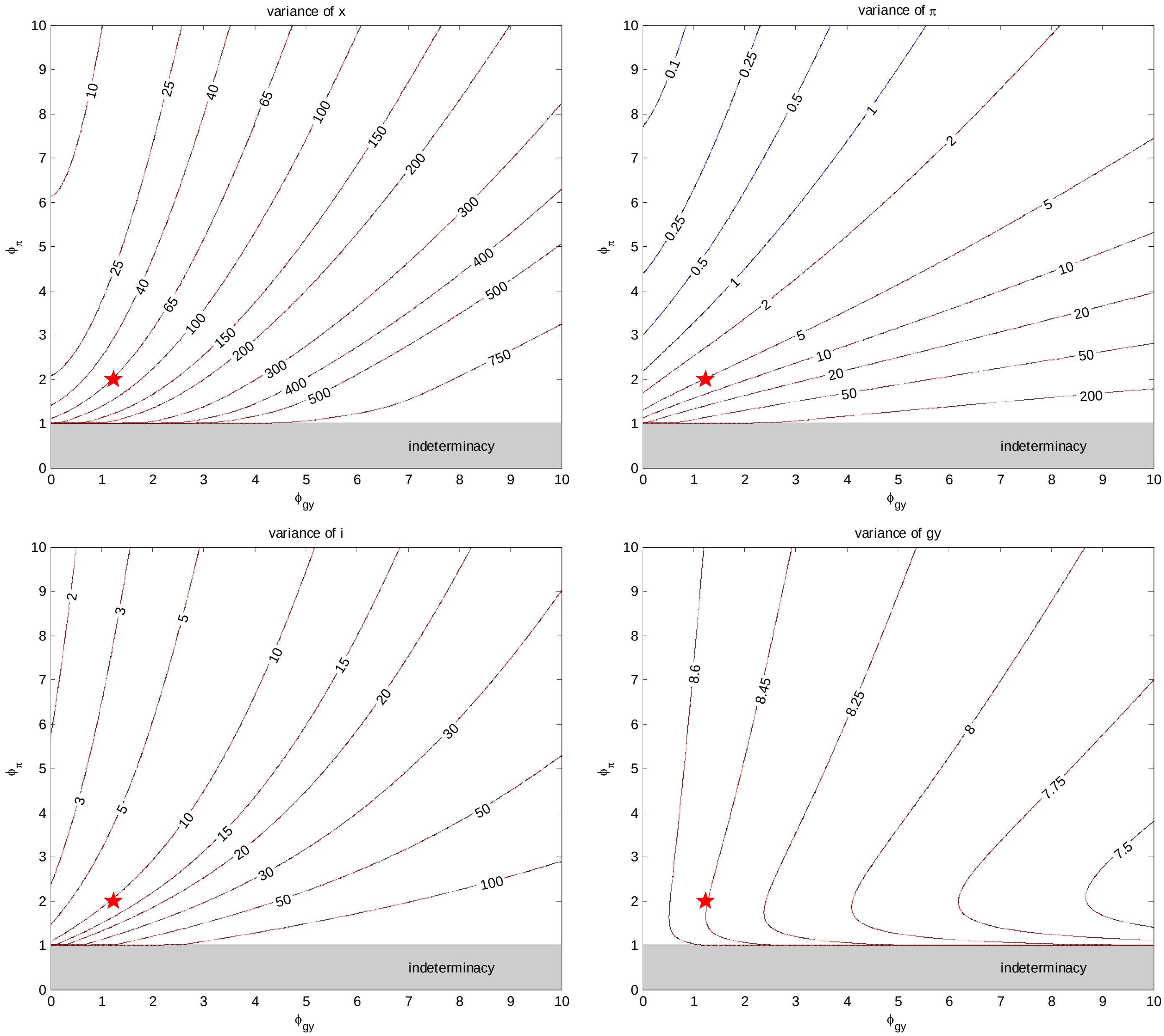
Note: The table displays the initial values used in MCMC algorithm, as well as the initial standard deviations of shocks used in generating distribution of parameter estimates.

Appendix Figure A1. Histograms of Baseline Parameters from MCMC.



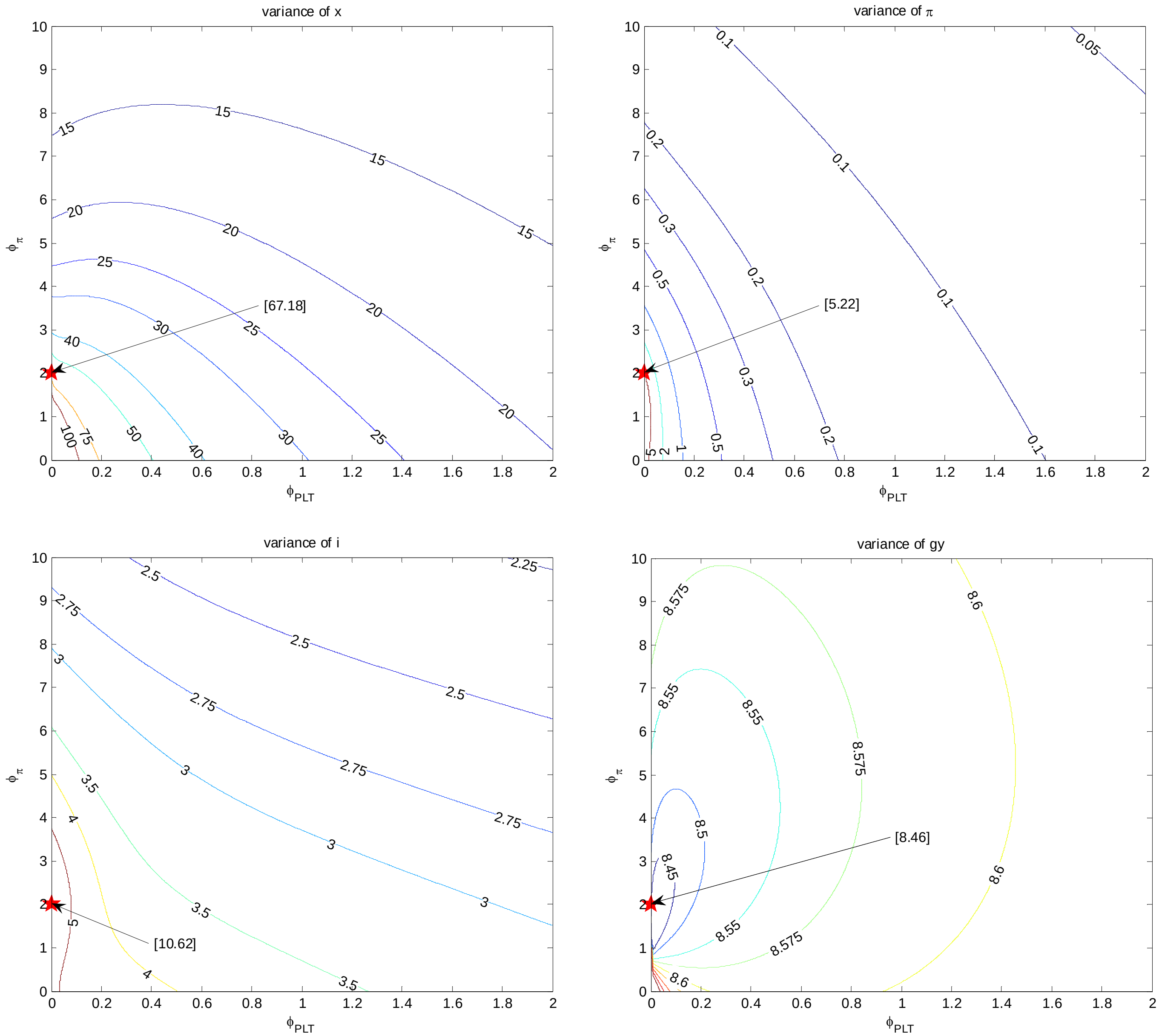
Note: The figure plots the distribution of the last MCMC 100,000 draws.

Appendix Figure A2. Baselines volatility maps for key macroeconomic variables.



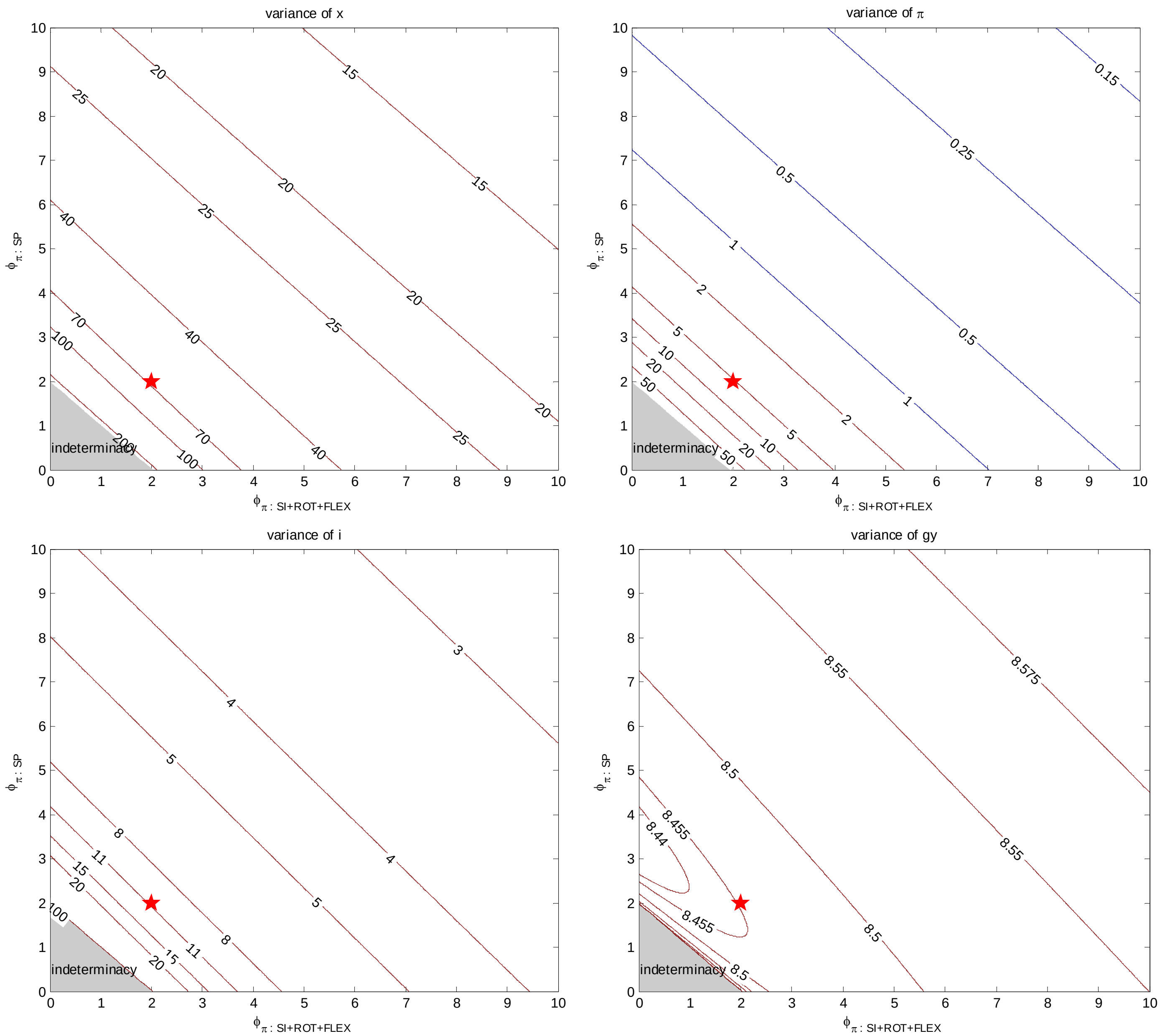
Notes: The figure plot iso-curves for volatility of output growth rate (*gy*), output gap (*x*), inflation (π) and interest rate (*i*). On the horizontal axis, ϕ_{gy} shows the response of the policy instrument (interest rate) to a unit increase in the output growth rate. On the vertical axis, ϕ_π shows the response of the policy instrument (interest rate) to a unit increase in the inflation. Other parameters in the Taylor rule (interest rate smoothing, volatility of the interest rate shock) are held constant. The red star denotes the combination of ϕ_{gy} and ϕ_π corresponding to the estimated Taylor rule. Volatilities of the variables are computed using the parameter estimates of the hybrid model.

Appendix Figure A3. Price level targeting and volatility maps for key macroeconomic variables.



Notes: The figure plot iso-curves for volatility of output growth rate (*gy*), output gap (*x*), inflation (π) and interest rate (*i*). On the horizontal axis, ϕ_{PLT} shows the response of the policy instrument (interest rate) to a unit increase in the deviation of the price level from its target. On the vertical axis, ϕ_π shows the response of the policy instrument (interest rate) to a unit increase in the inflation. Other parameters in the Taylor rule (interest rate smoothing, volatility of the interest rate shock, output growth rate response) are held constant. The red star denotes the combination of ϕ_{PLT} and ϕ_π corresponding to the estimated Taylor rule. The value in squared parentheses shows the level of volatility at the estimated Taylor rule. Volatilities of the variables are computed using the parameter estimates of the hybrid model.

Appendix Figure A4. Differentiated inflation response and volatility maps for key macroeconomic variables.



Notes: The figure plot iso-curves for volatility of output growth rate (*gy*), output gap (*x*), inflation (π) and interest rate (*i*). On the horizontal axis, $\phi_{\pi:\mathrm{SI+ROT+FLEX}}$ shows the response of the policy instrument (interest rate) to a unit increase in the aggregate inflation in the sticky-information, rule-of-thumb and flexible price sectors. On the vertical axis, $\phi_{\pi:\mathrm{SP}}$ shows the response of the policy instrument (interest rate) to a unit increase in the inflation in the sticky-price sector. Other parameters in the Taylor rule (interest rate smoothing, volatility of the interest rate shock, output growth rate response) are held constant. The red star denotes the combination of $\phi_{\pi:\mathrm{SI+ROT+FLEX}}$ and $\phi_{\pi:\mathrm{SP}}$ corresponding to the estimated Taylor rule where $\phi_{\pi:\mathrm{SI+ROT+FLEX}} = \phi_{\pi:\mathrm{SP}}$. Volatilities of the variables are computed using the parameter estimates of the hybrid model.

Appendix Figure A5. Welfare isoloss maps for alternative values for the weight on output volatility.

Loss function L_1 Loss function L_2