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ABSTRACT

We explore the importance of the nature of nominal price and wage adjustment for the design of effective monetary policy strategies, especially at the zero lower bound. Our analysis suggests that sticky-price and sticky-information models fit standard macroeconomic time series comparably well. However, the model with information rigidity responds differently to anticipated shocks and persistent zero-lower bound episodes – to a degree important for monetary policy and for understanding the effects of fundamental disturbances when monetary policy cannot adjust. These differences may be important for understanding other policy issues as well, such as fiscal multipliers. Despite these differences, many aspects of effective policy strategy are common across the two models: In particular, highly inertial interest rate rules that respond to nominal income or the price level perform well, even when hit by adverse supply shocks or large demand shocks that induce the zero-lower bound. Rules that respond to the level or change in the output gap can perform poorly under those conditions.

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1 Introduction

The Great Recession has led to a prolonged period of high unemployment, below-target inflation, and extraordinary policy actions from monetary authorities. While economists at central banks and other researchers have, by now, explored the nature of the recession and appropriate policy strategies in numerous models, the diversity across such models along key dimensions, including the controversial nature of nominal price adjustment, has been limited. This lack of diversity is potentially important for assessing how robust effective alternative strategies may be, as the standard "sticky-price" assumption–whereby price adjustment is based on current information and looks forward to expected future conditions–can imply large swings in the price level at the zero-lower bound (ZLB) in response to shocks or monetary-policy shifts.

In this paper, we consider how an alternative assumption about the nature of price and wage dynamics affects policy assessments. Specifically, we consider "sticky-information" paradigms (Mankiw and Reis, 2002) for price and wage adjustment, in which some price and wage setters do not base their decisions on current information. We explore the differences between sticky-price and sticky-information models, focusing on the efficacy of a range of monetary policy strategies.

Our analysis highlights several central results. First, the dominance of the sticky-price paradigm within central bank and academic research on monetary policy is not driven by superior fit to the usual macroeconomic data. Rather, while the fit of our sticky-information and sticky-price models to standard macroeconomic time series is comparable, the differences in price-level dynamics, especially at the zero-lower bound, can be significant–both quantitatively and from the perspective of effective policy design.

Second, many aspects of effective policy strategy off of the zero-lower bound are nevertheless very similar under these alternative models of price dynamics. In particular, aggregate demand remains primarily a function of long-term (or the sequence of expected short-term) interest rates, implying that inertial strategies, which strongly influence expected interest rates, are central to good policy design (as found in, for example, Levin et al. (2003)). Moreover, the importance of markup shocks in the trade-off between inflation and activity implies that strategies which respond strongly to the level of the output gap perform very poorly. While responding to output growth ameliorates this problem in the absence of the zero lower bound, such an approach performs poorly when that constraint binds. Instead, flexible price-level targeting is required to ameliorate the adverse effects of both cost-push shocks and the zero-lower bound.

When the zero lower bound is hit, however, several important differences emerge between the sticky-price and sticky-information models. Most notably, when the policy rate is bound, the forward-looking nature of inflation under sticky prices strongly amplifies adverse shocks relative to the sticky-information case. Similarly, the price level is far more volatile under sticky prices, as agents in the sticky-information framework choose price-level plans, which typically induce some degree of mean reversion in the aggregate price level.[1]

[1] This is a relative statement – amplification of adverse developments through the zero-lower bound (and hence the absence of some monetary accommodation) is a general feature – it simply tends to be larger under sticky prices.

The larger amplification of developments at the zero-lower bound within the sticky-price framework implies that steps to alleviate such adverse developments can also be amplified significantly – implying that, for example, a commitment to keep interest rates "lower-for-longer" can be very stimulative. Indeed, such promises can lead to large increases in inflation for seemingly moderate shifts in interest rates – a tendency that is again most apparent under sticky-prices, albeit present under the sticky-information approach as well.

While not our primary focus, the different amplification of shocks across the sticky-price and sticky-information frameworks may also be important for a range of issues in the recent literature, including the size of the fiscal multiplier and the potential for improvements in aggregate supply to place a drag on economic activity when the ZLB binds. Kiley (2014) explores these issues in a small model similar to that we outline in the next section.

Our exploration of these issues begins with a review of the frameworks for price dynamics used in central bank models (and academic research). We then illustrate, in a small model, some of the dimensions along which the predictions from the dominant sticky-price paradigm differ substantially from those associated with our alternative model of price adjustment, sticky information. With the intuition from such a small model in hand, we turn to an empirical comparison of sticky-prices and sticky-information. Our subsequent examination of policy strategies compares outcomes across the sticky-price and sticky-information models, with a particular focus on the ways in which the simple mechanisms identified in the small model continue to drive results in the larger, estimated models. In addition, we emphasize the parallels between the effective strategies we identify and the related literature on optimal monetary policy in New Keynesian models – although we refrain (for the most part) from focusing specifically on optimal policy, and instead focus on strategies which have received extensive attention in policy circles. Finally, we emphasize that some strategies that effectively stabilize prices and activity in response to ZLB events destabilize inflation in response to shocks to the Phillips curve. (Conversely, some strategies that stabilize inflation in response to Phillips-curve shocks perform very poorly in response to shocks that induce the ZLB.)

Before turning to our analysis, it is important to note that we build upon a substantial body of work. For example, our models simply replace the sticky-price assumptions in the model of Smets and Wouters (2007) with the sticky-information framework of Mankiw and Reis (2002) and Mankiw and Reis (2010). We chose these two models for two reasons: First, they are both tractable methods of incorporating nominal price adjustment into dynamics-stochastic-general-equilibrium (DSGE) models; and second, the dynamics of prices – and in particular the degree to which price setting is forward looking – are dramatically different across the two models (e.g., Mankiw and Reis (2002), with important implications for behavior at the zero lower bound (Kiley (2014))). Note that we do not choose these models for their realism from a microeconomic perspective – neither specification is capable of fitting (all of) the microeconomic facts of price adjustment (e.g., Klenow and Malin (2010)), and our focus is on empirically plausible models that are useful for policy analysis. In this regard, sticky information provides a model of price adjustment that is less forward looking than the sticky-price model, but which incorporates an important role for the interaction of monetary policy strategy and expectations formation (in contrast to the assumption of backward-looking price setting use in some studies of robustness, e.g., English et al. (2013)).

The discussion of policy strategies also builds on a long literature. For example, Levin et al. (2003) and Taylor and Williams (2010) emphasize the importance of examining the robustness of policy conclusions to model specification; herein, we take a focused approach to robustness and focus solely on the role of wage and price dynamics within a standard New Keynesian DSGE model. Taylor and Williams (2010) also find that, absent a lower bound on the policy rate, policies that respond to the change in the output gap tend to be close to optimal – a finding also suggested in, for example, Blake (2012). Billi (2011) raise questions about the efficacy of responding the change in the output gap once the analysis acknowledges the zero-lower bound – a concern that our analysis suggests is quantitatively very important.

Our focus on policies that actively anchor the price level builds off of the earlier analyses of Woodford (2003) and Ball et al. (2005), and our emphasis on the particular importance of such considerations at the zero-lower bound follows Eggertsson and Woodford (2003) and Woodford (2010). However, we use large, estimated models and emphasize how the predictions of the price level across the estimated sticky-price and sticky-information models differ in a manner that is quantitatively important for policy strategy at the zero lower bound.

2 Looking for Robustness

The basic New-Keynesian model, expanded to include some degree of detail with respect to the key components of aggregate demand (e.g., consumption, investment, government expenditure, and net exports) and, in some cases, indicators of financial frictions and their effects as captured in credit-market spreads, has become the core framework for monetary policy analysis in research and in practice. This can be seen in the frameworks employed at a range of central banks and affiliated institutions, as summarized in Table 1.

While a large number of models are employed, the models are very similar in key respects, even within an institution. For example, the core framework of the domestic DSGE models at the Federal Reserve Board and the Federal Reserve Banks of New York and Chicago (whose groups collaborate and for which specification details can be found in Kiley (2013), Del Negro et al. (2013), and Brave et al. (2012)) are similar in most respects. One key dimension along which these models is similar is the specification of price and wage dynamics: Each of these models – and all of the others on the list, which includes groups at the major central banks whose research groups have been advancing the modeling frontier – uses a variant of the Calvo (1983) or Rotemberg (1982) price adjustment mechanism (with various degrees of modification such as indexation or other methods to introduce inertia).

Table 1: DSGE Models at Selected Central Banks

Central Bank	Prices/Wages	Other	Documentation
Federal Reserve (FRB/US)	Sticky Price	Reduced form	Brayton and Tinsley (1996)
Federal Reserve (EDO)	Sticky Price	DSGE	Kiley (2013)
Federal Reserve (SIGMA)	Sticky Price	DSGE	Erceg et al. (2006)
Federal Reserve Bank of New York	Sticky Price	DSGE	Del Negro et al. (2013)
Federal Reserve Bank of Chicago	Sticky Price	DSGE	Brave et al. (2012)
ECB (NAWM)	Sticky Price	DSGE	Christoffel et al. (2008)
ECB (FF)	Sticky Price	DSGE	Christiano et al. (2010)
BoE (BEQM)	Sticky Price	Reduced Form	Harrison et al. (2005)
BoE (COMPASS)	Sticky Price	DSGE/Reduced Form	Burgess et al. (2013)
Riksbank (RAMSES I or II)	Sticky Price	DSGE	Adolfson et al. (2011)

2.1 Why So Little Diversity?

In some respects, it is not surprising that there exists little diversity in the core model of price and wage adjustment used in central bank models or within academic research. The sticky-price model delivers "reasonable" empirical fit: This property was emphasized in the (single equation) analysis of Gali and Gertler (1999) and Sbordone (2002) and confirmed in a number of later studies concurrent with the rise of DSGE models at central banks (e.g. Kiley (2007)). As a consequence, the first set of empirically successful DSGE models adopted this framework (e.g., Smets and Wouters (2007)). Moreover, there is research that has confirmed that such models are as good (or perhaps bad, as forecasting is difficult) as professionals at prediction (e.g., Edge et al. (2009) and Del Negro and Schorfheide (2013)). Subsequent modeling efforts drew on this literature.

A variety of studies have pointed to concerns regarding the sticky-price specification. We highlight those raised in Mankiw and Reis (2002) and subsequent work – in particular, their emphasis on the notion that the forward-looking nature of the sticky-price model had seemingly counterfactual predictions regarding the effects of anticipated shocks; this observation will prove useful in our analysis, as behavior at the zero-lower bound depends importantly on anticipation effects. The alternative of sticky-information delivers a central role for expectations management – but the expectations that matter are past expectations for current conditions, rather than expectations for future conditions – a contrast that will prove important. Empirical work has found mixed evidence regarding the fit of this approach, largely based on smaller models (e.g., Meyer-Gohde (2010)), This evidence does not suggest such a framework should not be considered in applied policy research. Given this, it may be that other factors, including inertia in the research process and the fact that sticky-information models are (slightly) more challenging to incorporate and estimate in DSGE models: For example, the models do not fit compactly in the state-space representation of software such as DYNARE (Adjemian et al. (2011)); that said, estimation and simulation is certainly feasible (e.g., Reis (2009)) and there is code widely available (e.g., Meyer-Gohde (2010)).

2.2 Consequences of A Lack of Diversity

A comprehensive review of the differences between the sticky-price and sticky-information frameworks is well beyond our scope. But there are differences in how these specifications behave at the zero-lower bound which bear importantly on our consideration of effective policy strategies and which suggest that greater consideration of significantly different frameworks, such as sticky prices and sticky information, would benefit policy analysis.

These differences can be illustrated with a three-equation model, consisting of a New-Keynesian IS curve (determining output y), a monetary policy reaction function (determining the nominal interest rate r), and an inflation/price (p) equation (where the last is either a sticky-price or sticky-information Phillips curve):

$$y_t = -\sigma \sum_{j=0}^{\infty} E_t \left[r_{t+j} - (p_{t+1+j} - p_{t+j}) - r^*_{t+j} \right], \tag{1}$$

$$r_t = \max \left\{ r^*_t + \phi_{\Delta p} E_t(p_{t+1} - p_t) + \phi_y y_t, 0 \right\}, \tag{2}$$

The nominal interest rate (r_t) is constrained by the zero-lower bound and r^*_t is the natural (real) rate of interest, which is assumed to be exogenously determined. The parameter σ (> 0) controls the interest rate elasticity of output, while $\phi_{\Delta p}$ and ϕ_y govern the monetary authority's response to inflation and output, respectively. If the current and anticipated natural rate of interest does not lead to a binding zero lower bound (ZLB), the nominal interest rate will equal the natural rate, and output and the price level will be stabilized at their steady-state values.

The price equations in the sticky-price and sticky-information cases are given by

$$p_t - p_{t-1} = E_t \sum_{j=0}^{\infty} \eta \alpha y_{t+j}, \tag{3}$$

$$p_t = \lambda \sum_{j=0}^{\infty} (1-\lambda)^j E_{t-j} [p_t + \alpha y_t] \tag{4}$$

where α governs the link between marginal cost and output and η and λ are related to the process of price or information adjustment. Note that we have included no disturbances other than the real natural rate of interest. As a result, the output gap, in the price equations, equals output.

Absent the ZLB, these models predict exactly the same sequence for output, nominal interest rates, and prices. While this result is special to the very limited set of disturbances and type of monetary policy considered, it is a clue that empirical work may have trouble differentiating between these models, as we will find below. However, the models can differ notably at the ZLB. As can be seen through comparing (3), which includes expectations of future conditions, with (4), a persistent anticipated swing in output has potentially important effects under sticky prices that are absent under sticky information; as a result, a persistently binding ZLB may lead to quite different movements in output and the price level across frameworks. To see this, consider an example in which it is known that the natural rate of interest will be $\underline{rr^n} < 0$ for T periods (and set

Table 2: ZLB Episode (of $T+1$ periods) in Sticky-Price and Sticky-Information Models

Period (j)	Sticky Price y_j	Sticky Price $p_j - p_{j-1}$	Sticky Information y_j	Sticky Information p_j
$t+T+1$	0	0	0	0
$t+T$	$\sigma \underline{rr^n}$	$\eta\alpha\sigma\underline{rr^n}$	$\sigma \frac{(1-\lambda)^{T+1}}{((1-\lambda)^{T+1}+(1-(1-\lambda)^{T+1})\alpha\sigma)}\underline{rr^n}$	$\frac{1-(1-\lambda)^{T+1}}{(1-\lambda)^{T+1}}\alpha y_{t+T}$
$t+T-1$	$\sigma(2+\eta\alpha\sigma)\underline{rr^n}$	$\eta\alpha\sigma(1+(2+\eta\alpha\sigma))\underline{rr^n}$	$2\sigma \frac{(1-\lambda)^{T}}{((1-\lambda)^{T}+(1-(1-\lambda)^{T})\alpha\sigma)}\underline{rr^n}$	$\frac{1-(1-\lambda)^{T}}{(1-\lambda)^{T}}\alpha y_{t+T-1}$

Notes: Assumes that the natural rate of interest equals $\underline{rr^n} < 0$ in periods t through T and 0 in all other periods.

to 0 in all other periods). This brings about a binding zero lower bound from periods t through $t+T$. The effects on output and prices for each model are reported in Table 2.

Several properties of these outcomes are important. First, the output response in the sticky-price model is bounded above (that is, the decline in output is larger, as $\underline{rr^n} < 0$) by the remaining drop in the natural rate of interest multiplied by the interest rate elasticity (e.g., σ in period t+T, 2σ in period $t+T-1$, etc.), whereas this is the *lower* bound for the drop in output (that is, the decline in output is smaller) in the sticky-information model. Moreover, the initial decline in output can be much larger than this upper bound for the sticky-price case for a very persistent event (a large T) because the additional disinflation in each intervening period between t and $t+T$ can raise real interest rates substantially. Indeed, summing the inflation responses for the sticky price case can imply a large swing in the price level for this model in the event of a persistent zero lower bound episode. In contrast, the price level (in this particular example) is anchored, in the long run, at baseline in the sticky-information model. This occurs because the passive approach to the price level in the monetary policy rule (2), which only responds to expected inflation and output (and not the price level) interacts with the sluggish adjustment of information to limit price level movements (as those price setters with updated information want to keep their prices near those from price setters without updated information, which remain near baseline). Because the price level is anchored, real interest rates do not rise by a large amount through the effects a substantial period of disinflation on real interest rates, and hence the output (and inflation) declines are moderate relative to the sticky price model.

Perhaps just as significantly, amplification of "larger" shocks can be large in the sticky-price model. Consider the sticky-information model first: Iterating backward to period t, we see that the response of output in period 0 increases linearly with the size of the shock, where size is denoted by its length, T; in particular, the long-run price level is pinned down, and hence disinflation does not contribute to a large increase in real interest rates that depresses output substantially. In contrast, in the sticky-price model the response of inflation increases (that is, inflation falls) exponentially with increases in the horizon T, as anticipated disinflation feeds through to current disinflation and lower real interest rates. Therefore, amplification is highly nonlinear at the zero-lower bound under sticky prices – extending the duration of the zero-lower bound leads to larger and larger declines in output.

The simple intuition we have highlighted depends on the simple nature of the model, as well as the assumed form of monetary policy (where the fact the the nominal interest rate responds to expected (one-period ahead) inflation contributes to the anchored long-run price level under sticky-information). Nonetheless, aspects of this intuition will carry over to a larger model – which includes more complicated dynamics and alternative policy strategies. Moreover, this intuition is important for understanding a spate of research on the New Keynesian model at the zero lower bound. For example, the effects of backward induction in the sticky-price model (through Equation 3) explain why forward guidance is so very powerful in the sticky-price model, as reported in, for example, Levin et al. (2010), Laseen and Svensson (2011), Del Negro et al. (2012), Carlstrom et al. (2012), and Burgess et al. (2013). Under extended forward guidance to be accommodative, inflation, through backward induction, can *raise* inflation substantially and lower real interest rates, thereby stabilizing activity and inflation. These effects are absent under sticky information, as only past expectations of current conditions matter – not current expectations of future conditions.[2]

3 Empirical Evidence

We now turn to an empirical examination of the sticky-price and sticky-information frameworks. First, we introduce the model and data used in the estimation and subsequent policy experiments. Next, we compare the estimated sticky-price and sticky-information variants of the model in their assessments of key drivers and mechanism behind the US economy. Then, we examine the fit of both models using measures of in-sample fit. Finally, we discuss some the robustness of the results.

3.1 Model Description

We use the model of Smets and Wouters (2007) as a baseline model for estimation and simulation exercises. The model is a benchmark in macroeconomics and forms the core of many larger, more recent New Keynesian DSGE models such as those displayed in Table 1.

We present the key log-linearized equilibrium conditions for the sticky-price and sticky-information variants of the model; Smets and Wouters (2007) contains more details. Consumers face both consumption ($\hat{c}_t$) and labor ($\hat{l}_t$) decisions–which enter non-separably into their utility function. Denoting the nominal interest rate by $\hat{r}_t$ and inflation by $\hat{\pi}_t$, the intertemporal consumption decision

[2] Kiley (2014) shows that this intuition is important for a range of results at the zero lower bound associated with the sticky-price New Keynesian model, including the power of forward guidance, the size of the fiscal multiplier, the paradox of thrift, and the paradox of volatility. Carlstrom et al. (2012) note the first of these points – that is, that forward guidance performs differently in the sticky-information model.

is described by the following linearized Euler equation.

$$\begin{aligned} \hat{c}_t &= \frac{h/\gamma}{1+h/\gamma}\hat{c}_{t-1} + \frac{1}{1+h/\gamma}E_t\hat{c}_{t+1} + \frac{wl_c(\sigma_c - 1)}{\sigma_c(1+h/\gamma)}(\hat{l}_t - E_t\hat{l}_{t+1}) \\ &\quad - \frac{1-h/\gamma}{(1+h/\gamma)\sigma_c}(\hat{r}_t - E_t\hat{\pi}_{t+1}) - \frac{1-h/\gamma}{(1+h/\gamma)\sigma_c}\varepsilon_t^b \end{aligned} \tag{5}$$

The quantity h/γ denotes habit in consumption, adjusted for technological growth; σ_c is the the coefficient of relative risk aversion over consumption-leisure bundles; wl_c weights steady-state labor income to consumption. The variable ε_t^b is an exogenous process. It can be thought of as a wedge between the nominal rate controlled by the Central Bank (r_t) and those faced by consumers ($\hat{r}_t + \varepsilon_t^b$). It follows an autoregressive process: $\varepsilon_t^b = \rho_b \varepsilon_{t-1}^b + \eta_t^b$, with η_t^b independently- and normally-distributed. We will tend to refer to this shock as a "risk premium" shock, reflecting its role as a wedge between the central bank rate and the return affecting household decisions.

Output is produced using installed capital ($\hat{k}_t^s$) and labor ($\hat{l}_t$) via an aggregate Cobb-Douglas production technology subject to fixed costs.

$$\hat{y}_t = \Phi(\alpha\hat{k}_t^s + (1-\alpha)\hat{l}_t + \varepsilon_t^a) \tag{6}$$

Φ is an parameter incorporating fixed costs (which generate short-run increasing returns to scale) and $1-\alpha$ represents labor's share of income. The exogenous variable ε_t^a represents total factor productivity, it follows an autoregressive process: $\varepsilon_t^a = \rho_a \varepsilon_{t-1}^a + \eta_t^a$, with η_t^a independently- and normally-distributed. Capital is available only with a lag, but can be utilized at different rates contemporaneously, or, $\hat{k}_t^s = \hat{k}_{t-1} + \hat{z}_t$, where $\hat{k}_t$ is capital and $\hat{z}_t$ represents utilization. Utilization is a function of the return on capital $\hat{r}_t^k$, $\hat{z}_t = (1-\psi)/\psi\hat{r}_t^k$, where ψ is parameter reflecting the (real) cost of adjustment.

Capital depreciates at rate δ and is accumulated via investment $\hat{i}_t$. The accumulation process is given by:

$$\hat{k}_t = \frac{(1-\delta)}{\gamma}\hat{k}_{t-1} + (1-(1-\delta)/\gamma)\hat{i}_t + (1-(1-\delta)/\gamma)\varphi\gamma^2(1+\beta\gamma^{(1-\sigma_c)})\varepsilon_t^i \tag{7}$$

The exogenous variable ε_t^i is an investment-specific technology shock, which has been suggested as an important driver of the business cycle.[3] It follows an autoregressive process: $\varepsilon_t^i = \rho_i \varepsilon_{t-1}^i + \eta_t^i$, with η_t^i independently- and normally-distributed. The parameter φ represents the real cost of adjustment of capital. The presence of adjustment costs implies that investment responds sluggishly, as described by its own Euler equation:

$$\hat{i}_t = \frac{1}{1+\beta\gamma^{(1-\sigma_c)}}\hat{i}_{t-1} + \frac{\beta\gamma^{(1-\sigma_c)}}{1+\beta\gamma^{(1-\sigma_c)}}E_t\hat{i}_{t+1} + \frac{1}{\varphi\gamma^2(1+\beta\gamma^{(1-\sigma_c)})}\hat{q}_t + \varepsilon_t^i \tag{8}$$

[3]The code on the American Economic Review website for Smets and Wouters (2007) is missing the factor $(1 + \beta\gamma^{(1-\sigma_c)})$; we reintroduce it into the model.

Here $\hat{q}_t$ represents the value of the capital stock. Demand for capital is linked to the marginal product of capital and the interest rates in the model, $\hat{r}_t^k$, and $\hat{r}_t$, via:

$$\hat{q}_t \quad = \quad \beta(1-\delta)\gamma^{-\sigma_c} E_t \hat{q}_{t+1} - \hat{r}_t + E_t \hat{\pi}_{t+1} + (1-\beta(1-\delta)\gamma^{-\sigma_c}) E_t \hat{r}_{t+1}^k - \varepsilon_t^b. \tag{9}$$

Price Setting. The Smets and Wouters (2007) features a continuum of firms exerting some pricing power via monopolistic competition. The model assumes the "standard" sticky-price framework with pricing as in Calvo (1983): each period, a (random) fraction $1-\lambda_p$ of firms may freely adjust their price. Other firms may partially index a fraction (ι_p) of their price to an inflation adjusted version of last periods price. This framework leads to a version of the New-Keynesian Phillips curve:

$$\begin{aligned} \hat{\pi}_t = & \frac{\beta\gamma^{(1-\sigma_c)}}{1+\iota_p\beta\gamma^{(1-\sigma_c)}} E_t \hat{\pi}_{t+1} + \frac{\iota_p}{1+\beta\gamma^{(1-\sigma_c)}} \hat{\pi}_{t-1} \\ & + \frac{(1-\beta\gamma^{(1-\sigma_c)}\lambda_p)(1-\lambda_p)}{(1+\iota_p\beta\gamma^{(1-\sigma_c)})(1+(\Phi-1)\epsilon_p)\lambda_p} \hat{mc}_t + \varepsilon_t^p \end{aligned} \tag{PC-SP}$$

Here, ϵ_p represents the steady state markup over costs, while the steady state profit share enters due to assumption on the aggregator used combine differentiated goods. While the parameter restrictions are specific to this model, Equation (PC-SP) embodies the contemporary Phillips curve: current inflation depends on both lagged inflation and expectations of tomorrow's inflation. The "fundamental" relationship is one between price inflation and marginal costs ($\hat{mc}_t = \alpha r_t^k + (1-\alpha)\hat{w}_t - \varepsilon_t^a$). In Smets and Wouters (2007), an important exogenous driver of inflation is the price markup shock ε_t^p, which follows an ARMA(1, 1) process: $\varepsilon_t^p = \rho_p \varepsilon_{t-1}^p + \eta_t^p - \mu^p \eta_{t-1}^p$.

Our formulation of the Phillips curve with sticky-information follows Reis (2009). In each period only a fraction (λ_p) firms can update their information set.

$$\hat{\pi}_t = \frac{\lambda_p}{(1-\lambda_p)(1+(\Phi-1)\epsilon_p)} \hat{mc}_t + \lambda_p \sum_{j=0}^{\infty} (1-\lambda_p)^j E_{t-j-1} \left[\frac{\Delta \hat{mc}_t}{(1+(\Phi-1)\epsilon_p)} + \hat{\pi}_t \right] + \varepsilon_t^p. \tag{PC-SI}$$

Note that only past expectations of the *current* marginal costs and inflation matter for inflation today. There is no direct influence of expected future conditions, as is present in in the sticky-price case (as can be seen by iterating Equation (PC-SP) forward).

In Smets and Wouters (2007) wages are governed by similar mechanisms, with the fundamental driver being the marginal rate of substitution between leisure and consumption as in Erceg et al. (2000). The dynamics for real wages ($\hat{w}_t$) follows

$$\hat{w}_t = \frac{\beta\gamma^{(1-\sigma_c)}}{1+\beta\gamma^{(1-\sigma_c)}}(E_t\hat{w}_{t+1} + E_t\hat{\pi}_{t+1}) + \frac{1}{1+\beta\gamma^{(1-\sigma_c)}}(\hat{w}_{t-1} - \iota_w\hat{\pi}_{t-1}) \quad (10)$$

$$- \frac{1+\beta\gamma^{(1-\sigma_c)}\iota_w}{1+\beta\gamma^{(1-\sigma_c)}}\hat{\pi}_t + \frac{(1-\beta\gamma^{(1-\sigma_c)}\lambda_w)(1-\lambda_w)}{(1+\beta\gamma^{(1-\sigma_c)})(1+(\Phi_w-1)\epsilon_w)\lambda_w}\hat{\mu}_t^w + \varepsilon_t^w.$$

$$-\hat{\mu}_t^w = \hat{w}_t - \sigma_l\hat{l}_t - \frac{1}{1-h/\gamma}(\hat{c}_t - h/\gamma\hat{c}_{t-1}) \quad (11)$$

The parameters λ_w and ι_w are the wage counterparts of their price parameters, while ϵ_w and Φ_w are related to the steady-state wage markup. The variable μ_t^w refers to the wedge between the wage and the marginal rate of substitution. The exogenous markup shock ε_t^w follows an ARMA(1, 1), like the price process: $\varepsilon_t^w = \rho_w\varepsilon_{t-1}^w + \eta_t^w - \mu_w\eta_{t-1}^w$. The sticky-information curve is, by contrast,

$$\frac{\hat{w}_t}{1-\lambda_w} - \hat{w}_{t-1} = \frac{\lambda_w}{(1-\lambda_w)(1+(\Phi_w-1)\epsilon_w)}\hat{\mu}_t^w \quad (12)$$

$$+ \lambda_w\sum_{j=0}^{\infty}(1-\lambda_w)^j E_{t-j-1}\left[\frac{\Delta_t\hat{\mu}_t^w}{(1+(\Phi_w-1)\epsilon_w)} + \hat{\pi}_t\right] + \varepsilon_t^w.$$

As with the price Phillips curve, it is the past expectations of the (change in the) wedge between the wage and the marginal rate of substitution that drive the sticky-information curve.
Closing the Model. The model is closed by the resource constraint,

$$\hat{y}_t = c_y\hat{c}_t + i_y\hat{i}_t + z_y\hat{z}_t + \varepsilon_t^g. \quad (13)$$

The variable ε_t^g represents an exogenous demand shock which follows the following process: $\varepsilon_t^g = \rho_g\varepsilon_{t-1}^a + \rho_{ga}\eta_t^a + \eta_t^g$. The presence of the technology shock η_t^a in the process reflects the fact that productivity may influence demand–such as through net exports–see Smets and Wouters (2007). Finally, the monetary authority follows the Taylor-type rule:

$$\hat{r}_t = \rho\hat{r}_{t-1} + (1-\rho)(r_\pi(\hat{\pi}_t - \hat{\pi}_t^*) + r_y(\hat{y}_t - \hat{y}_t^*)) \quad (14)$$

$$+ r_{\Delta y}((\hat{y}_t - \hat{y}_t^*) - (\hat{y}_{t-1} - \hat{y}_{t-1}^*)) + \varepsilon_t^r.$$

The starred variables refer to the counter-factual quantities in the absence of nominal rigidities in prices and wages, so that the monetary authority is responding to the so-called "flexible-price output gap." Here ρ indicates the inertia embodied in the monetary policy rule, while r_π, r_y, and $r_{\Delta y}$, refer to the monetary authorities response to inflation, the output gap, and the change in the output gap, respectively. We have departed from Smets and Wouters (2007) by adding an exogenous, time-varying inflation target $\hat{\pi}_t^*$ (as in Del Negro and Schorfheide (2013)). The target follows an AR(1) process, $\hat{\pi}_t^* = \rho\hat{\pi}_{t-1}^* + \eta_t^{\pi^*}$, with $\eta_t^{\pi^*}$ independently- and normally-distributed. The monetary policy shock ε_t^r also follows an AR(1) process, $\varepsilon_t^r = \rho_r\varepsilon_{t-1}^r + \eta_t^r$, with η_t^r independently- and normally-distributed.

3.2 Estimation

We estimate the sticky-price and sticky-information versions of the model to assess the relative empirical fits of the paradigms and to recover plausible parameterizations for the policy experiments given later. Our estimation is informed by eight macroeconomic time series. The first seven are those of Smets and Wouters (2007), given below.

$$\begin{aligned}
\text{per capita output growth} &= \gamma + \hat{y}_t - \hat{y}_{t-1} \\
\text{per capita consumption growth} &= \gamma + \hat{c}_t - \hat{c}_{t-1} \\
\text{per capita investment growth} &= \gamma + \hat{i}_t - \hat{i}_{t-1} \\
\text{per capita wage growth} &= \gamma + \hat{w}_t - \hat{w}_{t-1} \\
\text{hours index} &= \bar{l} + \hat{l}_t \\
\text{GDP deflator} &= \bar{\pi} + \hat{\pi}_t \\
\text{federal funds rate} &= \bar{r} + \hat{r}_t
\end{aligned}$$

The parameter γ represents the steady state growth rate of output, consumption, investment, and wages, while $\bar{l}$, $\bar{\pi}$, and $\bar{r}$ represent steady state labor, inflation, and interest rates. The eigth time series is data on long-run expected inflation from the Survey of Professional Forecasters, which we link to the model by:

$$\text{expected inflation} = \bar{\pi} + \frac{1}{40}\sum_{j=1}^{40} E_t[\hat{\pi}_{t+j}].$$

Our estimation sample uses data from the so-called "Great Moderation" period (1984-2007), reflecting evidence of a break in monetary policy with important consequences for macroeconomic dynamics (e.g., Boivin et al. (2010)). In the robustness section, we consider including a larger portion of the postwar period. We do not include the zero-lower bound period in our estimation to avoid dealing with this non-linearity in estimation.

We employ likelihood-based methods to estimate the model. First, we solve the model for a (locally) unique rational expectations equilibrium, using the method of Meyer-Gohde (2010). Importantly, this method accounts explicitly for the presence of an infinite number of lagged expectations within the sticky-information model and avoids arbitrarily truncating equilibrium conditions, which can affect inference. The solution for the observables, denoted by y_t in a slight abuse of notation, is described by MA(∞),

$$y_t = \bar{y} + \sum_{j=0}^{\infty} \Theta_j \eta_{t-j}, \tag{15}$$

where $\eta_t = [\eta_t^a, \eta_t^i, \eta_t^b, \eta_t^g, \eta_t^m, \eta_t^w, \eta_t^p, \eta_t^{\pi^*}]'$, the vector of innovations to structural shocks and $\bar{y}$ is the unconditional mean of y_t. A key to the Meyer-Gohde (2010) algorithm is that for sufficiently large j, Θ_j follows a recursive law of motion.

The objective is to estimate the parameter vector θ, where θ is comprised of 37 parameters: the 35 estimated by Smets and Wouters (2007) and $[\rho_{\pi^*}, \sigma_{\pi^*}]$.[4] To estimate θ for both models, which we index $\mathcal{M}_{si}$ (sticky information) and $\mathcal{M}_{sp}$ (sticky price), we rely on Bayesian inference. Under the Bayesian approach, a prior distribution, represented by the density $p(\theta|\mathcal{M}_i)$ is combined with the likelihood function $p(\mathcal{Y}^o|\theta, \mathcal{M})$ for the observed data $\mathcal{Y}^o(=\{y_t\}_{t=1}^T)$, to obtain, via Bayes rule, the posterior:

$$p(\theta|\mathcal{Y}^o, \mathcal{M}_i) \propto p(\mathcal{Y}^o|\theta, \mathcal{M}_i)p(\theta|\mathcal{M}_i) \quad i \in \{sp, si\}.$$

The autocovariance function for y_t from (15), together with the normality assumption on η_t, makes construction of the likelihood function is straightforward. To complete the model specification, we must specify a prior distribution over the parameters for each model, $p(\theta|\mathcal{M}_i)$. For both models, we use the priors for Smets and Wouters (2007), which are listed in Appendix Table A-1. This means that the priors for the parameters representing information rigidities in the sticky information model, $[\lambda_p, \lambda_w]$, are the same as the Calvo parameters in the sticky-price model.

To facilitate estimation, we must access the posterior $p(\theta|\mathcal{Y}^o, \mathcal{M}_i)$ for each model. Unfortunately, the posteriors are analytically intractible, owing to the complex ways θ enters the likelihood function. To produce draws from the posteriors, we resort to Sequential Monte Carlo (SMC) techniques for the baseline models and Markov-Chain Monte Carlo (MCMC) methods for the expanded suite of models in the robustness section. Detailed information on SMC and MCMC for DSGE models can be found in Herbst and Schorfheide (forthcoming) and An and Schorfheide (2007).

3.3 Results

Parameter Estimates. Overall, the estimates for parameters not directly related to the wage and price blocks–including those associated with the monetary policy rule–are similar across the two models. We present a complete description of the posterior in the Appendix (Table A-2) and concentrate here on the parameters which exhibit meaningful differences. Table 3 displays the posterior estimates for the parameters associated with wages and prices in the model. For the sticky-information model (the left set of columns), the estimates indicate that both wages and prices exhibit substantial sluggishness via information adjustment. The posterior mode of $\lambda_p \approx 0.33$, indicates that only a third of firms adjust behavior in response to current shocks (the mean is slightly lower, because the posterior is assymmetric). Wages are only marginally more responsive, with a central tendency of $\lambda_w \approx 0.40$. Compared to the sticky-price estimates, the proportion of firms or unions which change their prices contemporaneously is roughly the same, in our formulation, because under the sticky-price model λ_i, is the probability a firm (union) *will not* be able to reset its prices (wages). For the sticky-price model, both of these are around one half, which the price

[4] For the sticky information model, we do not estimate $[\iota_p, \iota_w]$ the indexation parameters. As in SW, we fix $\delta = 0.025$, $g_y = 0.18$, $\epsilon_p = \epsilon_w = 10$, $\Phi_w = 1.5$, and $\gamma = 0.43$ for both models.

Table 3: Posterior Moments of Key Parameters

	Sticky Information			Sticky Prices		
Parameter	Mode	Mean	[0.05, 0.95]	Mode	Mean	[0.05, 0.95]
λ_p	0.34	0.26	[0.16, 0.35]	0.65	0.64	[0.55, 0.73]
ι_p	NA			0.39	0.43	[0.30, 0.58]
ρ_p	0.92	0.89	[0.82, 0.94]	0.93	0.92	[0.84, 0.98]
μ_p	0.52	0.50	[0.36, 0.61]	0.72	0.67	[0.48, 0.80]
σ_p	0.18	0.18	[0.16, 0.21]	0.10	0.10	[0.09, 0.12]
λ_w	0.42	0.41	[0.23, 0.56]	0.47	0.49	[0.38, 0.62]
ι_w	NA			0.48	0.48	[0.31, 0.64]
ρ_w	0.95	0.92	[0.81, 0.97]	0.97	0.97	[0.93, 0.99]
μ_w	0.45	0.40	[0.20, 0.62]	0.69	0.66	[0.48, 0.83]
σ_w	1.34	1.37	[0.96, 1.92]	0.38	0.38	[0.30, 0.47]

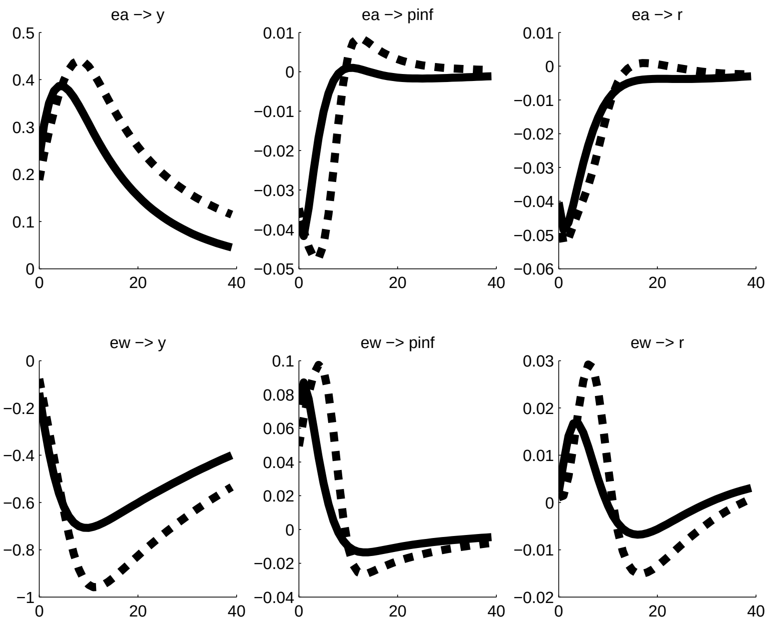
Calvo parameter being slightly higher at 0.64. The sticky-price model features substantial price and wage inertia in the form of indexation ($\iota_p \approx 0.4, \iota_w \approx 0.5$), while this is not present in the sticky-information model (by assumption). No less important are the differences between the parameter estimates of the exogenous markups in the model. Recall that the exogenous markups ε_t^i follow ARMA(1, 1) processes,

$$\varepsilon_t^i = \rho_i \varepsilon_{t-1}^i + \eta_t^i - \mu_i \eta_{t-1}^i, \quad i \in \{p, w\}.$$

While the ARMA processes have roughly similar AR components, the MA parameters are substantially different. For example, the means of the MA parameter associated with the wage markup is about two-thirds the magnitude in the sticky-information model ($\mu_w \approx 0.40$) than in the sticky-price model ($\mu_w \approx 0.66$). The purpose of this structure in the original SW model is to allow the model to better track high frequency movements in the markup (and its effect on observables). The attenuated coefficients for the sticky-information model–coupled with the fact that the overall fit of the two models are about the same under that baseline setup–suggests the that dynamics of the sticky-information model are better suited to explain the aggregate wage and price data with less help from elaborate exogenous drivers. (On the other hand, the magnitude of the innovations to the markup shocks is larger in the sticky-information model.) We later consider the effect of fixing the parameters at 0 to confirm this hypothesis.

Model Dynamics. The model responses to two important (unanticipated) shocks, namely the neutral technology and wage markup shock, illustrate some of the similarities of the alternative price specifications for macroeconomic dynamics. Figure 1 shows the response of output, inflation, and interest rates to one standard deviation shocks. Responses are broadly similar across the sticky-price and sticky-information models. Notice that the peak (trough) of the output/inflation responses is delayed (and larger) under the sticky-information model than under the sticky-price model. The wage markup shock, in particular, implies a difficult choice for the monetary author-

Figure 1: Responses to Technology and Wage Markup Shocks



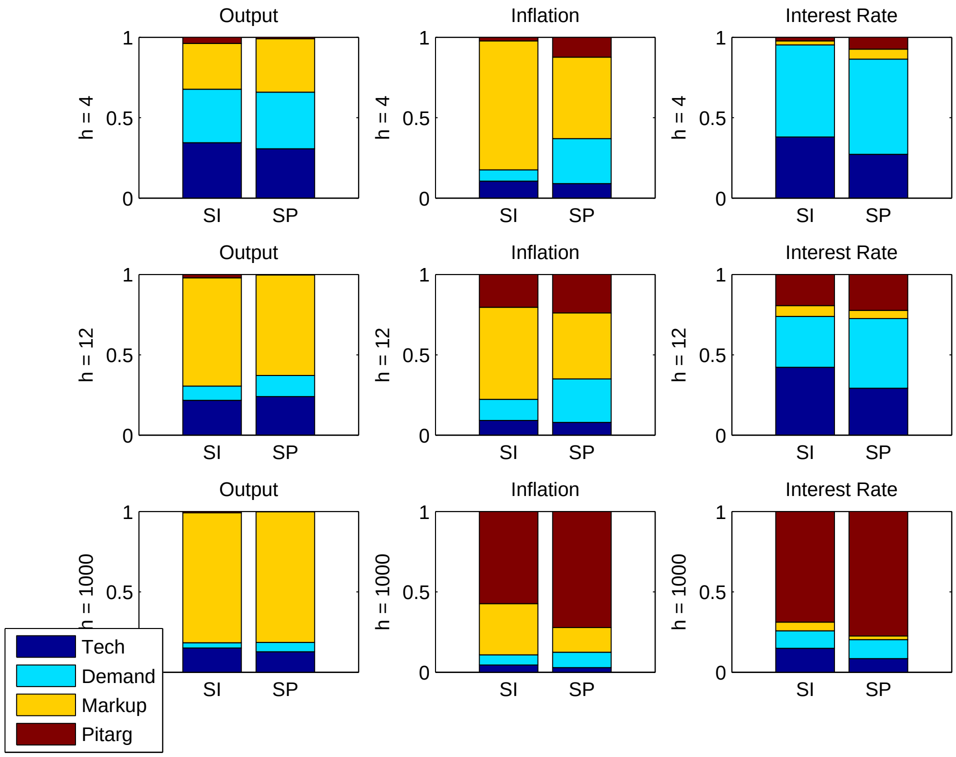
Notes: Figures show response of the sticky-price (solid line) and sticky-information (dashed line) models to an unanticipated technology shock (top row) and an unanticipated wage markup shock (bottom row), computed at the respective posterior modes.

ity, as output falls and inflation rises in response to this shock. This similarity in response to shocks is shared across the shocks hitting the models.

Another way to compare the sticky-price and sticky-information models is by examining the relative importance each model assigns to shocks at various horizons. Figure 2 shows forecast error variance decompositions for output, inflation, and interest rates for 4-quarters, 12-quarters, and 1000-quarters ahead. Roughly speaking, the decompositions for the sticky-price and sticky-information models are about the same, indicating that the two paradigms point to the same drivers of the business cycle. One slight difference, however, is that inflation at shorter horizons (4 and 12 quarters), is less affected by demand shocks in the sticky-information model. To the extent that one views the importance of markup shocks as a measure of misspecification, this is a strike against the sticky-information model. On the other hand, this indicates that the sticky-information model can rationalize readings of moderate inflation in the face of large amounts of slack in the economy, as seen in the Great Recession. Overall, though, these decompositions indicate the the models view business cycles similarly.

Another way to examine differences across models is to ask how these models have interpreted the last 30 or so years in terms of the sources of business cycles. While there are many ways of potentially examining this issue, we look at a simple measure of differences between models. Specifically, at the posterior mode of each model, we use the Kalman Smoother to produce smoothed sequences of fundamental shocks from each model. We then compute the (contemporaneous) cor-

Figure 2: Variance Decompositions for Sticky-price and Sticky-information Models



Notes: Figure show the forecast error variance decompositions for 4-quarter (top row), 12-quarter (middle row), and 1000-quarter (bottom) row for output, inflation, and interest rates.

relations across the models, listed in Table 4. As can be seen in Table 4, the correlations for the smoothed estimates of the technology, monetary policy, demand, and inflation targets shocks are very close to one, implying that these shocks are estimated virtually identically (up to a scale) in the sticky-information and sticky-price models. Less highly correlated are the risk and price and wage markup shocks. In particular, the price markup "only" has a correlation of 0.908 between the two models, which though still high, represents a substantive difference between the two models, touched on above.

Table 4: Correlations of Smoothed Structural Shocks

Shock	Correlation	Shock	Correlation
Neutral Technology Shock	0.998	Price Markup Shock	0.908
Risk Shock	0.939	Wage Markup Shock	0.930
Demand Shock	0.999	Monetary Policy Shock	0.996
Investment-specific Tech. Shock	0.994	Inflation Target Shock	0.994

Model Fit. In the Bayesian paradigm, a summary of in sample model fit is reflected in the so called "marginal data density" (MDD), $p(\mathcal{Y}^o) = \int p(\mathcal{Y}^o|\theta)p(\theta)d\theta$. We run the SMC sampler on each model five times. As a by-product of the sampler, we get (five) estimates of the log of the marginal data density, $\ln \hat{p}(\mathcal{Y}^o|\mathcal{M}_i), i \in \{si, sp\}$. Table 5 reports the mean estimate of the log marginal data density, as well as the standard deviation across the five runs, for both the sticky-information and sticky-price model. The sticky-information model has a log marginal data density of -257.83, very slightly higher than the sticky price model, which has a mean of -257.97. In fact, a strict Bayesian decision-maker who had placed equal prior probability on the two models would place a posterior probability of about 0.54 on the sticky-information model. Still, posterior odds in the estimation of DSGE models are often implausible. Moreover, the standard errors associated with the point estimates are quite large, making it difficult to reject a simple equality-of-means hypothesis. Finally, as we show in the robustness section, these posterior odds can be easily magnified in favor of the one model over the other by, for example, eliminating the MA coefficients on exogenous markup shocks. Overall, we think the data shows that models fit about equally well.

Table 5: Log MDD Estimates

Model	Log MDD Estimate	
	Mean	Std. Dev.
Sticky-information	-257.83	0.41
Sticky-price	-257.97	0.50

Notes: Table shows mean and standard deviation of estimate of $\ln p(Y|\mathcal{M}_i)$ for the sticky-price and sticky-information model, computed across five runs of the SMC sampler.

While the MDD provides a summary measure of model fit, the statistic can be opaque with respect to exact dimensions of fit, especially in a multivariate setting. An additional tool for assessing model adequacy is the so-called predictive check, as detailed in, for example, Geweke (2005). Under the posterior, the predictive distribution for the observables can be constructed as,

$$p(Y^*|\mathcal{Y}^o) = \int p(Y^*|\theta)p(\theta|\mathcal{Y}^o)d\theta.$$

Empirically this can be constructed by taking draws from the posterior and simulating data, Y^*. Objectives of interest are generally statistics of these simulations, $S(\cdot)$, for example standard deviations or autocorrelations. Given the posterior predictive distribution $p(Y^*|\mathcal{Y}^o)$, it is easy to construct distributions $p(S(Y^*)|\mathcal{Y}^o)$. A view of fit can be informed by how far the statistic for the observed data $S(\mathcal{Y}^o)$ falls in the tail of the predictive distribution. With a view towards understanding the differences between the two models, Table 6 displays posterior predictive checks for the standard deviations and autocorrelations of each of the seven observables under the baseline model. Both models behave very similarly – with some trouble fitting all of the (marginal) first and second autocovariances. Evidently the sticky-information model is slightly better at capturing the behavior of wage growth, owing to the differences in the estimated wage markup shock processes. On the other hand, the sticky-price model exhibits less overall persistent dynamics and lower volatility. In the end, no clear model emerges as the winner.

Table 6: Predictive Checks: Standard Deviations and Autocorrelations

	YGR	CGR	IGR	WGR	H	PI	R	PI_EXP
				Standard Deviations				
Data	0.54	0.50	1.48	0.72	1.99	0.23	0.59	0.30
SI	0.83 [0.69, 1.05]	0.71 [0.53, 0.93]	1.94 [1.54, 2.49]	0.76 [0.65, 0.89]	3.16 [1.82, 6.06]	0.46 [0.27, 0.69]	0.38 [0.23, 0.55]	0.20 [0.10, 0.31]
SP	0.79 [0.66, 0.92]	0.68 [0.57, 0.80]	1.80 [1.44, 2.27]	0.84 [0.67, 1.00]	2.43 [1.40, 3.71]	0.46 [0.33, 0.63]	0.37 [0.26, 0.55]	0.18 [0.10, 0.34]
				Autocorrelations				
Data	0.18	0.10	0.50	0.13	0.95	0.60	0.96	NaN
SI	0.44 [0.23, 0.63]	0.53 [0.33, 0.71]	0.65 [0.52, 0.77]	0.11 [-0.11, 0.30]	0.95 [0.91, 0.98]	0.85 [0.66, 0.93]	0.91 [0.85, 0.96]	0.93 [0.85, 0.97]
SP	0.40 [0.25, 0.56]	0.49 [0.30, 0.63]	0.60 [0.46, 0.75]	0.31 [0.06, 0.51]	0.94 [0.88, 0.98]	0.83 [0.74, 0.90]	0.91 [0.84, 0.95]	0.92 [0.84, 0.97]

Notes: The table shows moments (mean, 5th and 95th percentile) of the posterior predictive distribution for the sticky-price (SP) and sticky-information (SI) model under the baseline assumptions.

3.4 Robustness.

We take the above results to show that the sticky-information and sticky-price model have very similar properties in response to (unanticipated) shocks, point to the same key drivers of the business cycle. In fact, a strictly Bayesian decision-maker with only the two above models at her disposal would place substantial weight on the both models, based on the marginal data densities in Table 5. In this section, we examine the effects changes in the estimation sample and other model modifications, listed below.

1. **AR(1) shock processes.** We have above discussed that some of the key differences in the estimation relate to the parameters associated with exogenous wage and price markups. Moreover, the ARMA(1, 1) specification of these processes is at odds with the other exogenous processes assumed in Smets and Wouters (2007). This might be important, because in likelihood-based estimation, the parameters of a DSGE models are identified, roughly speaking, by matching the model-implied autocovariances of observables to those seen in the data. The assumptions on the autocovariance structure of the exogenous process could play an important role in the identification. In this variant of the model, we consider the SW model with AR(1) exogenous processes. That is,

$$\rho_{ga} = 0, \mu_p = 0, \mu_w = 0.$$

2. **Sticky-information: prices only, wages only.** To assess the marginal impact of each the sticky-information assumptions, we estimate variants of the model with either sticky-information in only prices or wages.

3. **Financial Frictions.** The lack of so-called financial frictions in DSGE models was brought into sharp relief during the recent financial crisis. We incorporate financial frictions by included the BBB spread as an observable:

$$\text{Spread} = \bar{sp} + \frac{1}{40}\sum_{j=1}^{40} E_t \left[\varepsilon^b_{t+j}\right].$$

   To avoid stochastic singularity, we also incorporate a preference shock into the model. This is an easy way of capturing empirically the mechanisms at play.[5]

We estimate the models on the relevant datasets using samples from 1966-2007 and 1984-2007. We compute point estimates of marginal data densities using the harmonic mean estimator, instead of the SMC sampler, as in the baseline cases, for computational feasibility. The results are displayed in Table 7. A few clear points emerge. For one, as under the baseline case, there is no clearly preferred model. Indeed, small model changes can push model odds more than one might expect–this kind of implausibility of posterior odds is pervasive in estimated DSGE models. Second, on the other hand, is it clear that the sticky-price model "relies" much more heavily on the ARMA(1, 1) markup processes to improve model fit than the sticky-information model. The sticky-information model is less sensitive to changes along these lines. For example, the inclusion of the MA coefficients result in an incremental improvement of fit of the sticky-price model by about 40 log points when considering the model where spreads are observed. Moreover, the sticky-information variants of the model are uniformly heavily favored under this modification. Third, the relative importance of the sticky-information assumption in prices versus wages is sensitive to sample size and auxiliary model assumptions: it is safer to say, then, that the joint dynamics of these objects are crucial.[6]

Taken together, we view this evidence as suggesting that the sticky-information model represents a reasonable alternative to the sticky-price model in tracking the co-movements of major macroeconomic aggregates over the past 50 years. Given that, it should be among the frameworks used when conducting policy experiments going forward.

[5] We also estimated versions with a financial accelerator under sticky-information and sticky-prices with broadly similar results.

[6] An important caveat when interpreting marginal data density estimates from the modified harmonic mean (MHM) estimator may be unreliable when taken over large and complex posteriors. Herbst and Schorfheide (forthcoming) document that with standard priors, the MHM does reliably estimate the log MDD for the Smets-Wouters model.

Table 7: Log Marginal Likelihood Estimates

	Sticky Prices	Sticky Information	Prob(SI)
Dataset: SW07 + Inflation Expectations, 1966-2007			
Baseline	-803.49	-813.93	(0.00)
No MA terms	-838.02	-830.84	(1.00)
SI Prices Only	-811.47		—
SI Wages Only	-803.66		—
Dataset: SW07 + Inflation Expectations, 1984-2007			
Baseline	-257.83	-257.97	(0.54)
No MA terms	-274.18	-269.73	(0.99)
SI Prices Only	-255.64		—
SI Wages Only	-264.17		—
Dataset: SW07 + Inflation Expectations + Spread, 1966-2007			
Baseline	-668.93	-677.04	(0.00)
No MA terms	-711.52	-696.84	(1.00)
SI Prices Only	-678.62		—
SI Wages Only	-667.51		—
Dataset: SW07 + Inflation Expectations + Spread, 1984-2007			
Baseline	-158.72	-154.03	(0.99)
No MA terms	-178.76	-169.75	(1.00)

Notes: First two columns list the point estimates of log MDDs for the sticky-information and sticky-price models. The last column lists the marginal posterior model probability for the sticky-information model, assuming a prior probability of 0.5.

4 Differences in the Environment Between Sticky-Price and Sticky-Information Equilibria

Our empirical analysis suggests that the alternative specifications of price adjustment imply quite similar dynamics following key structural shocks, present a similar decomposition of history into structural drivers, and provide similar fits of the data. In sum, a look at macroeconomic data provides little discrimination across the alternative views of price dynamics.

Nonetheless, the models differ along an important dimension – specifically, how anticipated future conditions feed into current outcomes. And these differences have implications for monetary policy,

4.1 Anticipation Effects and Monetary Policy Shocks

As highlighted in the simple model presented in Section 2.2, anticipation effects are different across sticky-price and sticky-information models: Sticky-price models imply that expected future conditions directly affect inflation (and hence real activity through real interest rates), whereas such effects are indirect, and hence less important, under sticky information.

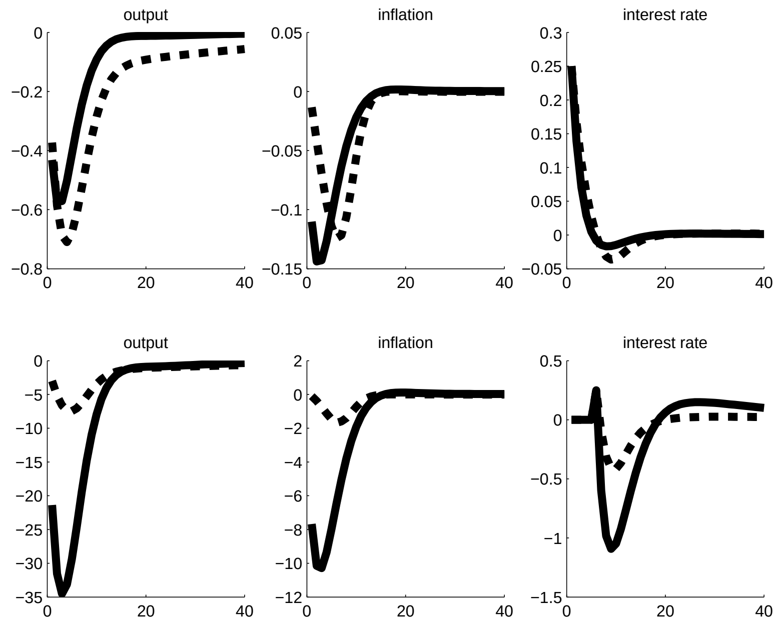
These differences can be seen by examining the response of the models to *unanticipated* and *anticipated* surprises in monetary policy. Figure 3 displays the responses of output, inflation, and interest rates to a 25 basis-point unanticipated monetary policy shock (top row) and a monetary policy shock anticipated 6 quarters in advance, with the central bank holding the interest fixed for the preceding 5 quarters. The solid line shows the response of the sticky-price model while the dashed line shows the response of the sticky information model, both computing using the parameters at the respective posterior modes. The top row shows that the behavior of the sticky-price and sticky-information models to *unanticipated* shocks are broadly similar. In particular, the output responses are nearly identical across the models. The movements in inflation are broadly similar, although the inflation drop is a bit sharper in the sticky-price model and more delayed in the sticky-information model.

On the other hand, the responses of output and inflation to a sequence of *anticipated* monetary policy shocks keeping the federal funds at its steady state value, then increasing increasing 25 basis points in period 6, are quite different across models. First, the drop in output and inflation is much sharper in the sticky-price model. In the sticky-price model, output falls by about 35% percent at its trough, while for the sticky-information model the corresponding fall is about 7%. The fall for inflation shares similar features, with a drop in inflation about 10% in the sticky-price model. Note also that these falls come to a large extent in the initial period of the impulse response in the sticky price model. The reason for the differences across models is the pricing mechanisms. As discussed in Section 2.2, the anticipated spike in period 6 feeds heavily backwards towards firms pricing decisions for periods 5, 4, and so on, in the sticky price model. This raises real interest rates in those periods and further depresses output. The end result is a massive initial drop in output and inflation, about two orders of magnitude larger than under an unanticipated shock. By contrast, the feedback mechanism described above is not a feature of the sticky-information model. Here the driver of the initial drop in output and inflation is mainly coming from the IS relationship–the fact that consumption depends on the entire path of real rates. Lastly, observe that interest rates fall in both cases after the anticipated shock is realized. [7] These varying reactions to anticipated shocks across models will have effects on the policies which involve guidance or commitment about the future, as we highlight in this work.

Because of the differences in anticipation effects, the environment confronting monetary policymakers differs generically along several dimensions between sticky-price and sticky-wage economies. The heart of these differences is the incentive for price-setters in a sticky-price economy to act pre-emptively in the face of anticipated cost conditions – an incentive that is absent in the sticky-information economy. Policymakers acting in a sticky-price environment must therefore account for significant spill-overs between policy effects on costs and prices in the medium and short terms. In sticky-information economies, by contrast, the impulse response of inflation is driven either by contemporaneous marginal cost or by the drift in the price level following the shock. Monetary policy may thus achieve a significant degree of separation between actions aimed at

[7] It should be noted that the dynamics under the sticky-price model can have oddly different properties under minor variations of this shock. As in Carlstrom et al. (2012), output and inflation can show strongly *positive* responses to very similar anticipated policy paths under a slightly different parameterization.

Figure 3: Responses to Monetary Policy Shocks



Notes: Figures show response of the sticky-price (solid line) and sticky-information (dashed line) models to an unanticipated (top row) and 6-quarter ahead anticipated (bottom show) monetary policy shock, computed at the respective posterior modes.

medium-term cost pressures and short-run inflation.

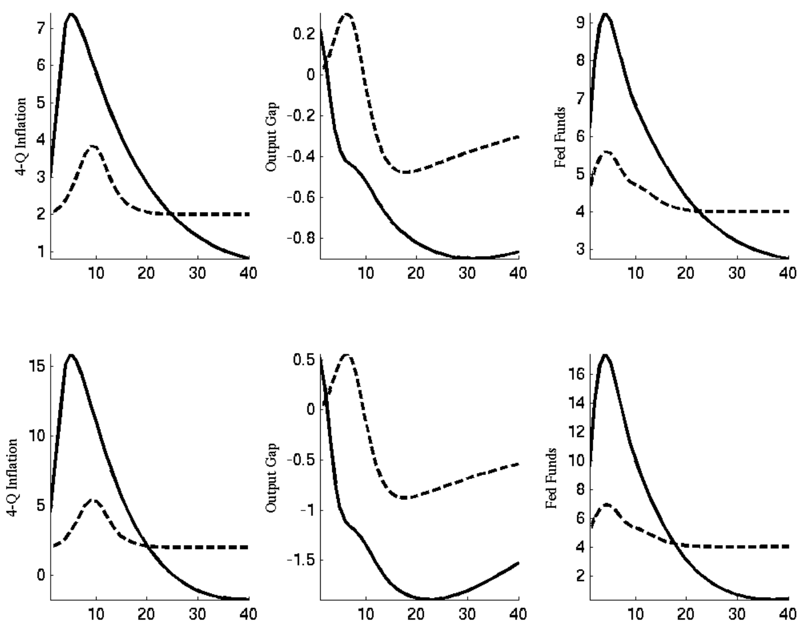
Under sticky information, the expected response of the economy to a shock converges to that under flexible prices, as the fraction of agents aware of the shock goes to one. (Our estimates put this horizon at around 12-16 quarters.) Accordingly, real effects from monetary policy after this date must arise through the endogenous propagation of the real state variables inherited as initial conditions. It follows that medium-term output gap stabilization unavoidably has consequences for real variables in the short-run.

Figure 4 illustrates some of these differences by considering the optimal response, under commitment, to a unit wage markup shock, where the solid line displays outcomes for the sticky-price equilibrium and the dashed line shows outcomes for the sticky-information economy. [8] Under sticky prices, in addition to the familiar conflict between inflation and output stabilization at a given time, such shocks generate considerable intertemporal trade-offs, as medium-term policy actions taken to limit the prolonged slump in output spill over severely to inflation in the short run. Given the discussion above, the situation under sticky information is less fraught, as very short-run inflation is less sensitive to the path of costs in general, while inflation after around three years can be stabilized without any output loss.

[8]The policy objective function underlying the simulations in this section equally weight the 4-quarter change in inflation, the output gap and the change in the federal funds rate. We discuss the motivation for this choice of objective in greater detail below.

The lower panel of Figure 4 presents results under a more persistent markup shock, with an autoregressive parameter of .95. Based on the reasoning above, the bottom panel should show a more stark difference from the top panel under sticky prices, as the spillovers from the (more-pronounced) medium-term movements in the face of a more persistent shock are greater. The predicted outcomes can be seen clearly in inflation and output movements, which are much more different across the top and bottom panels under sticky prices than under sticky information.

Figure 4: Responses of Inflation and the Output Gap Under Optimal Policy to Persistent Wage Mark-up Shock

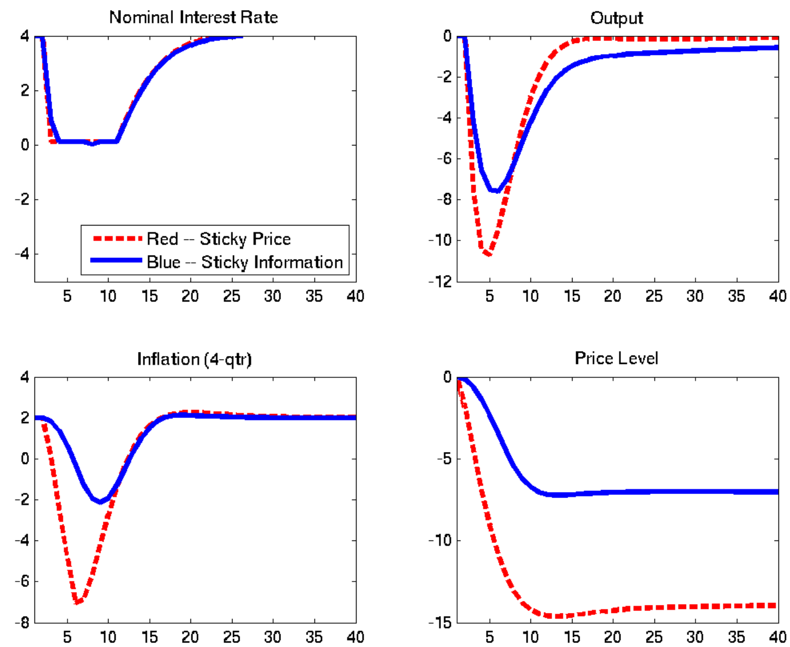


Notes: Figure shows the response of the 4-quarter change in inflation and the output gap to a wage mark-up shock under optimal policy. Top panel: Estimated persistence. Lower panel: 0.95 serial correlation. Black solid line: sticky-prices. Black dashed line: sticky-information.

4.2 Anticipation Effects and the Zero-Lower Bound in A Great Recession

We now present a simulation of the baseline version of each model that generates a fairly deep recession in which the nominal short-term interest rate falls to its effective lower bound quickly. Implementation of such scenarios requires assumptions about both the nature of the shock hitting the economy and the monetary policy strategy that is employed by the Federal Reserve and understood by the public. With regard to the latter, we assume, as our baseline, that the FOMC follows the estimated policy rule. With regard to the disturbance bringing about the recession, we assume an unusually persistent shift in the risk premium entering the households consumption Euler equation: The magnitude and persistence of this shock results in a 200bp increase in the spread between a (hypothetical) 10-yr risky bond and the 10-yr risk-free rate implied by the expectations hypothesis.[9] Emphasis on a widening of risk spreads bears resemblance to the recent recession – although our models, by hewing closely to Smets and Wouters (2007), ignore financial intermediation.

Figure 5: A Recessionary Shock (under estimated policy rule)



Notes: Figures show response of the sticky-price (red) and sticky-information (blue) models to the Great Recession shock

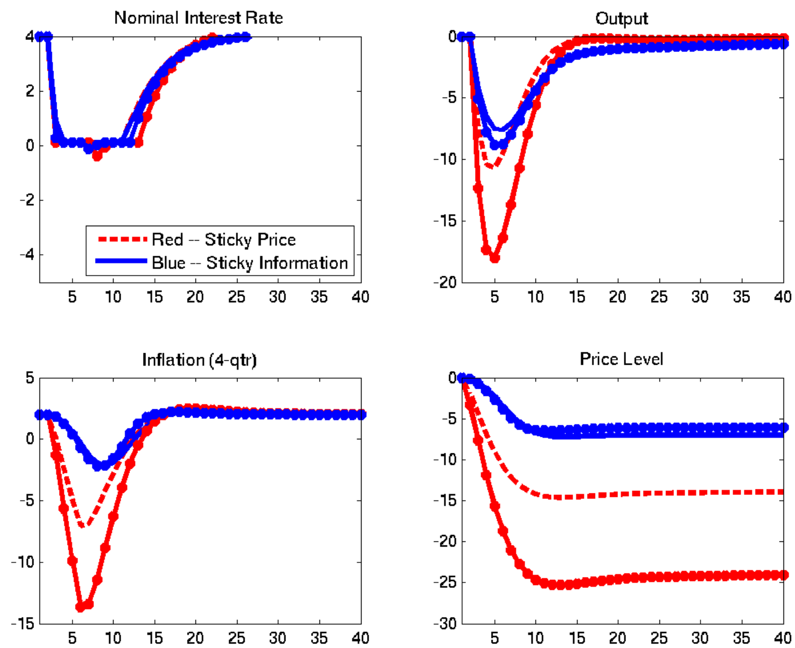
The scenarios are presented in Figure 5.[10] Regardless of the model of price and wage dynamics, output falls sharply (to a level about 7-1/2 percent below potential in the sticky-information model and nearly 11 percent below potential in the sticky-price model). In each model, the federal funds rate falls quickly to 0.125 percent (at an annual rate) and remains there until two years following the shock. Inflation (on a four-quarter basis and at an annual rate) in the sticky-price model drops dramatically to -7 percent (at an annual rate) by the start of the second year and rises as a recovery begins to take hold. In the sticky-information model, inflation declines to -2 percent in the second year. Note that the dramatic fall in inflation in both models is at odds with experience during the

[9]Specifically, the autocorrelation coefficient for the risk premium shock is set to 0.8 (instead of its estimated value). Note that a variety of studies have considered the implications of adverse shocks calibrated to yield large increases in 10-yr risk spreads, as such longer-maturity spreads are observable in data; an example is Christiano et al. (2013).

[10]A binding zero lower bound can result in equilibrium non-existence or in multiple equilibria , as noted in other research such as Brendon et al. (2013). We examined this later possibility by inspecting every possible configuration of dates at which the ZLB might bind between 1 and 40 quarters in the future, subject to the condition that the ZLB begins to bind within 4 quarters of the start of the simulation and that the ZLB does not bind again following lift-off. Where indeterminacy arises, we have chosen to focus on the equilibrium with the least volatile outcomes.

Great Recession – a feature of the sticky-price model that has been denoted the "missing deflation" in some recent research (e.g., King and Watson (2012)),[11]

Figure 6: Amplification of Recessionary Shock at the ZLB



Notes: Figures show response of the sticky-price (red) and sticky-information (blue) models to alternative Great Recession shocks, with a 200bp (-) or 250bp (-*) increase in the 10-yr risk spread

As we have emphasized, the non-linearity and amplification of the effects of shocks under the sticky-price framework is very large relative to that under sticky-information and increases with the size of the shock. To illustrate this difference more clearly clearly, Figure 6 presents the Great Recession scenario and an alternative in which the 10-yr risk spread rises by 250bp rather than 200bp. While the shock is only 25 percent larger, the declines in inflation and output are nearly twice as large under the larger shock with sticky prices, while amplification is modest under sticky information. As before, this reflects the logic of forward-looking price setting: A deeper recession lowers future inflation, and through backward induction has a large effect on current inflation. The decline in inflation boosts real rates, depressing output further. Under sticky information, this effect from forward looking behavior is absent.

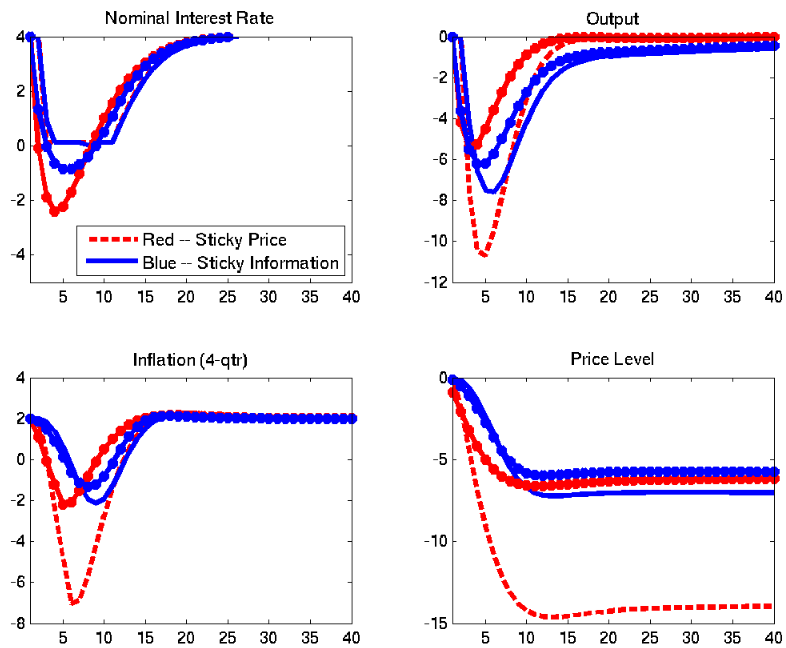
The tendency of amplification of the effects of shocks at the ZLB can also be seen through a simulation of the model that does not impose the ZLB, reported in Figure 7. In the absence of the ZLB, the effects of the demand shock on output are quite similar under sticky prices and sticky

[11] Giannoni et al. (2013) do not find a missing disinflation in their DSGE model, primarily because they estimate a flatter Phillips curve. Christiano et al. (2013) find a sharp drop in inflation due to the demand shocks in their analysis, but suggest the disinflation was curbed by slow growth in technology/productivity.

information (the black and blue lines, respectively), with a fall of about 5 1/2 percent in the sticky-price model and 6 1/2 percent in the sticky-information model. The inflation responses are also closer than in the case with the ZLB, with inflation falling to -2 1/4 percent under sticky prices and -1 1/4 percent under sticky information. These similarities are consistent with our earlier empirical analysis – outside of the ZLB, the models have similar empirical properties.

Imposing the ZLB in the sticky price model more than doubles the drops in output and inflation, and the decline in the price level is more than four times as large in the presence of the ZLB. The unanchoring of the price level at the ZLB under sticky prices is central to the amplification of shocks at the ZLB in this framework. In contrast, under sticky information (the blue lines), the price level is (relatively) anchored – with the decline at the ZLB a bit more than double that in the absence of the ZLB: As a result, the amplification of the adverse demand shock by the ZLB is relatively muted.

Figure 7: Risk Shock With And Without the ZLB

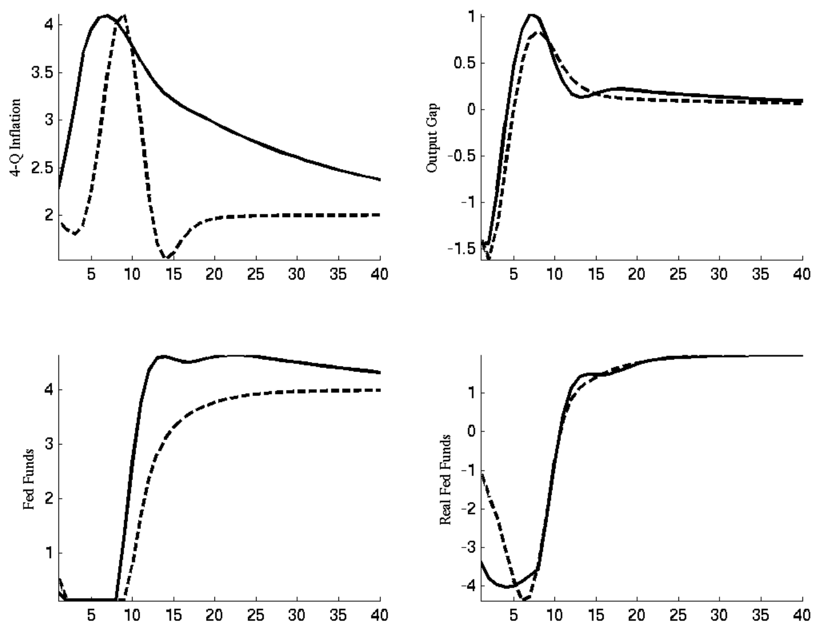


Notes: Figures show response of the sticky-price (red) and sticky information (blue) models to the Great Recession shock, with and without imposing the zero-lower bound. (-) line–With ZLB; (*) line – Without ZLB

We have now provided three examples of how anticipation effects result in different amplification in the sticky-price model than in the sticky-information model: Anticipated policy shocks are amplified more under sticky prices; markup shocks of greater persistence are amplified more under sticky prices; amd the ZLB amplifies deflationary forces more under sticky prices. These environmental features shape the optimal response to shocks once the policy rate hits its lower bound.

In particular, as shown in Figure 8, the optimal response to a severe aggregate demand shock under sticky prices involves a prolonged period during which inflation is considerably above target, as a necessary concomitant to the prolonged period of low real interest rates and high marginal costs. [12] Under sticky information, optimal policy delivers a very similar real interest rate path and thus achieves very similar real outcomes. However, the separability between medium- and short-term inflation stabilization under sticky information allows the optimal policy response to limit higher-than-target inflation to only two or three years.

Figure 8: Responses of Inflation and the Output Gap Under Optimal Policy to a Large Adverse Demand Shock



Notes: Figure shows the response of the 4-quarter change in inflation and the output gap to the Great Recession shock under optimal policy. Black solid line: sticky-prices. Black dashed line: sticky-information.

In the remainder of our analysis, we will focus on strategies that may approximate an optimal commitment strategy, but we will not revisit behavior under such approaches in general because simple strategies may be easier to communicate and more robust across different models (e.g., Taylor and Williams (2010)). Nonetheless, the forces illustrated in this example of outcomes under optimal strategies will be apparent.

[12]The shock in this scenario is a large increase in the risk premium. Absent the zero lower bound, the optimal policy would exactly offset this shock. We describe this shock in more detail below.

5 Effective Monetary Policies

5.1 Strategies we analyze

The set of policy strategies we consider begins with the estimated policy rule within each model – that is, **policy as usual**. In addition to representing the historical approach to policy within our models, such an approach– with substantial interest rate inertia and a sizable response to the change in the output gap–captures some of the features of good policy emphasized in the previous literature. [13]

Policymakers in the United States (and elsewhere) have discussed, and arguably pursued deviations from such policy as usual during the recent ZLB episode, in part inspired by the research literature. Focusing on the time-line and discussions within the United States (as discussed more thoroughly in English et al. (2013)), we highlight three distinct strategies related to the literature cited in the previous section.

More aggressive responses to economic activity: The estimated policy rule does not respond much to the level of economic activity. One key conclusion from Reifschneider and Williams (2000) was that a sizable response to economic activity was important for good monetary policy performance at the ZLB. Moreover, policymakers and recent analyses (e.g.,Yellen (2012) and English et al. (2013)) have discussed this aspect of good policy through the lens of an inertial version of the Taylor (1999) rule, as this rule includes of sizable response to output. This "inertial" Taylor (1999) rule is given by[14]

$$R_t = 0.75R_{t-1} + 0.25(1.5(P_t - P_{t-4} - 2) + y_t - y_t^f). \tag{16}$$

Lower for longer (time dimension): Starting in March 2009, the FOMC communicated that "economic conditions are likely to warrant exceptionally low levels of the federal funds rate for an extended period". In August 2011, the Committee substituted "at least through mid-2013" for the words "for an extended period." This date was adjusted several times, the last change occurring in September 2013, when the FOMC shifted the date to mid-2015.

As has been noted by others (e.g., Campbell et al. (2012)), these communications do not clearly outline whether the FOMC plan represented a forecast, and hence no deviation from "policy as usual" or a promise to keep the nominal interest rate "lower for longer" than policy as usual would imply. Our baseline case, with policy as usual as described by the estimated policy rule in the models we use, captures this possibility. Another possibility, however, is that market participants interpreted the Committee as undertaking a commitment to hold the federal funds rate at

[13]One class of strategies that we considered but do not report involve relating the change on the nominal interest rate to the change in prices and the change in the output gap; the estimated rule, following previous practice, does not allow a coefficient of unity on the lagged interest rate. Kiley (2012) suggests such rules explain U.S. data well and have a long history in related research.

[14]The interest rate rule, along with subsequent ones, are presented using annual rates for interest rates and inflation.

the ZLB over some fixed horizon, regardless (within limits) of contemporaneous economic conditions. We therefore also consider lower-for-longer policies specified in terms of *date-based guidance*. We assume, for illustrative purposes, that such date-based guidance is followed by reversion to the inertial Taylor (1999) rule.

As emphasized in our discussion of the basic New-Keynesian model earlier, Laseen and Svensson (2011), Del Negro and Schorfheide (2013), and Del Negro et al. (2012) show forward guidance can have very large effects in the sticky-price framework, whereas Kiley (2014) suggests that such forward guidance is less powerful in a sticky-information model. We only consider date-based guidance in our simulations of shocks that precipitate the zero-lower bound: Our more general discussion – of the properties or various rules in response to all types of shocks (via stochastic simulations or moments from the models) or of shocks to the Phillips curve will not consider date-based guidance. Nonetheless, analysis of these strategies is important for highlighting some of the distinctions related to amplification that arise across the sticky-price and sticky-information frameworks.

Lower for longer (thresholds): In December 2012, the FOMC announced that exceptionally low levels for the federal funds rate will be appropriate "at least as long as the unemployment rate remains above 6-1/2 percent, inflation between one and two years ahead is projected to be no more than a half percentage point above the Committees 2 percent longer-run goal, and longer-term inflation expectations continue to be well anchored." This language has remained in the FOMC statement, with minor adjustments, until March 2014.

Different thresholds have been explored or suggested in Campbell et al. (2012), English et al. (2013), and Kocherlakota (2013), with the latter two suggesting that economic performance would likely improve if the unemployment threshold were set to a lower value of 5.5 percent. We explore this approach for both the inertial rule we use as our baseline and the other strategies that we examine–but our emphasis is on results using the Taylor rule, as these illustrate the key points. As our models are all version of Smets and Wouters (2007), our model does not include a measure of the unemployment rate. Therefore, we implement such thresholds by assuming that the unemployment rate threshold of 6.5 percent corresponds to an output gap threshold of 2 percent, consistent with a natural rate of unemployment of 5.5 percent and an "Okun's Law" coefficient of 2. An unemployment rate threshold of 5.5 percent thus corresponds to an output gap threshold of 0 percent. We include an upper threshold of 2.5 percent for the year-ahead forecast of inflation.

Promising higher inflation: Threshold strategies following a large adverse demand shock have the property that policy accommodation does not begin to be removed until some combination of the inflation gap and the output gap turns positive– that is, accommodation is not removed until either inflation is above objective or output is above potential. This property is a reasonable one for efficient policies, as failure to satisfy this criterion implies that additional accommodation would result in improved outcomes for both goals (Svensson (2011) or Kocherlakota (2013)). Within the academic literature, this property is often emphasized within a class of targeting rules in which a weighted average of prices and the output gap is set equal to zero, as such approaches represent optimal policy in simple models (e.g., Woodford (2010)).[15] For this reason, we consider the following two targeting rules; the contrast between the two rules in response to shocks to the Phillips curve and to demand shocks that induce the zero-lower bound will be striking.

$$(P_t - P_{t-4} - 2) + y_t - y_t^f = 0, \tag{17}$$

$$P_t + y_t - y_t^f = 0. \tag{18}$$

Note that in (18) we suppress the deterministic drift in the price level (in the presentation; such drift is allowed in the simulations).

These strategies have the spirit of promising higher inflation to stimulate activity. In the case of 17, the promise is weak – the approach ensures that inflation is above target if output is below target, but does not promise to make up any shortfall in the targeting criterion induced by the zero-lower bound. In contrast, the price-level targeting approach promises to make up any shortfall in inflation until the price level is brought back to its desired path. excluding the zero-lower bound (e.g., Blake (2012)). Eggertsson and Woodford (2003), building off earlier work such as Krugman (1998) and Reifschneider and Williams (2000), suggest that a commitment to higher future inflation, through a mechanism such as price-level targeting, is an efficient response to the zero-lower bound.

Finally, we complement the strict nominal-income targeting approach shown in 18 with a simple nominal interest rate rule, largely to emphasize that such an instrument rule performs very similarly to the strict nominal income target:

$$R_t = R_{t-1} + 0.125(p_t + y_t - y_t^f). \tag{19}$$

Note that we have assumed the *change* in the nominal interest rate is proportional to the nominal income gap – as highly inertial policy strategies will dominate (in terms of economic performance) in all of our simulations. The price-level term in 19 and in the optimized rule below allows for deterministic growth in the price level of 2 percent.

5.2 Performance of Rules On Average (Outside the ZLB)

We first consider the performance of the rules outlined above in response to the typical set of shocks hitting the economy and abstracting from the zero lower bound on interest rates. Such an analysis follows in the tradition for monetary policy analysis summarized in Taylor and Williams (2010). As in much of this literature, our analysis focuses on 4-quarter change in prices, the output gap, and the change in the nominal interest rate.

[15] That is, in the simple sticky-price model presented to illustrate ideas, the discretionary optimal policy (ignoring the zero-lower bound) sets a weighted average of inflation and output to zero, and the commitment optimal policy sets a weighted average of the price-level and output to zero.

Table 8: Optimal Simple Rules

Taylor Rule (Sticky Prices)	$R_t = 0.352\bar{\pi}_t + 1.730(y_t - y_t^f) + 1.140R_{t-1} - 1.714(y_{t-1} - y_{t-1}^f)$
Taylor Rule (Sticky Information)	$R_t = 0.015\bar{\pi}_t + 0.048(y_t - y_t^f) + 1.069R_{t-1} - 0.038(y_{t-1} - y_{t-1}^f)$
Level Rule (Sticky Prices)	$R_t = 0.126p_t + 0.980(y_t - y_t^f) + 1.057R_{t-1} - 0.255(y_{t-1} - y_{t-1}^f)$
Level Rule (Sticky Information)	$R_t = 0.001p_t + 0.000(y_t - y_t^f) + 1.056R_{t-1} + 0.010(y_{t-1} - y_{t-1}^f)$

Notes: $\bar{\pi}_t$ is the 4-quarter change in the price level.

As benchmarks, we will also discuss outcomes under simple rules with optimized coefficients and under the optimal commitment policy. The focus on simple rules is consistent with our concern for robustness across specifications of price dynamics, while our examination of the more complex optimal rule provides a benchmark for what is achievable within the alternative frameworks. For these exercises, we adopt an ad hoc loss function depending only on variances of inflation, the output gap, and the change in the nominal interest rate (where inflation and interest rates are expressed at annual rates). This specification is in line with a substantial part of the literature cited above, but can differ importantly from the form of objective function derived from maximizing the welfare of the representative household, as in Levin et al. (2006), Schmitt-Grohé and Uribe (2006), or Reis (2009), where additional terms –for example, involving wage inflation – are typically very important.

In all of our simulations, we will assume that the alternative policy strategies are fully credible to the public and incorporated into the public's information set. As such, we are not focused on transition issues that may be associated with regime changes.

Before turning to performance, we present the optimal simple rules. Optimization is done over rules within two classes: In the Taylor (1999) class, we allow non-zero coefficients on the (four-quarter) inflation rate, the current and lagged output gap, and the lag of the nominal interest rate; in the level class, we allow response to the price level (in place of inflation). The optimal simple rules in each model are shown in Table 8.

Optimal Taylor rules respond to the change in output, not its level. While all sticky-information rules have very small coefficients on the determinants other than the lagged interest rate, these rules are also all super-inertial and so such small responses are consistent with very vigorous long-run responses to changes in fundamentals. Moreover, outcomes in the sticky-information model are relatively insensitive to variations in these coefficients, in the sense that responses to shocks are little affected if the optimal sticky-price coefficients are used.

Table 9 presents standard deviations for the 4-quarter change in the price level, the output gap and the change in the federal funds rate for our focal rules, as well as for the optimized rules. Given the more refractory economic environment under sticky-information discussed above, it is unsurprising that the sticky-information outcomes are uniformly worse than their sticky-price counterparts. Moreover, the estimated variances of price and wage mark-up shocks are substantially higher in the sticky information model.

Looking across rules, consistent with the previous literature, approaches which react strongly to the level of the output gap, such as the inertial Taylor rules (16), suffer quite severe deteriorations in inflation performance. The severity of this deterioration is driven chiefly by behavior following wage and price mark-up shocks. By contrast, rules which target either the change in the output gap (e.g., the estimated policy rule) or the nominal income gap deliver stabilization performance close to the optimal rule benchmark.[16] Finally, the simple rule for nominal-income targeting (19) delivers outcomes for inflation and output very similar to those under strict nominal income targeting (18), but with much higher variability in the nominal interest rate.

Table 9: Standard Deviations of Selected Variables, Under Sticky Prices and Sticky Information

	Sticky Prices			Sticky Information		
	$\bar{\pi}$	$y - y^f$	ΔR	$\bar{\pi}$	$y - y^f$	ΔR
Estimated rule (eq. 14)	1.04	4.43	0.40	1.54	7.41	0.39
Inertial Taylor (1999) (eq. 16)	6.71	3.69	0.65	10.01	5.47	0.67
Nominal Income targeting (eq. 18)	1.18	4.20	2.36	1.78	6.99	5.88
Nominal Income rule (eq. 19)	1.17	4.22	0.25	1.76	6.98	0.31
Optimal rule (inflation)	1.47	4.11	0.41	3.11	5.95	0.05
Optimal rule (price level)	1.50	4.08	0.31	3.31	5.88	0.03
Optimal Policy	1.49	4.07	0.30	2.68	6.03	0.47

Notes: $\bar{\pi}$ = 4-quarter change in prices (annual rate). Gap = output gap to flex price equilibrium. R = federal funds rate (annual rate).

We will now try to unpack these findings by illustrating the performance of alternative strategies in response to specific shocks, including demand shocks that induce a binding ZLB, in order to highlight key similarities and differences across the sticky-price and sticky-information frameworks.

5.3 Adverse Supply Shocks

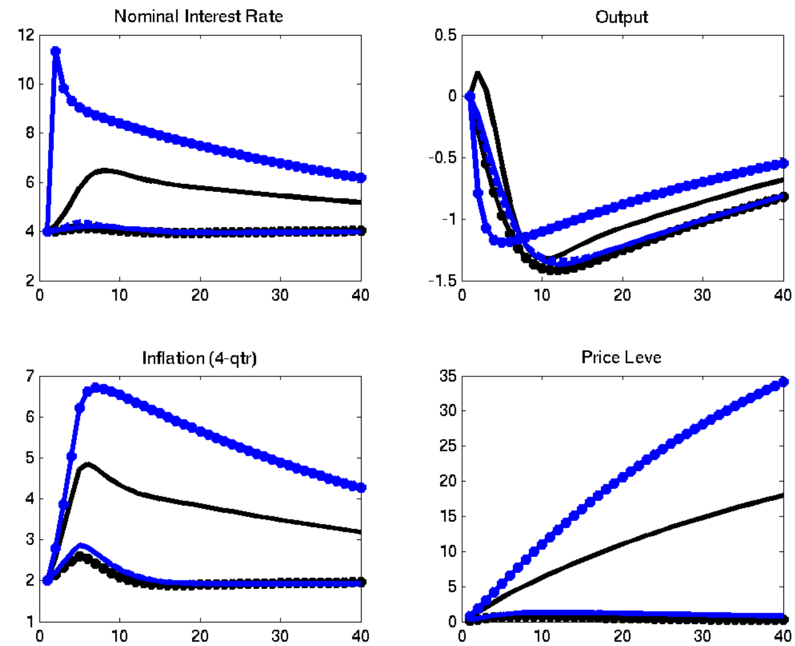
Strategies that perform well in the face of demand shocks may perform poorly in response to supply shocks, as shocks to the Phillips curve (for wages or prices) can imply important trade-offs between activity and inflation in New Keynesian DSGE model. In our models, however, key supply shocks, such as mark-up shocks, are "measures of our ignorance" (e.g., Chari et al. (2009)), with relatively weak or indeterminate micro-foundations. Nevertheless, they are essential to the models' fit to data on wages, prices, and even activity (especially activity in the labor market) and so ignoring their implications seems unwise. Moreover, as previously mentioned, these shocks importantly shape the types of policies that perform well in a variance analysis such as that in the previous section or in, for example. Taylor and Wieland (2012), and hence are important for understanding the literature.

To illustrate the implications of an adverse shock to the Phillips curve, we focus on a large

[16] We do not present results for the inflation-targeting rule 17 as it performs very poorly, as with the inertial Taylor rule; we highlight the reasons for this poor performance below in our deterministic simulations.

wage markup shock. Specifically, we consider a two standard deviation shock under each strategy outlined above except the threshold strategies.

Figure 9: Adverse Supply Shock in Sticky-Price Model



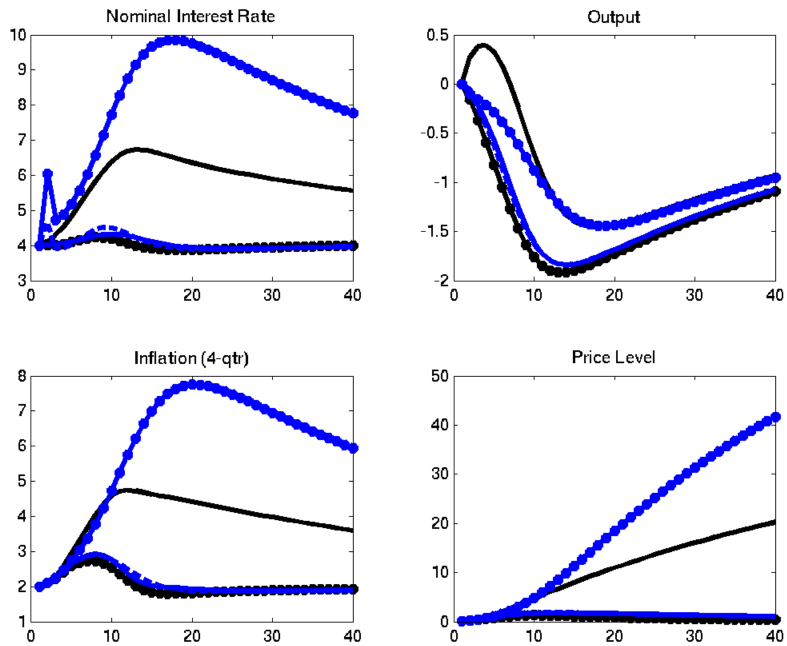
Notes: Figures show response of the sticky-price model to an unanticipated wage markup shock, computed at the posterior mode of the parameters. Black -* line–Estimated rule; black solid line – Taylor (1999); blue -* – Strict inflation targeting; blue dashed (–) line – Strict nominal income targeting; blue solid line – Nominal income rule.

Figure 9 reports results for the sticky-price model. The estimated policy rule performs well – inflation is held in check, and the decline in output is not greatly worse than that under other strategies. In contrast, the inertial Taylor (1999) rule performs very poorly, as the rule responds vigorously to the decline in output, which leads to a very large increase in inflation. Similarly, strict inflation targeting (17), which balances the level of inflation and output as in the inertial Taylor (1999) rule, performs poorly; this rule also includes a large response to output, and generates a very sizable acceleration in inflation. Given these dynamics, the poor average performance of these rules discussed in the previous section is not surprising.

Results for the sticky-information model, in Figure 10, are qualitatively similar: Inflation rises considerably (albeit less than under sticky prices) under the inertial Taylor (1999) rule or strict inflation targeting, but is well contained by the estimated policy rule.

Finally, the estimated rule, strict nominal-income targeting, and the nominal income targeting rules perform well in both models. These approaches also deliver relative price-level stability in these models (visible in the price response shown in the lower right corner). This is consistent

Figure 10: Adverse Supply Shock in Sticky-Price Model



Notes: Figures show response of the sticky-price model to an unanticipated wage markup shock, computed at the posterior mode of the parameters. Black -* line–Estimated rule; black solid line – Taylor (1999); blue -* – Strict inflation targeting; blue dashed (–) line – Strict nominal income targeting; blue solid line – Nominal income rule.

with the basic notion above that the approach including substantial interest rate persistence and a response to output growth embedded in the estimated rule has aspects of flexible price-level targeting (as previously emphaszied in Gorodnichenko and Shapiro (2007)).

5.4 Outcomes Under Alternative Strategies

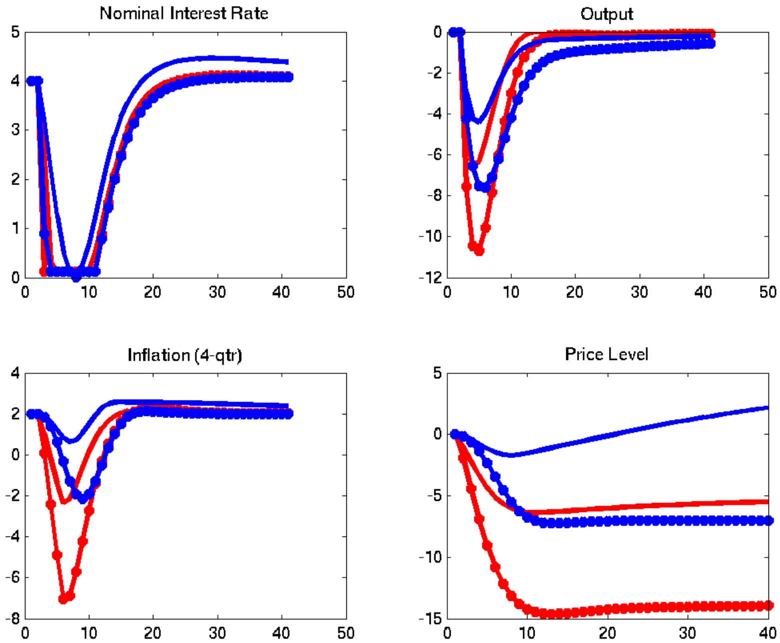
We compare performance under each strategy following the shock that precipitates the severe recession under the estimated rule.

5.4.1 Policy as usual vs. more aggressive response to the gap

It is instructive to first compare outcomes under policy as usual, as captured by the estimated policy rule, and a strategy that does not respond to the change in the output gap.. For this purpose, we present outcomes under the inertial rule 16 – as this approach implies a strong response to the output gap and ignores the change in the gap.

Figure 11 presents results for the estimated policy rule and the inertial rule 16. The red lines present the cases for the sticky-price model, and the blue lines present the cases for the sticky-

Figure 11: Outcomes Under Policy as Usual



Notes: Figures show response of the sticky-price (red) and sticky-information (blue) models to the Great Recession shock. -* – Estimated rule; Solid line – Inertial Taylor (1999) rule

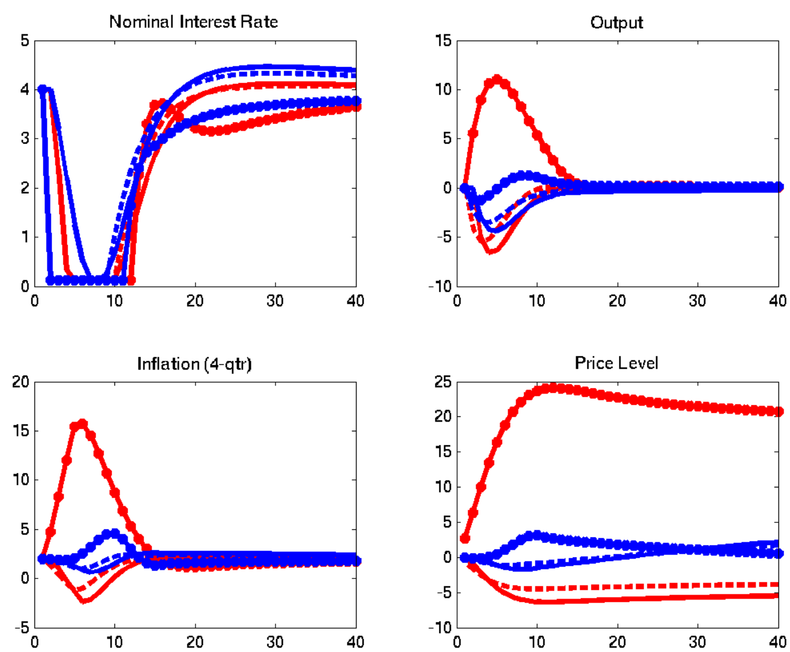
information model. it is immediately apparent: that, in both models, the estimated policy rule implies very poor performance relative to the alternative rule which ignores the change in the output gap. For example, output falls only 6 1/2 percent (at its trough) under the levels-only rule and sticky prices (in contrast to nearly 11 percent under the estimated rule) and only 4 1/2 percent under the levels-only rule in the sticky-information model (in contrast to 7 1/2 percent under the estimated rule). Inflation declines much less under the levels-only rule in both models, and deflation is avoided in the sticky-information model (with inflation falling to only 1 percent).

The results suggest that a strategy such as that embedded in the Taylor (1999) rule, with a modest degree of inertia, is much better than the estimated policy rule when zero-lower bound events transpire. One factor contributing to this finding is that strategies that commit to resisting declines in resource utilization vigorously perform better than strategies which do not. Indeed, the specific size of the response to output is not especially important (so long as the degree of inertia is held constant): For example, the outcomes from the rules with a response of unity (at an annual rate) to the output gap are similar to those under the Taylor (1993) rule, with a response of 0.5 (not shown). In addition, the estimated policy rule performs very poorly because of the strong response to output growth: This strong response implies policy tightens as soon as growth starts to pick up, despite a weak level of activity, which is very detrimental at the zero-lower bound (as emphasized before in, for example, Billi (2011)).

5.4.2 Lower-for-longer (Date-based)

We now consider date-based guidance. In particular, we assume that policymakers lower the policy interest rate to zero immediately and promise to keep the nominal interest rate at is lower bound 2 or 4 quarters later than they would have *if they were following the inertial Taylor (1999) rule and outcomes were as expected under that rule*. Moreover, we assume that this strategy is known to the public. After these intervals have passed (e.g., intervals of 8 and 10 quarters or 9 and 11 quarters, respectively, under sticky information and sticky prices), policy reverts to the inertial Taylor (1999) rule.

Figure 12: Outcomes Under Date-based Policy



Notes: Figures show response of the sticky-price (red) and sticky-information (blue) models to the Great Recession shock. Solid line – Inertial Taylor (1999) rule; dashed line–2 additional quarters of accommodation; -* – 4 additional quarters of accommodation.

Outcomes from these strategies, along with those from the inertial Taylor (1999) rule, are presented in figure 12. Clearly, a credible promise to remain highly accommodative can lead to substantial effects on real activity and inflation. Under sticky prices, these effects can be very large, again reflecting the type of backward-induction argument and wide swings in the price level associated with the forward-looking nature of that framework. Specifically, a promise of prolonged future accommodation raises future inflation, which leads to higher current inflation, which lowers real interest rates and raises output (which then raises inflation further). As a result, the promise of four quarters of extra accommodation leads to a sharp rise in the price level. These effects, while present, are much more muted under sticky information. As a result, date-based guidance does not lead to the explosive behavior–at least at these short horizons and under the assumption of reversion to the inertial Taylor (1999) rule–that characterizes sticky prices.

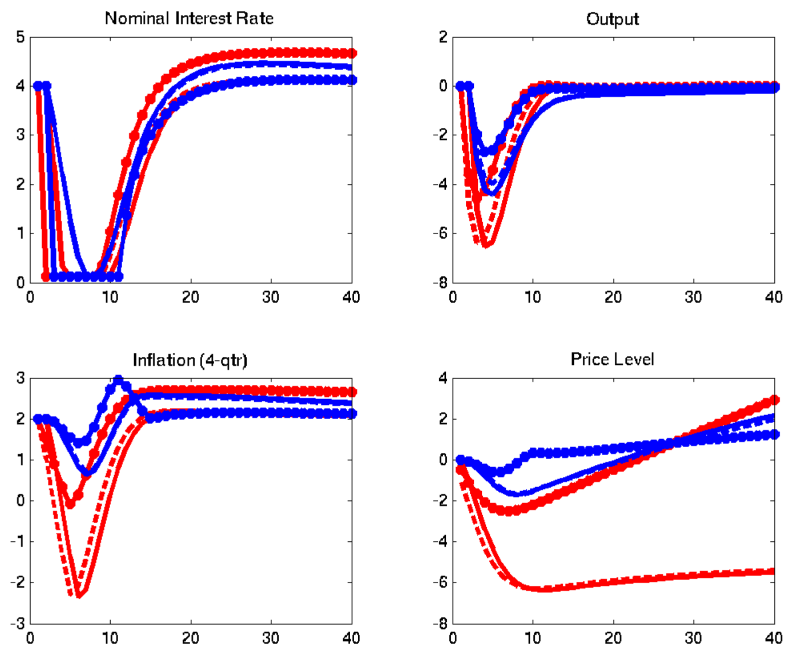
The effects of backward induction in the sticky-price model (through equation 3) explain why forward guidance is so very powerful in the sticky-price model, as reported in, for example, Levin et al. (2010), Laseen and Svensson (2011), Del Negro et al. (2012), Carlstrom et al. (2012), and Burgess et al. (2013). Kiley (2014) has previously shown that these effects can be much more muted under sticky information, with implications for a range of issues (including fiscal multipliers, and the paradoxes of thrift and volatility). Beyond these technical points, a variety of messages could be drawn from the simulation results. For example, it is clear that date-based guidance in the United States did not lead to a surge in inflation. This could be because such guidance was interpreted as only a forecast (e.g., Campbell et al. (2012)). It could also be because the more muted effects predicted by sticky information better characterize the data. Finally, it could be because the public understood that date-based guidance would not tolerate the kind of increase in inflation reported in the simulations, and that the underlying strategy was one that would resist such a large increase in inflation, as suggested by Kohn (2010). Indeed, the switch to thresholds by the FOMC included an explicit reference to an upper bound on inflation, and policymaker projections in the FOMC's Summary of Economic Projections, have not shown inflation rising above 2 percent under "appropriate policy".

5.4.3 Lower-for-longer (Thresholds)

We now pursue the idea that additional accommodation through thresholds for activity (or inflation) may improve performance. We consider thresholds similar to those announced by the FOMC in December 2012 – an output gap threshold of -2 percent (similar to an unemployment rate threshold of 6.5 percent) and a threshold for the inflation projection of 2.5 percent. We also consider whether an unemployment rate threshold closer to potential output (zero gap) or the natural rate of unemployment, as suggested in Kocherlakota (2013) and English et al. (2013), could prove beneficial. Before presenting simulations, it is instructive to recall what the optimal policy response is to the type of recession shock we have outlined. Specifically, the shock we have assumed generates the severe recession is a pure shock to the natural rate of interest: As such, the optimal policy (ignoring the zero-lower bound) is to perfectly offset the shock, implying no response of output, inflation, or any other variable. It is clear that the estimated rule or the inertial rule with a large response to the output gap fall short of this benchmark, and hence more accommodation – at least over the right horizon – would be welfare-improving. Indeed, this logic is the same as that suggesting lower thresholds may be appropriate in English et al. (2013) and Kocherlakota (2013).

Results for an output gap threshold of -2 percent suggest modest (or even essentially no) additional accommodation relative to the inertial rule 16 under sticky-prices, as shown in figure 13. This occurs because the thresholds, in this model, are very similar to conditions that generate

Figure 13: Outcomes Under Lower Unemployment Threshold



Notes: Figures show response of the sticky-price (red) and sticky-information (blue) models to the Great Recession shock. Solid line – Inertial Taylor (1999) rule; dashed line–Output gap threshold of -2 percent; -* – output gap threshold of 0 percent.

a departure from the ZLB under the levels-only rule 16. In contrast, this approach generates a modest, persistent degree of overshooting in inflation, to about 2 1/2 percent for much of the 10-year period following the shock, in the sticky-information model; as a result, output declines by a noticeably smaller amount.

The lower threshold for unemployment succeeds in stabilizing output to a significant degree in both the sticky-price and sticky-information models. In the sticky-information model, the greater stability in output is accompanied by more short-run overshooting of inflation than under the more conservative output gap threshold of -2 percent. In contrast, the aggressive thresholds lead to a very persistent overshooting of inflation under sticky prices – inflation is near 23/4 percent for much of the ten year period shown.

The possibility of prolonged overshooting of inflation may be desirable, depending on how policymakers weigh improved near-term performance relative to a persistent overshooting of inflation. Indeed, some degree of overshooting is the essence of the optimal strategy, as emphasized in Woodford (2010). In the case of threshold strategies, the overshooting can be quite persistent, reflecting the asymmetry inherent in the strategy in response to the shock. Specifically, policy is very accommodative while unemployment is above the natural rate, but tightens only in the "normal" and relatively-weak manner embedded in the inertial rule in subsequent years; these mechanisms will become more clear in the next section, in which another threshold-like approach is examined. Overall, these results suggest a set of thresholds may improve performance, but may also risk a deterioration in inflation performance, potentially leading to the concern about anchored inflation expectations reported in, for example, Kohn (2010).

5.4.4 Promising higher inflation: Nominal-income targeting

The simulations have identified several properties of responses under the various strategies examined so far. First, the responsiveness of inflation to monetary policy is very sensitive to the specification of the price-adjustment friction. Second, very accommodative strategies, such as a commitment to an output gap threshold near zero, can lead to persistent above-target inflation, even with a fairly low inflation trigger – an outcome which resonates with the fears of some policymakers, as noted above. Finally, responding to the change in the output gap, while effective in response to adverse supply shocks, can be problematic in response to large adverse demand shocks.

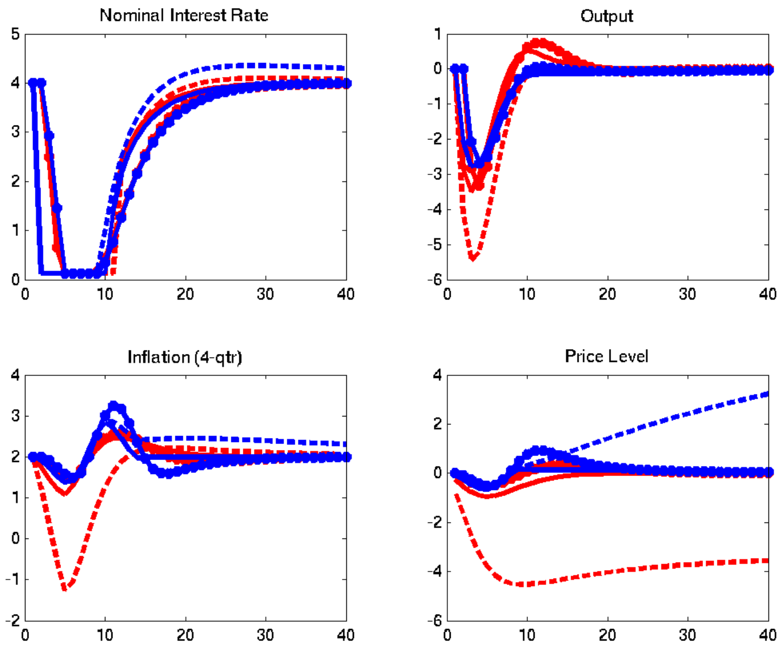
Given these issues, the policy options of date-based guidance or amplifying the focus on resource utilization through thresholds only indirectly address some important concerns for policymakers. In particular, these approaches are passive with respect to a key source of uncertainty – the dynamics of the price level over a prolonged period. A more direct response to such concerns would be a flexible price-level targeting approach – which actively seeks some stability in the price level path – such as nominal income targeting. Such an approach limits price level movements while having threshold like properties (in the sense that a certain level of nominal income must be reached before removing accommodation).

To illustrate this possibility, Figure 14 presents the results under the strict inflation targeting approach (17), the difference nominal income rule (19), and the strict nominal income targeting approach (18). As shown by the solid and starred lines, targeting nominal income delivers most of the output stabilization benefits of a zero output gap threshold, while also delivering good medium-term inflation performance and a stable long-run price level. This occurs despite the fact that policymakers do not begin to raise the federal funds rate under these strategies until the output gap is near zero, as in threshold approaches. It is also notable that strict-inflation targeting (the dashed lines) also performs better than something like the inertial Taylor (1999) rule, as it does include a commitment to have inflation above target if output is below target (so long as such a combination is possible given the zero-lower bound).

6 Lessons for policy and future research

Put most simply, we find that the dominance of the sticky-price paradigm in central bank models (reported in Table 1) is neither forced by fit to the usual set of macroeconomic data nor robust in its policy implications. These different policy implications arise because, in sticky-information economies, firms can specify plans for future prices and hence do not have an incentive to react

Figure 14: Outcomes Under Targeting Approaches



Notes: Figures show response of the sticky-price (red) and sticky-information (blue) models to the Great Recession shock. Dashed line – Strict inflation targeting; Solid line – Strict Nominal Income targeting; -* – Nominal income rule.

pre-emptively to anticipated demand conditions, as such. As a result, the price level tends to swing less sharply following shocks under typical policy strategies, particularly those in the Taylor (1993) form involving only levels of the output gap and inflation. Because the movements in the price level are less extreme in sticky-information models, a binding lower bound constraint yields considerably less amplification than under sticky prices. This result bears importantly on some other recent research: For example, some research has suggested a substantial missing disinflation under the sticky-price specification (e.g., King and Watson (2012), and Christiano et al. (2013)), and the sticky-information case suggests this may be less of a concern–a possibility for future research. Kiley (2014) suggests that the differences in amplification are also important for issues such as fiscal multipliers or the paradoxes of toil and volatility.

Second, the same mechanisms that reduce amplification in sticky-information models also reduce the power of date-based forward guidance. Such guidance has been shown to be very powerful in the sticky-price framework, reflecting the feedback from promises of higher future inflation to current inflation (and hence to real interest rates). These effects are attenuated under sticky-information, where the influence of expected future conditions on price decisions is indirect. [17]

[17] These differences across the two paradigms in responses to *anticipated* shocks may be important for the recent literature on "news" shocks, which has typically used the sticky-price framework. The sticky-information framework

That said, many aspects of good policy are common across sticky prices and sticky information. In particular, for policymakers focused on inflation and output stability, highly inertial policy strategies linked to nominal income or flexible price-level targeting rules behave well in response to supply and demand shocks, and strategies that respond to the level or change in the output gap perform poorly – in the former case, in response to supply shocks, and, in the latter case, once the zero-lower bound is considered.

Finally, we have focused exclusively on different models of price adjustment. Reis (2009) considered a broader deviation from Smets and Wouters (2007). Moreover, recent work has emphasized that other models of information imperfections may be more easy to rationalize as coherent microeconomic decision problems. While our interest, for the time being, has been in developing models to take to the data and that have potentially important differences for policy questions, our finding that information rigidities are as plausible an explanation for price dynamics as sticky prices simply reinforces the impetus to consider more fundamental variations in modeling approaches.

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could provide useful comparisons regarding the properties and importance of such shocks, while estimated models with news shocks may be able to better discriminate between the two classes of models.

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Online Appendix for *Effective Monetary Policy Strategies in New Keynesian Models: A Re-examination*

Hess Chung, Ed Herbst, and Michael T. Kiley

A Data for Estimation of Model.

The data covers 1966:Q1 to 2007:Q4. The construction follows that of Smets and Wouters (2007). Output data come from the NIPA; other sources are noted in the exposition.

1. **Per Capita Real Output Growth.** Take the level of real gross domestic product, (FRED mnemonic "GDPC1"), call it GDP_t. Take the quarterly average of the Civilian Non-institutional Population (FRED mnemonic "CNP16OV" / BLS series "LNS10000000"), normalized so that it's 1992Q3 value is one, call it POP_t. Then,

$$\text{Per Capita Real Output Growth} = 100\left[\log\left(\frac{GDP_t}{POP_t}\right) - \log\left(\frac{GDP_{t-1}}{POP_{t-1}}\right)\right].$$

2. **Per Capita Real Consumption Growth.** Take the level of personal consumption expenditures (FRED mnemonic "PCEC"), call it $CONS_t$. Take the level of the GDP price deflator (FRED mnemonic "GDPDEF"), call it $GDPP_t$. Then

$$\text{Per Capita Real Consumption Growth} = 100\left[\log\left(\frac{CONS_t}{GDPP_t POP_t}\right) - \log\left(\frac{CONS_{t-1}}{GDPP_{t-1} POP_{t-1}}\right)\right].$$

3. **Per Capita Real Investment Growth.** Take the level of fixed private investment (FRED mnemonic "FPI"), call it INV_t. Then,

$$\text{Per Capita Real Investment Growth} = 100\left[\log\left(\frac{INV_t}{GDPP_t POP_t}\right) - \log\left(\frac{INV_{t-1}}{GDPP_{t-1} POP_{t-1}}\right)\right].$$

4. **Per Capita Real Wage Growth.** Take the BLS measure of compensation per hour for the nonfarm business sector (FRED mnemonic "COMPNFB" / BLS series "PRS85006103"), call it W_t. Then

$$\text{Per Capita Real Wage Growth} = 100\left[\log\left(\frac{W_t}{GDPP_t}\right) - \log\left(\frac{W_{t-1}}{GDPP_{t-1}}\right)\right].$$

5. **Per Capita Hours Index.** Take the index of average weekly nonfarm business hours (FRED mnemonic / BLS series "PRS85006023"), call it $HOURS_t$. Take the number

of employed civilians (`FRED` mnemonic "CE16OV"), normalized so that its 1992Q3 value is 1, call it EMP_t. Then,

$$\text{Per Capita Hours} = 100 \log \left(\frac{HOURS_t EMP_t}{POP_t} \right).$$

The series is then demeaned.

6. **Inflation.** Take the GDP price deflator, then

$$\text{Inflation} = 100 \log \left(\frac{GDPP_t}{GDPP_{t-1}} \right).$$

7. **Federal Funds Rate.** Take the effective federal funds rate (`FRED` mnemonic "FED-FUNDS"), call it FFR_t. Then,

$$\text{Federal Funds Rate} = FFR_t/4.$$

8. **Inflation Expectations.** Take the SPF's measure of 10-year average inflation expectations, call it LRP_t. Since this is a CPI-based expectation, we subtract 0.5 percentage points from the annualized number to convert into a number comparable with the GDP deflator. Then,

$$\text{Inflation Expectations} = (LRP_t - 0.5)/4.$$

9. **Spread.** As a measure of financial spreads we use the difference between the S&P BBB rate (call it $RBBB_t$) and the 10-year Treasury rate, call it $RG10_t$. Then,

$$\text{Spread} = (RBBB_t - RG10_t)/4.$$

B Additional Tables

Table A-1: Prior Distribution for SW Model

Parameter	Type	Para (1)	Para (2)	Parameter	Type	Para (1)	Para (2)
$\bar{\beta}$	Gamma	0.25	0.10	ρ_a	Beta	0.50	0.20
$\bar{\pi}$	Gamma	0.62	0.10	ρ_b	Beta	0.50	0.20
$\bar{l}$	Normal	0.00	2.00	ρ_g	Beta	0.50	0.20
α	Normal	0.30	0.05	ρ_q	Beta	0.50	0.20
σ_c	Normal	1.50	0.38	ρ_m	Beta	0.50	0.20
Φ	Normal	1.25	0.12	ρ_p	Beta	0.50	0.20
φ	Normal	4.00	1.50	ρ_w	Beta	0.50	0.20
h	Beta	0.70	0.10	ρ_{π^*}	Beta	0.95	0.05
λ_w	Beta	0.50	0.10	g_y	Beta	0.50	0.20
σ_l	Normal	2.00	0.75	μ_p	Beta	0.50	0.20
λ_p	Beta	0.50	0.10	μ_w	Beta	0.50	0.20
ι_w	Beta	0.50	0.15	σ_a	Inv. Gamma	0.10	2.00
ι_p	Beta	0.50	0.15	σ_b	Inv. Gamma	0.10	2.00
ψ	Beta	0.50	0.15	σ_g	Inv. Gamma	0.10	2.00
r_π	Normal	1.50	0.25	σ_q	Inv. Gamma	0.10	2.00
ρ	Beta	0.75	0.10	σ_m	Inv. Gamma	0.10	2.00
r_y	Normal	0.12	0.05	σ_p	Inv. Gamma	0.10	2.00
$r_{\Delta y}$	Normal	0.12	0.05	σ_w	Inv. Gamma	0.10	2.00
ρ_a	Beta	0.50	0.20	σ_{π^*}	Inv. Gamma	0.10	2.00

Notes: Para (1) and Para (2) correspond to the mean and standard deviation of the Beta, Gamma, and Normal distributions and to the upper and lower bounds of the support for the Uniform distribution. For the Inv. Gamma distribution, Para (1) and Para (2) refer to s and ν, where $p(\sigma|\nu, s) \propto \sigma^{-\nu-1} e^{-\nu s^2/2\sigma^2}$.

Table A-2: Posterior For Sticky-Information and Sticky-Price Models

	Sticky Information		Sticky Price	
Parameter	Mean	[0.05, 0.95]	Mean	[0.05, 0.95]
$\bar{\beta}$	0.16	[0.08, 0.26]	0.18	[0.08, 0.29]
$\bar{\pi}$	0.69	[0.54, 0.88]	0.71	[0.55, 0.89]
$\bar{l}$	-1.40	[-4.00, 0.95]	-0.77	[-3.08, 1.35]
α	0.20	[0.16, 0.23]	0.20	[0.17, 0.24]
σ_c	1.13	[0.94, 1.34]	1.10	[0.89, 1.31]
Φ	1.48	[1.35, 1.61]	1.53	[1.39, 1.68]
φ	6.31	[4.47, 8.31]	5.97	[4.24, 8.08]
h	0.63	[0.52, 0.73]	0.60	[0.50, 0.72]
λ_w	0.41	[0.23, 0.56]	0.49	[0.38, 0.62]
σ_l	2.58	[1.63, 3.51]	2.00	[1.18, 2.89]
λ_p	0.26	[0.16, 0.35]	0.64	[0.55, 0.73]
ι_w	0.50	[0.27, 0.74]	0.48	[0.31, 0.64]
ι_p	0.49	[0.25, 0.74]	0.43	[0.30, 0.58]
ψ	0.74	[0.60, 0.86]	0.75	[0.62, 0.88]
r_π	2.13	[1.84, 2.43]	2.19	[1.92, 2.47]
ρ	0.88	[0.85, 0.92]	0.85	[0.81, 0.88]
r_y	0.01	[-0.03, 0.06]	-0.02	[-0.04, 0.01]
$r_{\Delta y}$	0.20	[0.16, 0.25]	0.17	[0.12, 0.22]
ρ_a	0.89	[0.85, 0.93]	0.91	[0.86, 0.95]
ρ_b	0.59	[0.25, 0.83]	0.62	[0.27, 0.80]
ρ_g	0.96	[0.94, 0.98]	0.96	[0.94, 0.98]
ρ_q	0.72	[0.60, 0.83]	0.69	[0.56, 0.81]
ρ_m	0.25	[0.12, 0.39]	0.35	[0.21, 0.50]
ρ_p	0.89	[0.82, 0.94]	0.92	[0.84, 0.98]
ρ_w	0.92	[0.81, 0.97]	0.97	[0.93, 0.99]
ρ_{π^*}	1.00	[0.99, 1.00]	1.00	[0.99, 1.00]
g_y	0.39	[0.22, 0.57]	0.40	[0.22, 0.58]
μ_p	0.50	[0.36, 0.61]	0.67	[0.48, 0.80]
μ_w	0.40	[0.20, 0.62]	0.66	[0.48, 0.83]
σ_a	0.37	[0.33, 0.42]	0.37	[0.33, 0.42]
σ_b	0.11	[0.07, 0.17]	0.11	[0.07, 0.17]
σ_g	0.39	[0.35, 0.45]	0.40	[0.35, 0.45]
σ_q	0.33	[0.26, 0.41]	0.33	[0.25, 0.41]
σ_m	0.13	[0.11, 0.15]	0.13	[0.11, 0.15]
σ_p	0.18	[0.16, 0.21]	0.10	[0.09, 0.12]
σ_w	1.37	[0.96, 1.92]	0.38	[0.30, 0.47]
σ_{π^*}	0.03	[0.03, 0.04]	0.03	[0.03, 0.04]