Effective Monetary Policy Strategies in New Keynesian Models: A Reconsideration*

Hess Chung† Edward Herbst‡ Michael T. Kiley§

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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. 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. By contrast, rules that respond to the level or change in the output gap can perform poorly under those conditions.

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†Board of Governors of the Federal Reserve System

‡Board of Governors of the Federal Reserve System

§Board of Governors of the Federal Reserve System

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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. Economists at central banks and researchers have explored the nature of the recession and appropriate policy strategies. While the number of models considered in such exercises is broad, 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 in assessing how robustly 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 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. In our analysis we highlight several issues.

First, the dominance of the sticky-price paradigm within central bank and academic research on monetary policy is not supported by the data. Our sticky-information and sticky-price models have quite similar fit to standard macroeconomic time series, yet 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 the zero-lower bound are 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 tradeoff 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 a 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]

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 – a tendency that is again most apparent under sticky-prices, albeit clearly present under the sticky-information approach as well.

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 ad-

[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.

justment 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 (2013b))). 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

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 (2013a)
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)

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 (2013a), 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).

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 counter-factual 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 parame-

ter 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 moves 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 at steady state 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.

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

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

1. Assumes that the natural rate of interest equals $\underline{rr^n} < 0$ in periods t through T and zero (baseline) in all other periods.

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 0, 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 inter-

est rate responds to expected (one-period ahead) inflation contributes to the anchored long-run price level under sticky-infromation). 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 $\hat{\pi}_t$,

[2] Kiley (2013b) 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.

the intertemporal consumption decision 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

[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.

process: $\varepsilon_t^i = \rho_i \varepsilon_{t-1}^i + \eta_t^i$. 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:

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

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:

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

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 ($\hat{mc}_t = \alpha r_t^k + (1-alpha)w_t - \varepsilon_t^a$). 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 current 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

$$\begin{aligned}\hat{w}_t = &\frac{\beta\gamma^{(1-\sigma_c)}}{1+\beta\gamma^{(1-\sigma_c)}}(E_t\hat{w}_{t+1}+E_t\hat{\pi}_{t+1})+\frac{1}{1+\beta\gamma^{(1-\sigma_c)}}(\hat{w}_{t-1}-\iota_w\hat{\pi}_{t-1}) \\ &-\frac{1+\beta\gamma^{(1-\sigma_c)}\iota_w}{1+\beta\gamma^{(1-\sigma_c)}}\hat{\pi}_t+\frac{(1-\beta\gamma^{(1-\sigma_c)}\lambda_w)(1-\lambda_w)}{(1+\beta\gamma^{(1-\sigma_c)})(1+(\Phi_w-1)\epsilon_w)\lambda_w}\hat{\mu}_t^w+\varepsilon_t^w. \end{aligned} \tag{10}$$

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

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,

$$\begin{aligned}\frac{\hat{w}_t}{1-\lambda_w}-\hat{w}_{t-1} = &\frac{\lambda_w}{(1-\lambda_w)(1+(\Phi_w-1)\epsilon_w)}\hat{\mu}_t^w \\ &+\lambda_w\sum_{j=0}^{\infty}(1-\lambda_w)^jE_{t-j-1}\left[\frac{\Delta_t\hat{\mu}_t^w}{(1+(\Phi_w-1)\epsilon_w)}+\hat{\pi}_t\right]+\varepsilon_t^w.\end{aligned} \tag{12}$$

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,

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

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:

$$\begin{aligned}\hat{r}_t = \rho\hat{r}_{t-1} + (1-\rho)(r_\pi(\hat{\pi}_t - \hat{\pi}_t^*) + r_y(\hat{y}_t - \hat{y}_t^*)) \\ + r_{\Delta y}((\hat{y}_t - \hat{y}_t^*) - (\hat{y}_{t-1} - \hat{y}_{t-1}^*)) + \varepsilon_t^r.\end{aligned} \tag{14}$$

The starred variables refer to the counterfactual 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, $\hat{\pi}_t^* = \rho\hat{\pi}_{t-1}^* + \eta_t^{\pi^*}$. The monetary policy shock ε_t^r also follows an AR(1) process, $\varepsilon_t^r = \rho_r\varepsilon_{t-1}^r + \eta_t^r$.

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 so as 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 has the form of an MA(∞),

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

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. A key to the Meyer-Gohde (2010) algorithm is that for sufficiently large j, Θ_j follows a recursive law of motion. Given this, it is easy to compute the autocovariance function for y_t. Together with the normality assumption on η, construction of the likelihood function is straightforward.

To estimate the parameter vector θ for both models, 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 $\mathcal{Y}^o$, to obtain, via Bayes rule, the posterior:

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

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 10. 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.

Since the posterior is analytically intractable, we resort to Markov-chain Monte Carlo simulation techniques to generate draws from the posterior. In particular, we use the random walk Metropolis-Hastings following 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 11) and concentrate here on the parameters which exhibit meaningful differences. Table 3 displays the posterior estimates for the parameters associated

Table 3: Posterior Moments of Key Parameters

	Sticky Information		Sticky Prices	
Parameter	Mean	[0.05, 0.95]	Mean	[0.05, 0.95]
λ_p	0.33	[0.28, 0.37]	0.64	[0.57, 0.70]
ι_p	NA		0.41	[0.29, 0.54]
ρ_p	0.90	[0.86, 0.94]	0.93	[0.89, 0.97]
μ_p	0.48	[0.39, 0.57]	0.70	[0.57, 0.81]
σ_p	0.18	[0.16, 0.20]	0.10	[0.09, 0.11]
λ_w	0.43	[0.29, 0.56]	0.47	[0.35, 0.57]
ι_w	NA		0.51	[0.36, 0.65]
ρ_w	0.93	[0.90, 0.96]	0.98	[0.96, 0.99]
μ_w	0.45	[0.22, 0.67]	0.64	[0.44, 0.80]
σ_w	1.42	[1.07, 1.79]	0.39	[0.32, 0.46]

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 in information adjustment. The posterior mean of $\lambda_p = 0.33$, indicates that only 33 percent of firms adjust behavior in response to current shocks, while wages are only marginally more responsive ($\lambda_w = 0.42$). Compared to the sticky-price estimates, the proportion of firms/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 Calvo parameter being slightly higher at 0.64.

The sticky-price model features substantial price/wage inertia in the form of indexation ($\iota_p \approx 0.41, \iota_w \approx 0.50$), 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 MA parameter associated with the wage markup is about two-thirds the magnitude in the sticky-information model ($\mu_w = 0.45$) than in the sticky-price model ($\mu_w = 0.64$). 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. Intuition for subsequent results is aided through familiarity with the different responses of the models to surprises in monetary policy. Figure 1 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, and subsequently endogenously falling 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

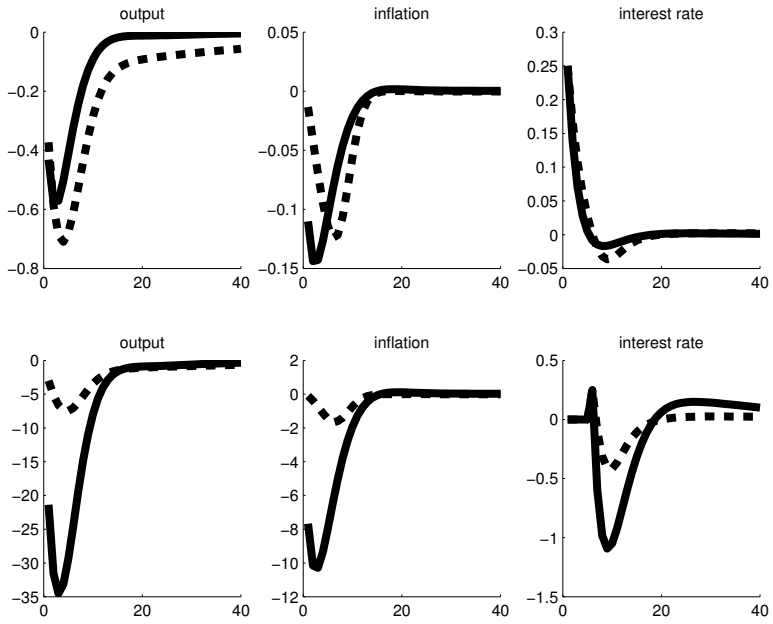
fall for inflation shares similar features, with a drop in inflation about 10% in the sticky-price model. Note also that these falls come to a large extent in the initial period of the impulse response in the sticky price model. The reason for the differences across models is the pricing mechanisms. 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. [4] 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. Finally, it is also important to note that neither model incorporates so-called "news" or anticipated monetary policy as a feature of the *estimated* model. It is left to future work to examine model fit in sticky-price and sticky-information settings with news.

We next consider the different model responses to two other (unanticipated) shocks, namely the neutral technology and wage markup shock. Figure 2 shows the response of output, inflation, and interest rates to one standard deviation shocks. As with the unanticipated monetary policy shock, 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 authority, as output falls and inflation rises in response to this shock.

Another way to compare the sticky-price and sticky-information models is by examining the relative importance each model assigns to shocks at various frequencies. Figure 3 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 im-

[4] 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 1: Responses to Monetary Policy Shocks

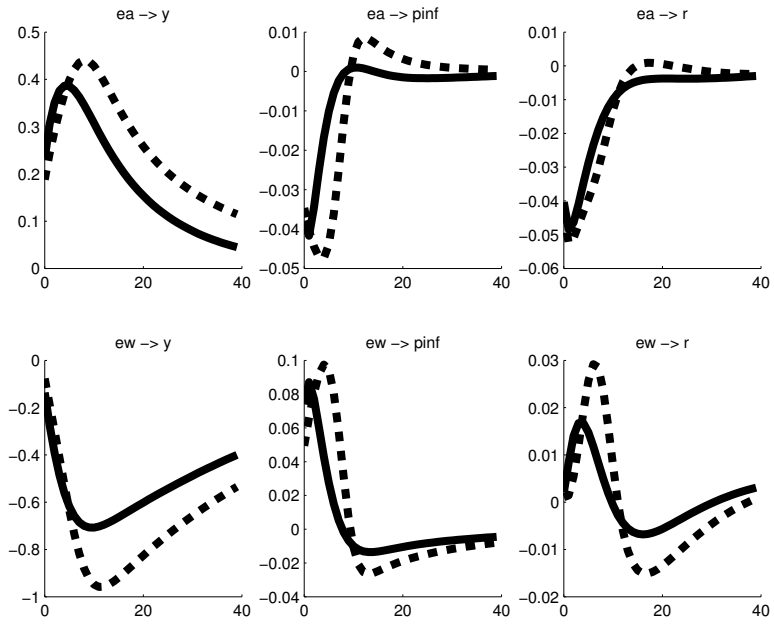


Notes: Figures show response of the sticky-price (solid line) and sticky-information (dashed line) models to an unanticipated (top row) and 6-quarter ahead anticipated (bottom show) monetary policy shock, computed at the respective posterior modes.

portance 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) correlations 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, risk and demand shocks is 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 inflation target and price and wage markup shocks. In particular, the price markup only has a correlation of 0.84 between

Figure 2: Responses to Technology and Wage Markup Shocks



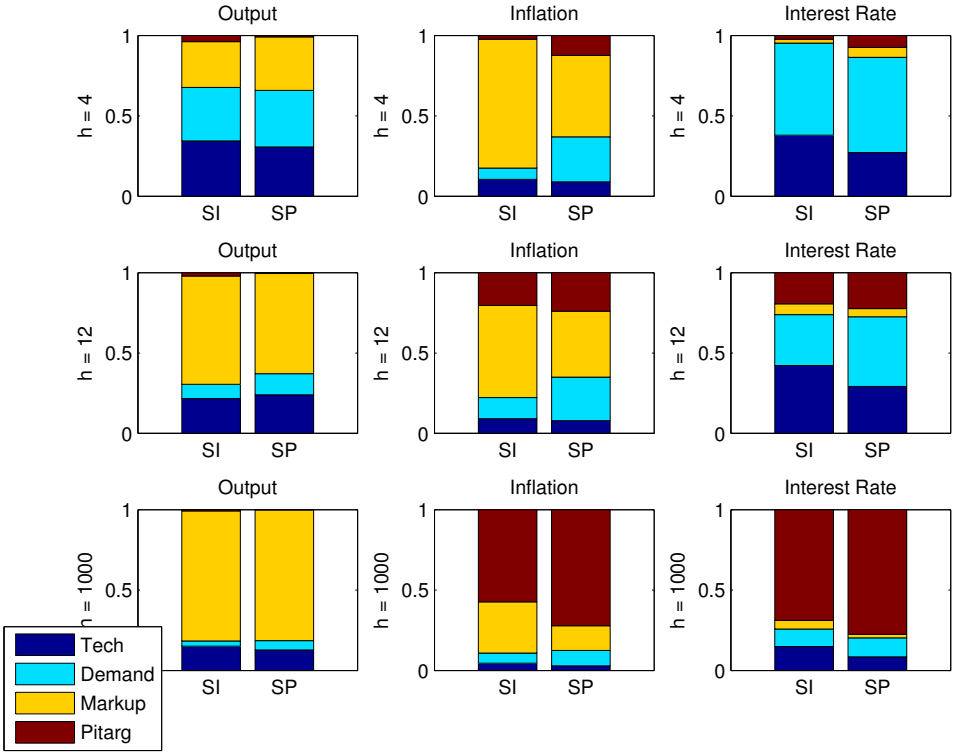
Notes: Figures show response of the sticky-price (solid line) and sticky-information (dashed line) models to an unanticipated technology shock (top row) and an unanticipated wage markup shock (bottom row), computed at the respective posterior modes.

the two models, which though small, represents a substantive difference between the two models, touched on above.

Model Fit. In the Bayesian paradigm, a summary of in sample model fit is reflected in the so called "marginal data density" (MDD), $p(\mathcal{Y}^o) = \int p(\mathcal{Y}^o|\theta)p(\theta)d\theta$. Table 5 reports the difference in log marginal data densities. The sticky-information model has a log marginal data density of -258.81, almost one half point lower than the sticky-price model, indicating that it does indeed fit modestly worse, consistent with earlier studies.[5] In fact, a strict Bayesian decision-maker who had placed equal prior probability on the two models would place a posterior probability of about 37% on the sticky-information model. However, posterior odds in the estimation of DSGE models are often implausible. Indeed, as we show in the robustness section, these posterior odds can be easily flipped in favor of the sticky information model by, for example, eliminating the MA coefficients on exogenous markup shocks. Therefore, we think that this in itself shouldn't be taken as

[5] 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.

Figure 3: 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.

strong evidence in favor of the sticky price model.

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 4: Correlations of Smoothed Structural Shocks

Shock	Correlation
Neutral Technology	0.999
Risk Shock	0.993
Demand Shock	0.999
Price Markup Shock	0.841
Wage Markup Shock	0.933
Monetary Policy Shock	0.986
Investment-specific Technology Shock	0.990
Inflation Target Shock	0.952

Table 5: Log MDD Estimates

Model	Log MDD Estimate
Sticky-information	-258.81
Sticky-price	-258.26

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. Still, it is clear that the SI model delivers slightly more volatility in real quantities, which is at odds with the data, possibly due to higher variances detailed previously. However, when one makes small changes to auxiliary assumptions, the sticky-information model dominates the sticky-price model, suggesting that this is not a robust result.

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, but that the sticky-price model fits the data (slightly) better in a statistical sense. In fact, a strictly Bayesian decision-maker with only the two above models at her disposal would place most of the weight on the sticky-price price, based on the marginal data densities in Table 5. We show that this is highly sensitive to the particular data and auxiliary assumptions used in our model, and that it is easy to reverse model ranking. Thus, it's difficult to claim that one model outperforms the other.

With a view towards examining the robustness of the results, we estimate variants of

Table 6: Predictive Checks: Standard Deviations and Autocorrelations

	YGR	CGR	IGR	WGR	H	PI	R	PIEXP
				Standard Deviations				
Data	0.54	0.50	1.48	0.72	1.99	0.23	0.59	0.30
SI	0.86 [0.73, 1.05]	0.74 [0.60, 0.89]	1.95 [1.52, 2.36]	0.75 [0.63, 0.90]	3.80 [1.97, 7.33]	0.51 [0.33, 0.67]	0.36 [0.26, 0.49]	0.16 [0.10, 0.28]
SP	0.75 [0.63, 0.87]	0.65 [0.55, 0.76]	1.71 [1.41, 2.06]	0.79 [0.66, 0.95]	2.19 [1.36, 3.35]	0.43 [0.32, 0.55]	0.35 [0.24, 0.49]	0.15 [0.08, 0.27]
				Autocorrelations				
Data	0.18	0.10	0.50	0.13	0.95	0.60	0.96	NaN
SI	0.49 [0.31, 0.65]	0.57 [0.39, 0.72]	0.65 [0.52, 0.76]	0.08 [-0.13, 0.30]	0.96 [0.91, 0.98]	0.88 [0.80, 0.94]	0.91 [0.85, 0.95]	0.93 [0.87, 0.97]
SP	0.37 [0.20, 0.52]	0.47 [0.32, 0.59]	0.59 [0.43, 0.73]	0.26 [0.05, 0.51]	0.94 [0.89, 0.97]	0.81 [0.68, 0.89]	0.90 [0.84, 0.95]	0.92 [0.81, 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.

the sticky-price and sticky-information models:

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:

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

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.[6]

We estimate the models on the relevant datasets using samples from 1966-2007 and 1984-2007. As above, we compute marginal data densities using the harmonic mean estimator. The results are displayed in Table 7. A few clear points emerge. For one, 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.

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.

4 Effective Monetary Policies

4.1 Setting the Stage

The literature on effective monetary policy strategies is broad: Taylor and Williams (2010) discuss some of the central issues and findings related to the use of simple rules; Wood-

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

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	-258.26	-258.81	(0.37)
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 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.

ford (2010) exposits the nature of optimal policy in the basic New-Keynesian model, including policy at the ZLB; and Svensson (2011) tries to draw on these literatures in case studies of U.S. and Swedish monetary policy following the financial crisis of 2008, with a particular focus on forecast-targeting approaches.

Previous research has suggested that monetary policy should not respond too aggressively to output in the sticky-price New-Keynesian model. In some cases, this is importantly driven by the effects of price rigidity on price dispersion and hence welfare in this model– links which imply that a strong focus on inflation (or wage-inflation) stabilization is (nearly) optimal (e.g., Levin et al. (2006) and Schmitt-Grohé and Uribe (2006)). We will not focus on the representative households' utility and instead focus on stability in inflation and activity. Even in such a case, previous work has suggested that it is not generally optimal to respond too aggressively to output, as this can exacerbate inflation volatility significantly; a strong response to output growth (as is featured in many estimated rules, including in our models) better stabilizes inflation and output (Taylor and

Wieland (2012))).

However, previous work has suggested these results change at the zero lower bound: In this case, an aggressive response to output has been deemed important (e.g., Reifschneider and Williams (2000)). Some policymakers and central bank staff have adopted this suggestion, at least to some extent, in suggesting that a policy rule with a large output coefficient or maintaining accommodation until unemployment falls below its natural rate is appropriate in such situations (e.g., Yellen (2012), Kocherlakota (2013), English et al. (2013)). Moreover, research has suggested that responding to output growth leads to poor performance at the ZLB: In particular, raising the policy interest rate in response to a return to strong growth, when policy has been unable to completely react to the shortfall in growth because of the ZLB and the *level* of activity remains depressed, can short-circuit the economic recovery (e.g., Billi (2011)).

Some policymakers and researchers have expressed concern that the type of aggressive policy strategies noted above in response to a ZLB event or the suggestion in research to actively seek higher inflation in an effort to lower real interest rates and spur activity, as in Krugman (1998), Eggertsson and Woodford (2003), or Woodford (2010), may risk of inflation getting out of control. This concern is highlighted in the following excerpt from remarks by Donald Kohn (Kohn (2010)) during his tenure as Vice Chairman of the Federal Reserve Board:

> "We have not followed the theoretical prescription of promising to keep rates low enough for long enough to create a period of above-normal inflation... a policy of achieving temporarily higher inflation over the medium term would run the risk of altering inflation expectations beyond the horizon that is desirable. Were that to happen, the costs of bringing expectations back to their current anchored state might be quite high."

In these remarks, Kohn was particularly concerned about the possibility of a persistent run of inflation above the central bank's target. We will explicitly consider whether the strategies we consider entail such a risk. Indeed, the realization of such a risk in the models we have presented – in which expectations are rational and the commitment of policymakers to their long-run objectives is unquestioned – may be surprising. Our analysis will suggest a very aggressive threshold strategy poses such a risk.

Finally, as mentioned above, estimates from both sticky-price and sticky-information models favor volatile and persistent wage and mark-up shocks. These high variances drive large differences in average performance across simple rules, as documented below.

It is accordingly worthwhile to discuss in some detail how this dispersion of outcomes comes about, as we do in section 4.3.

4.2 Differences in the Monetary Policy Environment Between Sticky-Price and Sticky-Information Equilibria

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 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.

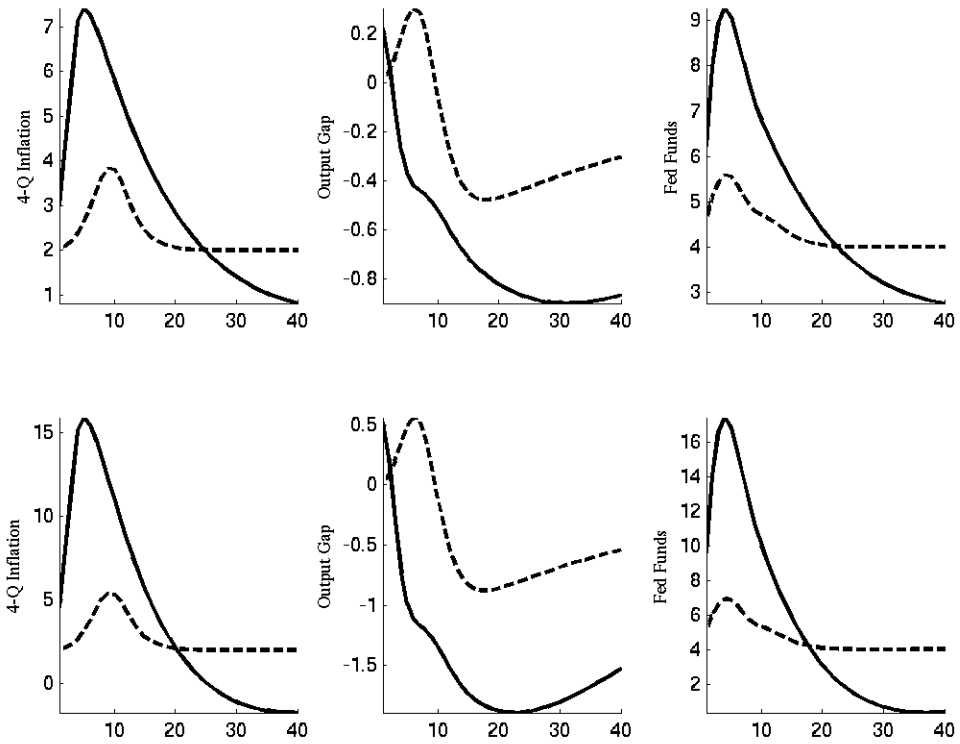
Figure 4 illustrates some of these differences by considering the optimal response, under commitment, to a unit wage markup shock, where the solid line displays outcomes for the sticky-price equilibrium and the dashed line shows outcomes for the sticky-information economy. [7] Under sticky prices, in 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.

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

[7] 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.

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



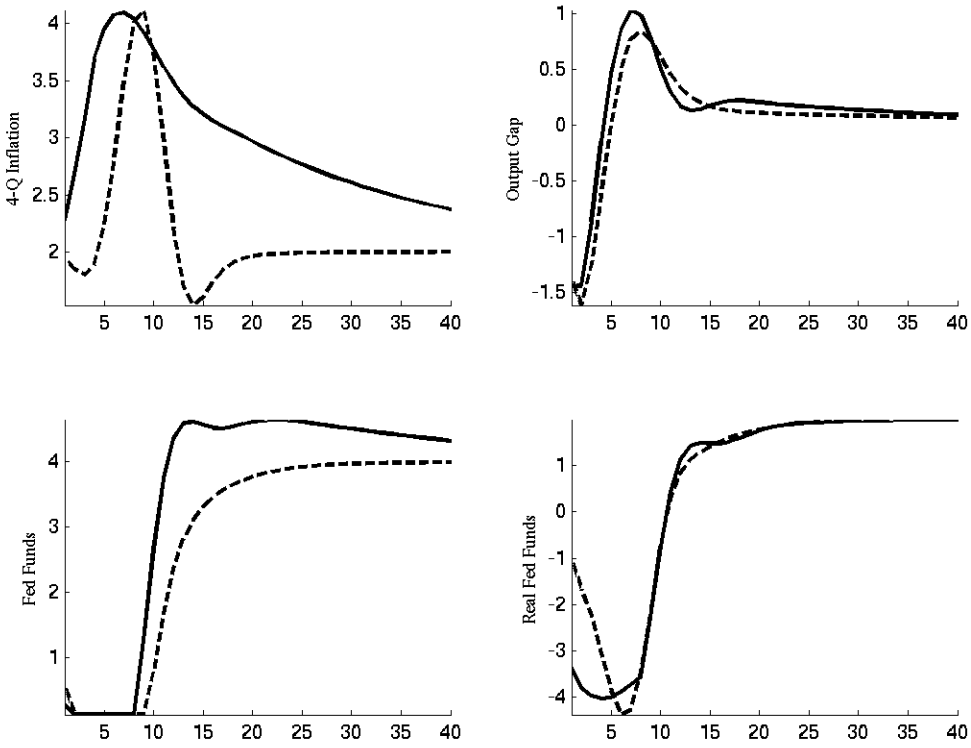
Notes: Figure shows the response of the 4-quarter change in inflation and the output gap to a wage mark-up shock under optimal policy. Top panel: Estimated persistence. Lower panel: 0.95 serial correlation. Black solid line: sticky-prices. Black dashed line: sticky-information.

These environmental features continue to shape the optimal response to shocks once the policy rate hits its lower bound. In particular, as shown in Figure 5, 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. [8] Under sticky in-

[8]The shock in this scenario is a large increase in the risk premium. Absent the zero lower bound, the

formation, optimal policy delivers a very similar real interest rate path and thus achieves very similar real outcomes. However, the sepability 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 5: 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.

optimal policy would exactly offset this shock. We describe this shock in more detail below.

4.3 Strategies we analyze

Of course, our set of policy strategies contains 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.

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[9]

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

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

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

commitment to hold the federal funds rate at 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 such forward guidance can have very large effects in the sticky-price framework, whereas Kiley (2013b) 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 of 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, since that time.

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. 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.

In our review of the recent policy literature, we noted that there is one class of strategies closely related to suggestions for an unemployment threshold near the natural rate of unemployment. In particular, **Super-inertial rules**–that is, rules which relate the change in the nominal interest rate to inflation, the output gap, or other factors–have threshold-like properties. In particular, such a specification captures the simple intuition of efficient policy from Kocherlakota (2013) – during a recession, policy is not tightened until a weighted average of inflation and resource utilization is positive; moreover, this weighted-average acts like a threshold at the zero-lower bound, as policy is not tightened until the weighted average moves above zero. For example, if inflation is near target, the threshold is not breached until the output moves above potential. For these reasons, we consider versions of the rule depending on inflation and either the level or the change of the output gap. 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.

$$R_t - R_{t-1} = 0.5((P_t - P_{t-4} - 2) + y_t - y_t^f). \tag{17}$$

$$R_t - R_{t-1} = 0.5((P_t - P_{t-4} - 2) + y_t - y_t^f - (y_{t-1} - y_{t-1}^f)). \tag{18}$$

Note that an approach like 18 bears similarities to the estimated rule. A rule such as 17 has a long history – both as a positive description of the FOMC's decisions and in normative analysis. With regard to positive analysis, Fuhrer and Moore (1995) and Kiley (2012) suggest such a rule fits FOMC behavior well over the post-1960 time period.[10] Fuhrer and Moore (1995) discuss normative properties–namely, that such rules perform well in models in which financial conditions, spending, and/or prices and wages have important forward-looking elements.

Finally, these strategies –in the absence of the zero-lower bound – embed a concern for price-level stabilization (as emphasized in Woodford (2010) and can be seen by integrating 17, for example) and therefore have some of the properties of efficient policy. Rules akin to 18 have been shown to be nearly optimal excluding the zero-lower bound (e.g., Blake (2012)).

Promising higher inflation: 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.

[10] Our empirical analysis ruled out such behavior, following Smets and Wouters (2007), through a prior that placed no weight on this possibility.

In policy circles (e.g., Romer (forthcoming)), the most prominent strategy discussed embodying this principle is the possibility of "nominal income targeting", (taken in a broad sense to include a differential response to current economic activity and the price level). We operationalize this approach through the following rule (which embeds inertia as above):

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

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.

4.4 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.

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

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)	$R_t = 0.001p_t + 0.000(y_t - y_t^f) + 1.056R_{t-1} + 0.010(y_{t-1} - y_{t-1}^f)$

Table 8: Optimal Simple Rules. $\bar{\pi}_t$ is the 4-quarter change in the price level.

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) and (17), 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.

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.

	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
Change rule (output gap) (eq. 17)	4.09	4.01	0.48	6.25	6.24	0.51
Change rule (output growth) (eq. 18)	0.61	4.57	0.25	0.84	8.04	0.28
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

Table 9: Standard deviations of selected variables, under sticky prices and sticky information. $\bar{\pi}$ = 4-quarter change in prices (annual rate). Gap = output gap to flex price equilibrium. R = federal funds rate (annual rate).

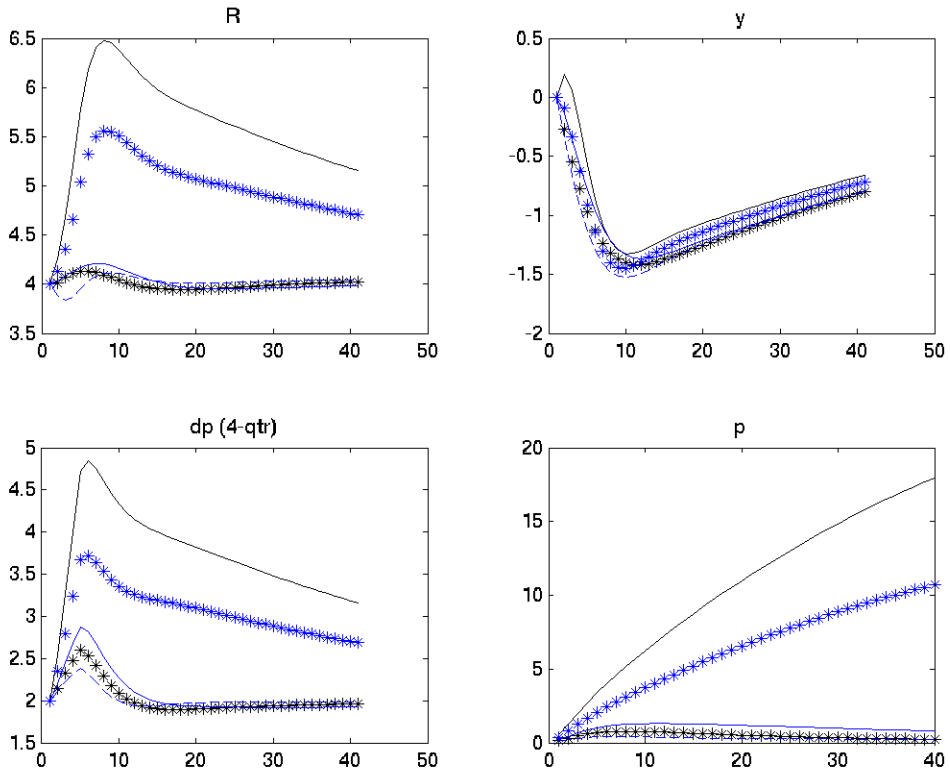
4.5 Adverse Supply Shocks

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

Figure 6 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, the rule in which the change in the nominal interest rate responds to the level of the output gap also performs poorly; this rule also includes a large response to output, and generates a very sizable acceleration in inflation. Given these dynamics, the

Figure 6: Adverse Supply Shock in Sticky-Price Model



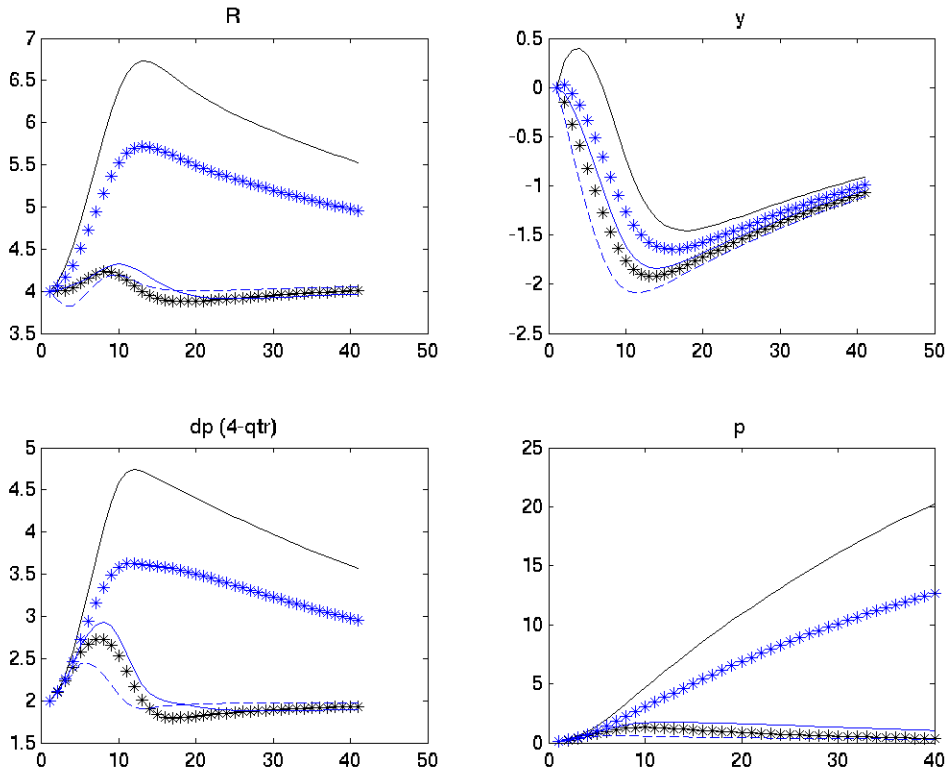
Notes:
Figures show response of the sticky-price model to an unanticipated wage markup shock, computed at the posterior mode of the parameters. Black * line–Estimated rule; black solid line – Taylor (1999); blue * – Change rule (output gap); blue dashed line – Change rule (output growth); blue solid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

poor average performance of these rules shown in the previous section is not surprising.

Results for the sticky-information model, in Figure 7, are qualitatively similar: Inflation rises considerably (albeit less than under sticky prices) under the inertial Taylor (1999) rule or the rule in which the change in the interest rate responds to the level of the output gap, but is well contained by the estimated policy rule.

Finally, the estimated rule, the rule in which the change in the nominal interest rate responds to the change in the output gap, 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 with the basic notion above that such approaches have aspects of flexible price-level targeting.

Figure 7: Adverse Supply Shock in Sticky-Price Model



Notes:
Figures show response of the sticky-information 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 * – Change rule (output gap); blue dashed line – Change rule (output growth); blue solid line – Nominal income rule)

4.6 A Great Recession

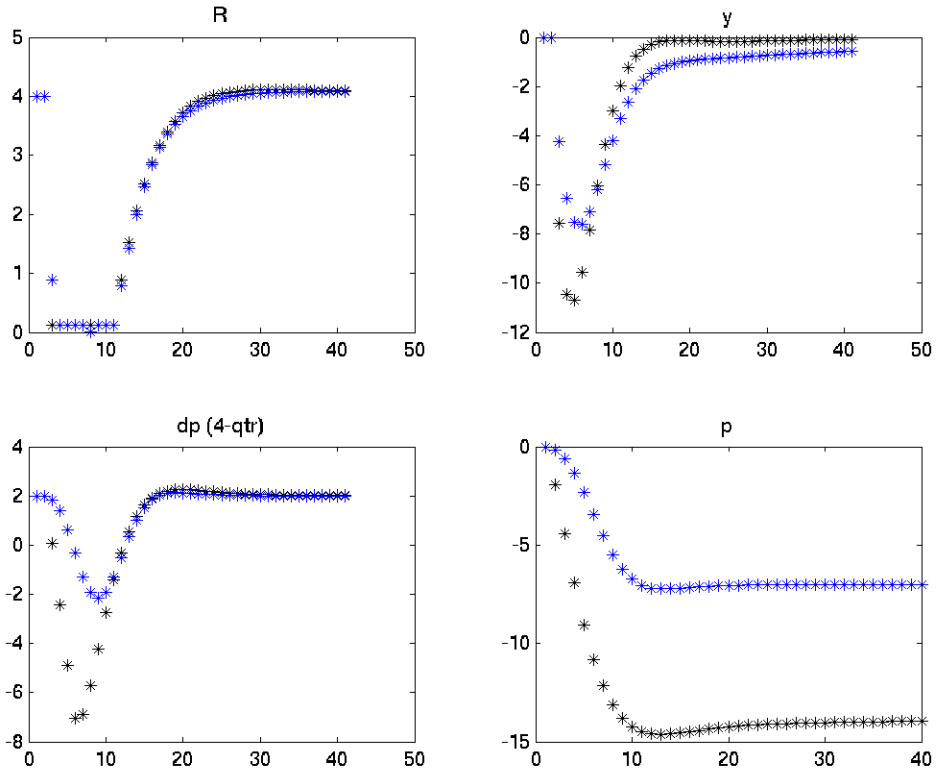
In order to illustrate some of the principles of efficient policy strategies in a manner that highlights the implications of both the sticky-price and sticky-information frameworks for effective responses to *adverse demand shocks*, we now present a simulation of the baseline version of each model that 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 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.[11] 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 8: A Recessionary Shock (under estimated policy rule)



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

The scenarios are presented in figure 8.[12] Regardless of the model of price/wage dy-

[11]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).

[12]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. We also examined all possible configurations between 1 and 15 quarters in the future. Where indeterminacy arises, we have chosen to focus on the equilibrium with the least volatile outcomes.

namics, 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 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)),[13]

4.7 Price Level Movements and Amplification

As we emphasized earlier, the non-linearity/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 drive this difference across models home more clearly, figure 9 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 resulting dynamics are clearly important for understanding the fluctuations within the different frameworks, and will have implications for policy as well.[14]

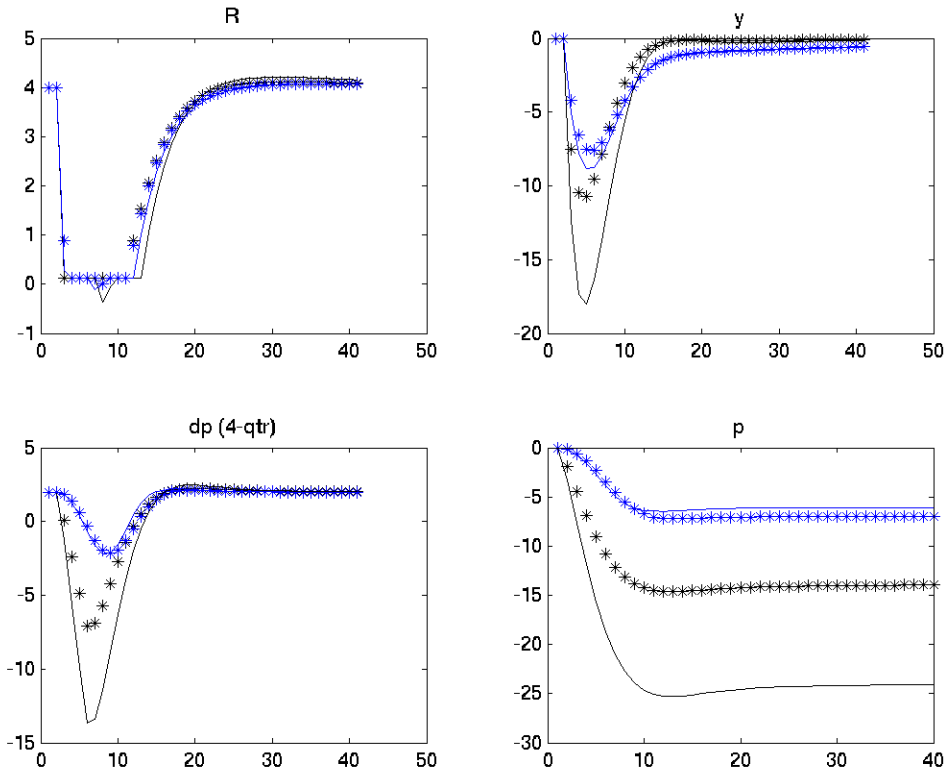
4.8 Outcomes Under Alternative Strategies

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

[13]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.

[14]Appendix C illustrates this amplification issue further.

Figure 9: Amplification of Recessionary Shock at the ZLB)



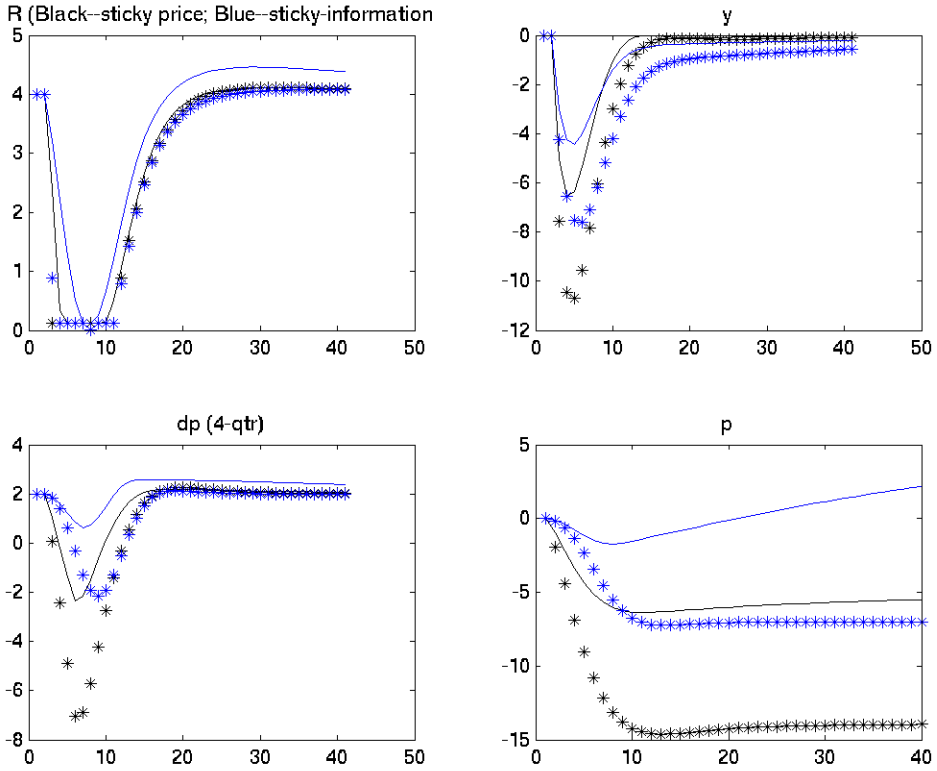
Notes:
Figures show response of the sticky-price (black) and sticky-information (blue) models to alternative Great Recession shocks, with a 200bp (*) or 250bp (solid line) increase in the 10-yr risk spread

4.8.1 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 10 presents results for the estimated policy rule and the inertial rule 16. The black lines present the cases for the sticky-price model, and the blue lines present the cases for the sticky-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

Figure 10: Outcomes Under Policy as Usual



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

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).

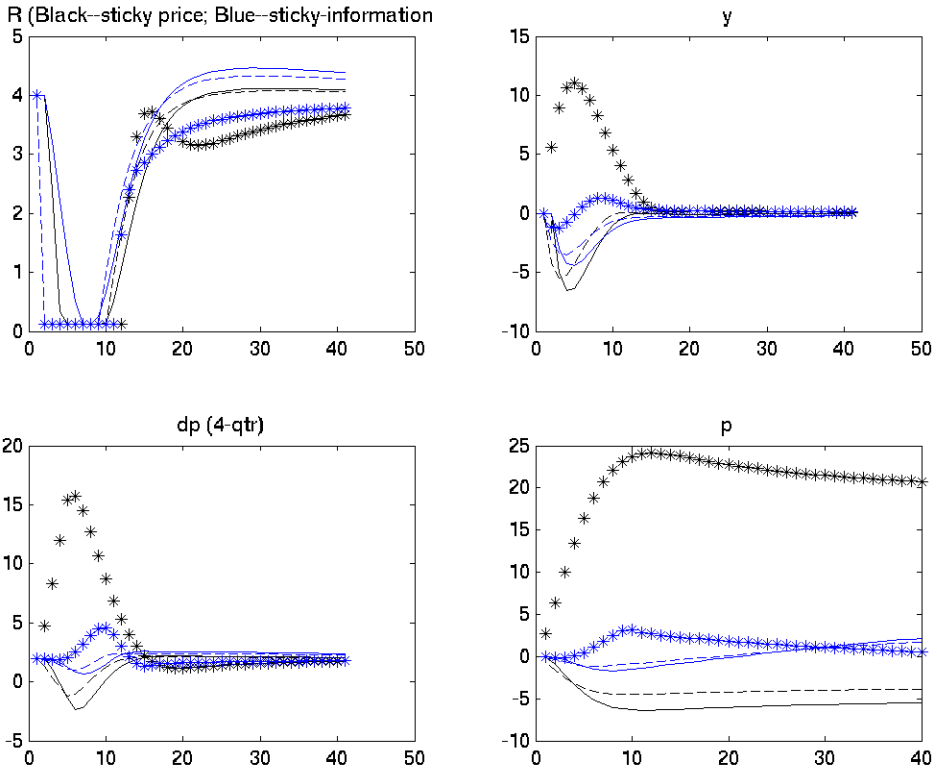
The results suggest that a strategy such as that embedded in the Taylor (1999) rule, with a modest degree of inertia, is much better than the estimated policy rule when zero-lower bound events transpire. One factor contributing to this finding is that strategies that commit to resisting declines in resource 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)).

4.8.2 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 11: Outcomes Under Date-based Policy



Notes:
Figures show response of the sticky-price (black) 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 11. 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.

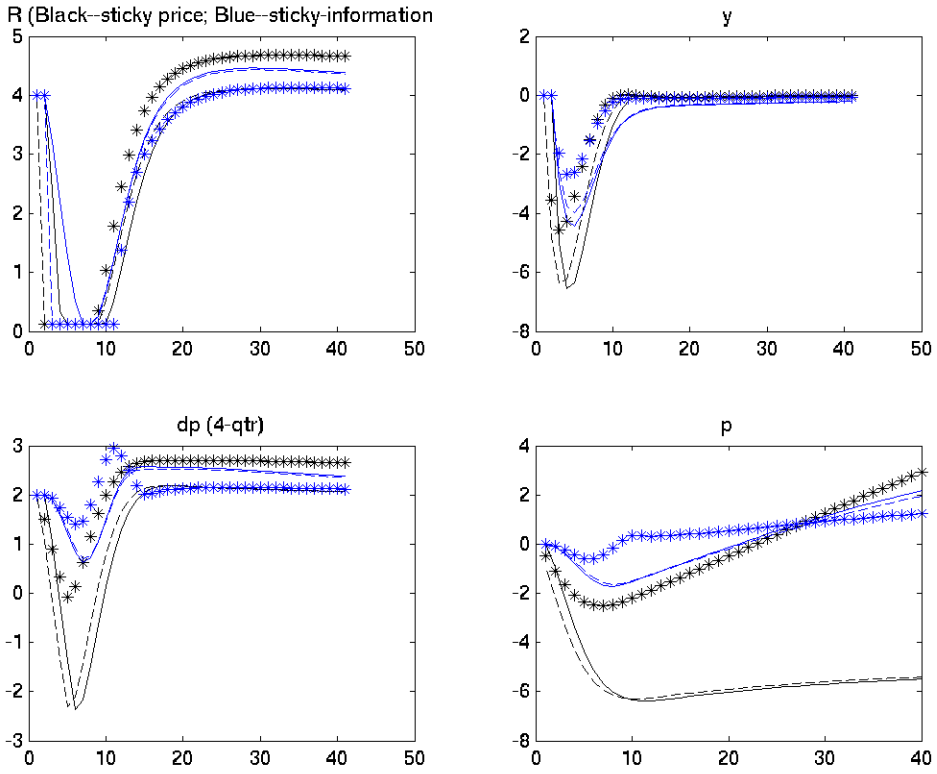
The effects of backward induction in the sticky-price model (through equation 3) explain why forward guidance is so very powerful in the sticky-price model, as reported in, for example, Levin et al. (2010), Laseen and Svensson (2011), Del Negro et al. (2012), Carlstrom et al. (2012), and Burgess et al. (2013). Kiley (2013b) 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.

4.8.3 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).

Figure 12: Outcomes Under Lower Unemployment Threshold



Notes:
Figures show response of the sticky-price (black) 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.

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 12. This occurs because the thresholds, in this model, are very similar to conditions that generate a departure from the ZLB under the levels-only rule 16. In contrast, this approach generates a modest, persistent degree of overshooting in infla-

tion, 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.

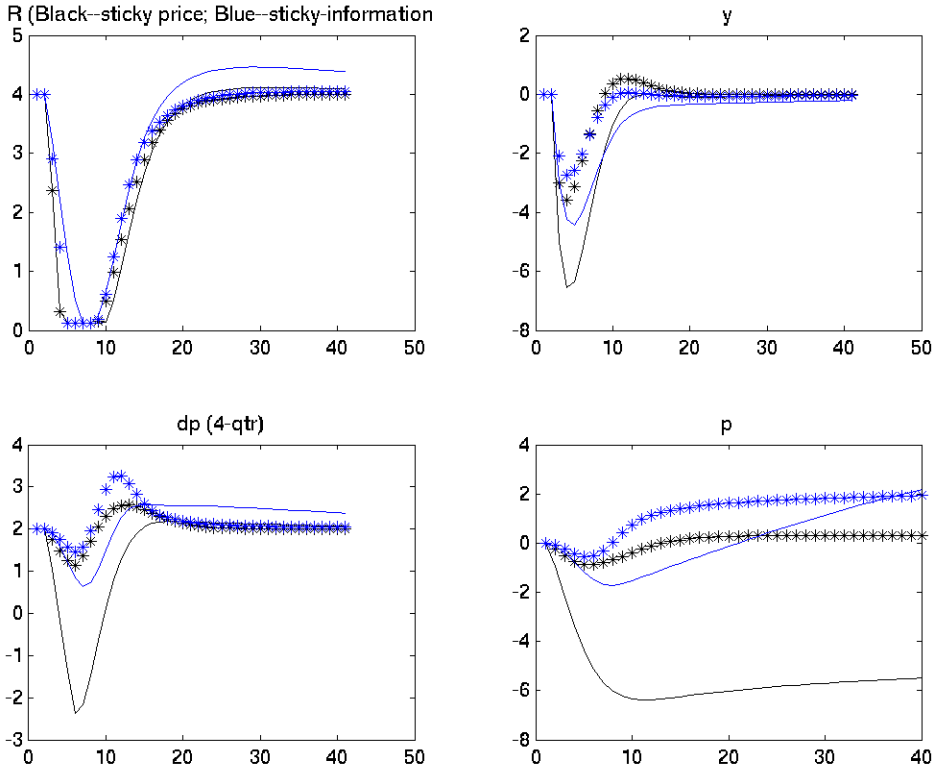
The possibility of prolonged overshooting of inflation may be desirable, depending on how policymakers weigh improved near-term performance relative to a persistent overshooting of inflation. Indeed, some degree of overshooting is the essence of the optimal strategy, as emphasized in Woodford (2010). 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).

Linking the change in the policy rate to inflation and the output gap has properties similar to setting a threshold equal to the natural rate: Holding inflation at objective, the policy rate only increases when the output gap signals that resource utilization has shifted into high gear. In addition, such strategies, in the absence of the ZLB, imply price-level targeting, as can be seen by multiplying both sides of rule 17 by $(1 - L)^{-1}$ (where L is the lag operator).

The performance of such strategies in the case where the change in the nominal interest rate is linked to inflation and the output gap is reported in figure 13 (along with outcomes under the inertial Taylor (1999) rule for comparison). The difference rule stabilizes activity to a greater degree than even the more aggressive output-gap threshold strategy. In the sticky-price case, inflation overshoots 2 percent moderately but only for a short period (with inflation at 3 percent three years after the shock but near 2 percent shortly thereafter) reflecting the "quasi price-level targeting" aspects of the difference rule. Inflation overshoots by a larger degree in the sticky-information case (to 4 percent) and the price level rises substantially over the long run.

The super-inertial rule tends to keep the federal funds rate near zero until the output

Figure 13: Outcomes Under Super-inertial Rules



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

gap is near zero (or unemployment rate is near 5.5 percent), as with the aggressive threshold strategies above. However, the super-inertial rules imply rapid increases in the policy rate once the ZLB period is over – as the *change* in the nominal interest rate is linked to inflation or output developments: For example, inflation persistently near $2\frac{3}{4}$ percent, as under the aggressive threshold strategies in both the sticky-price and sticky-information models, would imply an increase in the federal funds rate of 1 percentage points after one year and 3 percentage points after 3 years; in contrast, the inertial Taylor-type rule implies an increase in the federal funds rate of only 75 basis points. The commitment to respond strongly limits the possibility for persistently high inflation. As a result, inflation overshoots – and does so significantly in the sticky-information model – but only for a short period.

We do not report results under the Great Recession shock for the rule link the change in the nominal interest rate to the change in the output gap (equation 18): This rule per-

forms very poorly (even relative to the estimated rule). As with the estimated rule, a strong response to the change in activity short-circuits the recovery, leading to a deep and prolonged recession. Overall, these results show that responding to the change in the output gap is very effective following cost-push shocks (markup shocks), but problematic following large adverse demand shocks.

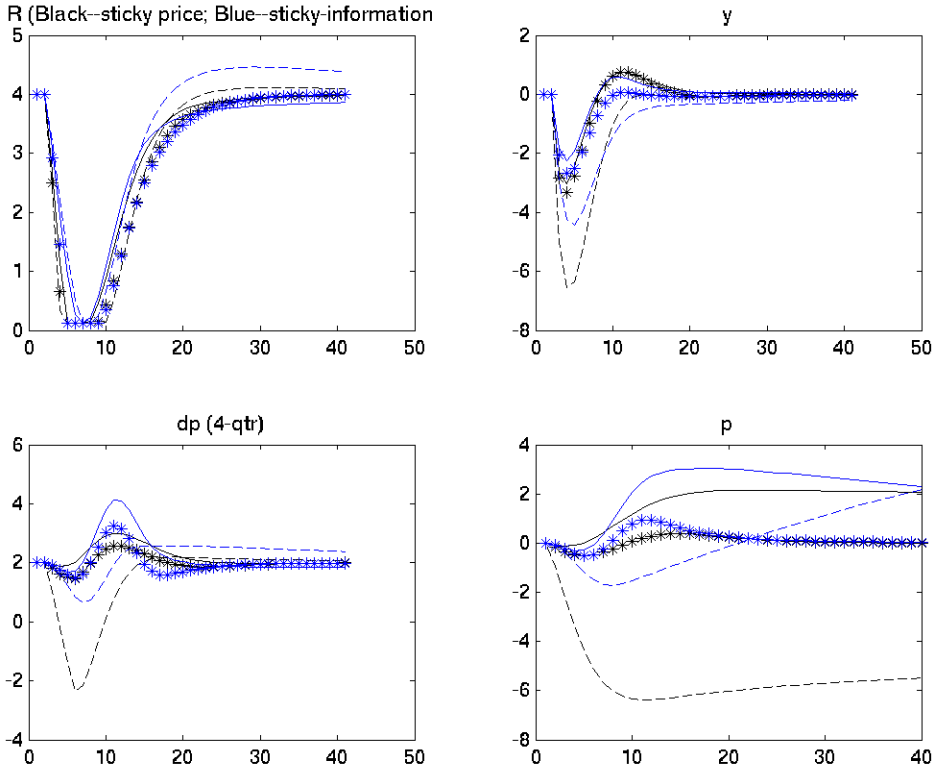
4.8.4 Promising higher inflation: Nominal-income targeting

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 difference rule that responds to inflation and the output gap (rule 17), the difference nominal income rule (19), and the inertial Taylor (1999) rule (16). As shown by the dashed and starred lines, targeting nominal income delivers most of the output stabilization benefits of a zero output gap threshold (e.g., the difference rule linked to the gap), 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.

Figure 14: Outcomes Under Lower Nominal-Income Targeting



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

5 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 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 (2013b) 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. [15]

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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[15] 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 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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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 "FEDFUNDS"), 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 10: :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 11: Posterior For Sticky-Information and Sticky-Price Models

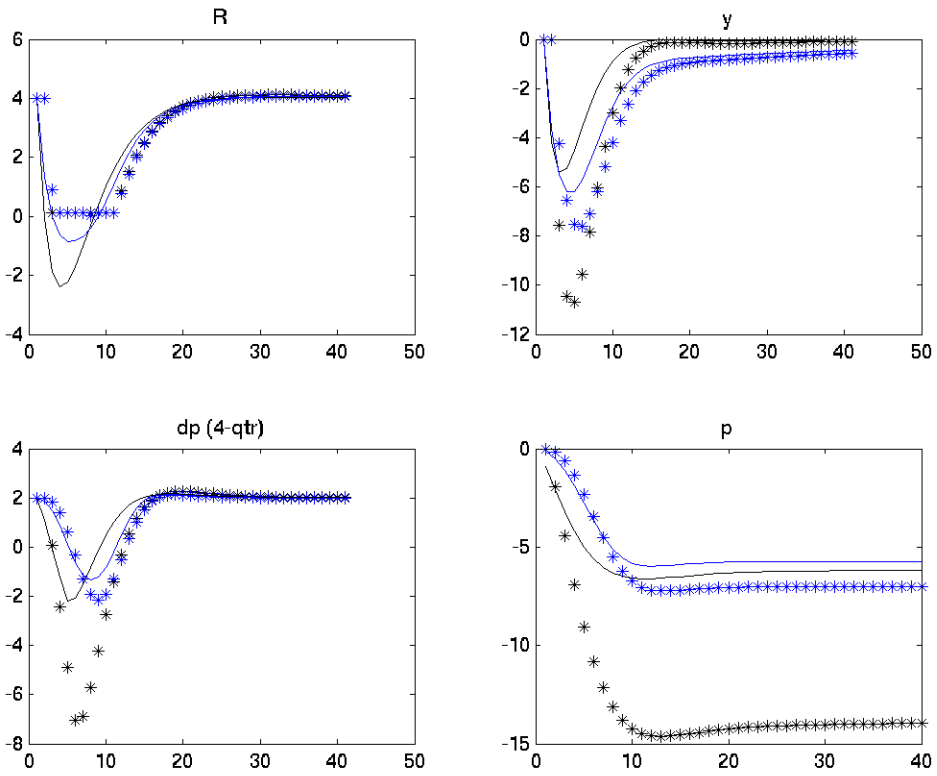
	Sticky Information		Sticky Price	
Parameter	Mean	[0.05, 0.95]	Mean	[0.05, 0.95]
$\bar{\beta}$	0.17	[0.09, 0.25]	0.17	[0.09, 0.26]
$\bar{\pi}$	0.68	[0.53, 0.86]	0.69	[0.54, 0.88]
$\bar{l}$	-1.80	[-3.96, 0.34]	-1.66	[-3.77, 0.39]
α	0.19	[0.17, 0.22]	0.21	[0.18, 0.24]
σ_c	1.19	[1.00, 1.41]	1.14	[0.93, 1.30]
Φ	1.50	[1.39, 1.61]	1.54	[1.39, 1.69]
φ	6.60	[4.87, 8.28]	6.37	[4.69, 8.17]
h	0.62	[0.52, 0.72]	0.66	[0.52, 0.77]
λ_w	0.43	[0.29, 0.56]	0.47	[0.35, 0.57]
σ_l	2.66	[2.10, 3.22]	2.21	[1.28, 3.24]
λ_p	0.33	[0.28, 0.37]	0.64	[0.57, 0.70]
ι_w	0.51	[0.30, 0.74]	0.51	[0.36, 0.65]
ι_p	0.53	[0.27, 0.81]	0.41	[0.29, 0.54]
ψ	0.73	[0.61, 0.83]	0.72	[0.56, 0.86]
r_π	2.23	[1.95, 2.47]	2.21	[1.95, 2.49]
ρ	0.87	[0.84, 0.89]	0.84	[0.81, 0.87]
r_y	-0.00	[-0.02, 0.01]	-0.01	[-0.03, 0.00]
$r_{\Delta y}$	0.19	[0.15, 0.23]	0.16	[0.11, 0.20]
ρ_a	0.89	[0.84, 0.93]	0.91	[0.86, 0.95]
ρ_b	0.52	[0.20, 0.75]	0.43	[0.13, 0.75]
ρ_g	0.95	[0.92, 0.98]	0.96	[0.94, 0.98]
ρ_q	0.70	[0.54, 0.81]	0.67	[0.56, 0.76]
ρ_m	0.24	[0.12, 0.35]	0.35	[0.21, 0.48]
ρ_p	0.90	[0.86, 0.94]	0.93	[0.89, 0.97]
ρ_w	0.93	[0.90, 0.96]	0.98	[0.96, 0.99]
ρ_{π^*}	0.99	[0.99, 0.99]	0.99	[0.99, 1.00]
g_y	0.42	[0.25, 0.61]	0.37	[0.22, 0.51]
μ_p	0.48	[0.39, 0.57]	0.70	[0.57, 0.81]
μ_w	0.45	[0.22, 0.67]	0.64	[0.44, 0.80]
σ_a	0.38	[0.34, 0.43]	0.37	[0.34, 0.41]
σ_b	0.13	[0.08, 0.18]	0.14	[0.08, 0.20]
σ_g	0.39	[0.35, 0.44]	0.40	[0.36, 0.45]
σ_q	0.33	[0.26, 0.43]	0.33	[0.27, 0.39]
σ_m	0.13	[0.11, 0.14]	0.13	[0.11, 0.14]
σ_p	0.18	[0.16, 0.20]	0.10	[0.09, 0.11]
σ_w	1.42	[1.07, 1.79]	0.39	[0.32, 0.46]
σ_{π^*}	0.03	[0.03, 0.03]	0.03	[0.02, 0.03]

C Amplification through the ZLB

The tendency for amplification of the effects of shocks at the ZLB within the sticky-price framework that we highlighted in the main text is quite clear in the estimated models. This can be seen through a simulation of the model that does not impose the ZLB, reported in figure 15. In the absence of the ZLB, the effects of the demand shock on output are quite similar under sticky prices and sticky 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.

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 (and will also imply large effects from policy strategies that differ from the Taylor rule). 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 15: Amplification of Recessionary Shock at the ZLB)



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