

## Optimal Monetary Policy Rules in an Estimated Sticky-Information Model<sup>†</sup>

By RICARDO REIS\*

*This paper uses a dynamic stochastic general equilibrium (DSGE) model with sticky information as a laboratory to study monetary policy. It characterizes the model's predictions for macro dynamics and optimal policy at prior parameters, and then uses data on five US macroeconomic series to update the parameters and provide an estimated model that can be used for policy analysis. The model answers a few policy questions. How does sticky information affect optimal monetary policy? What is the optimal interest rate rule? What is the optimal elastic price-level targeting rule? How does parameter uncertainty affect optimal policy? Are the conclusions for the Euro area different? (JEL E13, E31, E43, E52)*

Following in the footsteps of John B. Taylor (1979), recent work by Stephanie Schmitt-Grohé and Martín Uribe (2007), Andrew T. Levin et al. (2006), Michel Juillard et al. (2006) and others has estimated dynamic stochastic general equilibrium models (DSGE) using several macroeconomic series for policy advice. All of these papers use variants of the Lawrence J. Christiano, Martin Eichenbaum, and Charles L. Evans (2005) model, with many rigidities impeding adjustment, from sticky (but indexed) prices and wages to habits in consumption. This paper presents an alternative DSGE model of macroeconomic fluctuations in which there is only one departure from a classical benchmark that applies to all markets, sticky information. In the model, at any date, only a fraction of consumers, workers, and firms update their information and make plans for consumption, wages, and prices for the future. I discuss the basic properties of the model, estimate it on US and Euro area data, and characterize optimal monetary policy.

After presenting the model, I choose parameter values following the conventions that have emerged from prior studies, and study the dynamics properties of the model and its policy implications. In particular, I examine the impact of sticky information on the response to monetary policy shocks and on the optimal instrument and targeting rules. By comparing the differences in impulse response and optimal policies as information stickiness changes, I characterize the impact of informational frictions on monetary policy.

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Next, I update the parameter values to take into account uncertainty in a Bayesian sense, using US data since 1986. The contrast in the impulse responses to shocks at the prior and posterior parameters provides further insights into the properties of the model. Moreover, the model can then be used to provide concrete guidance to policymakers. I investigate which are the optimal interest rate and price targeting rules, as well as their robustness to parameter estimates, by calculating robustly optimal policy rules (in the sense of Bayesian model averaging) and by repeating the analysis for the Euro area.

The motivation for this work is twofold. First, there is still an active debate on the merits and flaws of different models of rigidities. By characterizing optimal policy in a model that is quite different from the ones where optimal policy has been studied so far, this paper provides both a check on which policy prescriptions are robust across models of rigidities, as well as a contrast between the monetary transmission mechanisms in different models.

Second, sticky information models are interesting in their own right, but monetary policy has only been studied analytically in simple models where only price-setters are inattentive (Laurence Ball, N. Gregory Mankiw, and Reis 2005; William A. Branch et al. 2009). This paper provides the first systematic study of optimal monetary policy in a medium-scale model with pervasive sticky information estimated to mimic the features of the US data. The model was first sketched in Mankiw and Reis (2006, 2007), and is further explored in a companion paper to this one, Reis (2009), that presents the microfoundations in detail, the algorithms that solve it, and the sensitivity of estimates to different specifications. This paper uses this theoretical framework to study concrete policy questions.

The paper is organized as follows. Section I presents the model, starting with the classical general equilibrium benchmark and its flexible equilibrium, and then introducing sticky information. Section II picks parameters using priors, and discusses the role of information frictions on the dynamics of the model and on optimal monetary policy. Section III updates the parameter values using data for the United States, discusses the fit of the models to the data, and answers several questions on optimal monetary policy through the lenses of the estimated DSGE model. Section IV discusses the robustness of the results to alternative parameter specifications, and compares the policy conclusions reached with the results in the literature. Section V concludes by discussing the strengths and weaknesses of the model and by stating lessons for monetary policy.

## I. The Model

This section starts by presenting a simple classical model of fluctuations. The first part describes the environment, agents, and markets, and the second part interprets the key reduced-form equilibrium relations that characterize the equilibrium in aggregate variables. Because the model is relatively standard, readers familiar with it may skip the environment and jump to the reduced-form equations directly. The third part characterizes the equilibrium dynamics in this model, and the fourth part introduces sticky information and derives its associated reduced-form equilibrium equations.

### A. The Environment

I consider a world with three types of markets: goods, labor, and savings, and three types of rational agents: consumers, workers, and firms.

A household is made up of a consumer and a worker, and there is a continuum of each indexed by  $j$  and  $k$ , respectively, in the unit interval.<sup>1</sup> Each household's utility function is

$$(1) \quad E_t \left\{ \sum_{t=0}^{\infty} \xi^t \left[ \ln(C_{t,j}) - \frac{\varkappa L_{t,k}^{1+(1/\psi)}}{1 + (1/\psi)} \right] \right\},$$

where  $C_{t,j}$  and  $L_{t,k}$  are consumption and hours worked, respectively, and the parameters  $\xi$ ,  $\psi$ , and  $\varkappa$  are the discount factor, the Frisch elasticity of labor supply, and the relative disutility of working, respectively. Consumption is a Dixit-Stiglitz aggregator of varieties with random elasticity of substitution  $\tilde{\nu}_t$ :

$$(2) \quad C_{t,j} = \left( \int_0^1 C_{t,j}(i)^{\frac{\tilde{\nu}_t}{\tilde{\nu}_t-1}} di \right)^{\frac{\tilde{\nu}_t-1}{\tilde{\nu}_t}}.$$

The household's budget constraint is

$$(3) \quad M_{t+1,j} = \Pi_{t+1} [M_{t,j} - C_{t,j} + (1 - \tau_w) W_{t,k} L_{t,k} / P_t + T_{t,j}],$$

where  $M_{t,j}$  is real wealth, and  $\Pi_{t+1}$  is the real interest rate on bonds. Consumers meet each other to trade these bonds in the savings market, where bonds are in zero net supply. The consumer makes purchases in the goods market, and  $P_t$  is the static cost-of-living index associated with (2), so that  $\int_0^1 P_{t,i} C_{t,j}(i) di = P_t C_{t,j}$ , and  $P_t = \left( \int_0^1 P_{t,i}^{1-\tilde{\nu}_t} di \right)^{1/(1-\tilde{\nu}_t)}$ . The worker sells her unique type of differentiated labor in the labor market in return for nominal wage  $W_{t,k}$  after a tax on labor income  $\tau_w$ . Finally, the household receives  $T_{t,j}$ , which are the profits from owning firms, lump-sum transfers from the government, and payments from an insurance contract that all households signed at the beginning of time when they were all ex ante identical, ensuring that they have the same wealth at all dates.

There is a continuum of firms in the unit interval indexed by  $i$ . They assemble the varieties of labor into composite labor  $N_{t,i}$  through a Dixit-Stiglitz aggregator:

$$(4) \quad N_{t,i} = \left( \int_0^1 N_{t,i}(k)^{\frac{\tilde{\gamma}_t}{\tilde{\gamma}_t-1}} dk \right)^{\frac{\tilde{\gamma}_t-1}{\tilde{\gamma}_t}},$$

with random elasticity of substitution  $\tilde{\gamma}_t$ . The cost of hiring labor is  $W_t N_{t,i} = \int_0^1 W_{t,k} N_{t,i}(k) dk$  given the static wage index  $W_t = \left( \int_0^1 W_{t,k}^{1-\tilde{\gamma}_t} dk \right)^{1/(1-\tilde{\gamma}_t)}$ . The labor input is then transformed through a diminishing returns-to-scale technology to produce a variety of good  $i$ ,  $Y_{t,i} = A_t N_{t,i}^\beta$ , where  $\beta$  is the degree of returns to scale, and

<sup>1</sup>I separate worker and consumer because, in the models with frictions, they may differ in their constraints. In the classical case though, one can think of the household making all decisions together.

$A_t$  is a common technology shock. The firm is a monopolist that chooses the price of its good  $P_{t,i}$  and pays a sales tax  $\tau_p$ , so that real profits are:

$$(5) \quad [(1 - \tau_p)P_{t,i}Y_{t,i} - W_tN_{t,i}]/P_t.$$

Finally, the government intervenes in the economy fiscally by charging taxes and by buying a random share  $1 - (1/G_t)$  of the goods in the market. These governmental purchases are wasted, and I refer to them broadly as aggregate demand shocks. The surpluses or deficits are rebated/charged to the households in a lump-sum way. A central bank supplies reserves to the bond market, and because it can generate money at will, it can target the nominal interest rate  $i_t \equiv \log[E_t(\Pi_{t+1}P_{t+1}/P_t)]$  (Michael Woodford 2003a). Monetary policy follows a Taylor rule with exogenous shocks  $\varepsilon_t$ :

$$(6) \quad i_t = \varphi_p \log(P_t/P_{t-1}) + \varphi_y \log(Y_t/Y_t^c) - \varepsilon_t.$$

In this expression,  $Y_t^c$  refers to the classical equilibrium, so, the second term is always zero in this economy, while in the first term,  $\varphi_p > 1$  to satisfy the Taylor principle.

Having described the agents, I now turn to the equilibrium in each market. In the savings market, each consumer is choosing  $C_{t,j}$  to maximize (1) subject to (3) and a no-Ponzi game condition. The standard consumption Euler equation is

$$(7) \quad C_{t,j}^{-1/\theta} = \xi E_t(\Pi_{t+1}C_{t+1,j}^{-1/\theta}).$$

In the market for good  $i$ , the demand by each individual consumer comes from choosing  $C_{t,j}(i)$  to maximize (2) subject to some total expenditure  $P_t C_{t,j}$ . Aggregating over all consumers, and taking into account government spending, the total demand for good  $i$  is

$$(8) \quad Y_{t,i} = (P_{t,i}/P_t)^{-\tilde{\nu}_t} G_t \int_0^1 C_{t,j} dj.$$

The producer of good  $i$ , in turn, chooses the price  $P_{t,i}$  to maximize (5) subject to the production function and the demand (8). The first-order condition is

$$(9) \quad P_{t,i} = (1 - \tau_p) \left( \frac{\tilde{\nu}_t}{\tilde{\nu}_t - 1} \right) \left( \frac{W_t N_{t,i}}{\beta Y_{t,i}} \right).$$

Prices are the product of three terms: the after-tax share of sales, a desired markup, and marginal cost, which equals the wage divided by the marginal product of labor (which, here, equals output per hour times  $\beta$ ).

In the market for labor variety  $j$ , each firm minimizes total costs  $W_t N_{t,i}$  subject to the aggregator (4). Integrating over all firms leads to the demand for variety  $k$ :

$$(10) \quad L_{t,k} = (W_{t,k}/W_t)^{-\tilde{\nu}_t} \int_0^1 N_{t,i} di.$$

Workers choose the nominal wage to charge  $W_{t,k}$  in order to maximize utility (1) subject to the budget constraint (3), a no-Ponzi game condition, and the demand for their variety (10). The Euler equation is

$$(11) \quad \left( \frac{\tilde{\gamma}_t}{\tilde{\gamma}_t - 1} \right) \frac{L_{t,k}^{1/\psi} P_t}{W_{t,k}} = \xi E_t \left[ \Pi_{t+1} \left( \frac{\tilde{\gamma}_{t+1}}{\tilde{\gamma}_{t+1} - 1} \right) \left( \frac{L_{t+1,k}^{1/\psi} P_{t+1}}{W_{t+1,k}} \right) \right].$$

If  $\tilde{\gamma}_t$  is fixed, this condition states that the marginal disutility of supplying labor today ( $L_{t,k}^{1/\psi}$ ) divided by the real wage ( $W_{t,k}/P_t$ ) is equated to the discounted marginal disutility tomorrow, ( $L_{t+1,k}^{1/\psi}$ ) divided by the real wage tomorrow ( $W_{t+1,k}/P_{t+1}$ ) times the real interest rate. With time-varying  $\tilde{\gamma}_t$ , the Euler equation takes into account the change in the markup that the monopolistic worker wants to charge.

To conclude, the optimality conditions above describe the monopolistically competitive equilibrium of a classical economy. There are five sources of shocks in this economy: productivity ( $A_t$ ), aggregate demand ( $G_t$ ), price and wage markups ( $\tilde{\nu}_t$  and  $\tilde{\gamma}_t$ ), and monetary policy ( $\varepsilon_t$ ). I will focus on explaining the dynamics of five variables: goods' price inflation ( $P_t/P_{t-1}$ ), output growth ( $Y_t/Y_{t-1} = \int_0^1 Y_{t,i} di / \int_0^1 Y_{t-1,i} di$ ), hours worked ( $L_t = \int L_{t,k} dk$ ), real wage growth ( $(W_t/P_t)/(W_{t-1}/P_{t-1})$ ), and nominal interest rates ( $i_t$ ).

### B. The Reduced-Form Expressions

Log-linearizing all variables around the nonstochastic Pareto-optimum steady state of this economy leads to five aggregate relations.

Starting with the aggregate production function, adding over all the log-linear production functions gives

$$(12) \quad y_t = a_t + \beta l_t,$$

relating total output ( $y_t$ ) to productivity shocks ( $a_t$ ) and hours worked ( $l_t$ ) subject to decreasing returns to scale with labor share  $\beta$ .

Turning to the aggregate supply relation (or Phillips curve), from the optimal behavior of the identical firms, their desired price  $p_t^*$  equals

$$(13) \quad p_t^* = p_t + \frac{\beta(w_t - p_t) + (1 - \beta)y_t - a_t}{\beta + \nu(1 - \beta)} - \frac{\beta\nu_t}{(\nu - 1)[\beta + \nu(1 - \beta)]}.$$

This equation states that desired prices equal the price level plus real marginal costs and desired markups. Real marginal costs rise with the cost of the labor input, real wages ( $w_t - p_t$ ), as well as with output ( $y_t$ ) because of decreasing returns to scale, and fall with productivity ( $a_t$ ). The desired markup rises whenever the random substitutability of varieties of goods decreases ( $\nu_t$ ), where  $\nu$  is the steady-state elasticity of substitution for goods.

Third, because all the consumers are identical, the Euler equation for output (or IS curve) is

$$(14) \quad y_t - g_t = -(i_t - E_t \Delta p_{t+1}) + E_t(y_{t+1} - g_{t+1}).$$

This equation notes that higher nominal interest rates ( $i_t$ ) or lower expected inflation ( $E_t \Delta p_{t+1}$ ) raise real interest rates, encouraging savings and depressing current consumption relative to future consumption. An aggregate demand shock, or increase in government consumption ( $g_t$ ), raises output for a fixed amount of private consumption.

Fourth, because all workers are identical, the labor supply condition (or wage curve) is

$$(15) \quad (\gamma + \psi)(w_t^* - p_t) = \gamma(w_t - p_t) + l_t - \psi(y_t - g_t) - \frac{\psi \gamma_t}{\gamma - 1}.$$

Desired wages ( $w_t^*$ ) increase one-to-one with prices ( $p_t$ ), since workers care about real income; increase with higher real wages in the economy ( $w_t - p_t$ ), since this pushes up the demand for a particular labor variety through substitution; increase with labor supplied, ( $l_t$ ), because of increasing marginal disutility of working; fall with consumption, ( $c_t = y_t - g_t$ ), because of the income effect; and fall with more substitutable labor varieties ( $\gamma_t$ ), since this lowers the random desired markups. The relevant parameters governing the strength of these effects are the steady-state elasticity of substitution across labor varieties ( $\gamma$ ) and the Frisch elasticity of labor supply ( $\psi$ ).

The fifth relation is the monetary policy rule:

$$(16) \quad i_t = \varphi_p \Delta p_t + \varphi_y (y_t - y_t^c) - \varepsilon_t,$$

where  $y_t^c$  is the classical equilibrium level of output (so without rigidities the second term is always zero), and  $\varepsilon_t$  is a monetary policy shock.

Using the condition that, in equilibrium, desired and actual prices and wages are the same, the five difference equations above, plus the initial condition  $p_{-1} = 0$ , characterize the equilibrium values of inflation, nominal interest rates, output growth, employment, and real wage growth  $x_t = \{\Delta p_t, i_t, \Delta y_t, l_t, \Delta(w_t - p_t)\}$  as a function of the five exogenous shocks to aggregate productivity growth, aggregate demand, goods markups, labor markups, and monetary policy  $s_t = \{\Delta a_t, g_t, \nu_t, \gamma_t, \varepsilon_t\}$ . I assume that each of these shocks follows an independent AR(1) with correlation parameter  $\rho_s$  and normally distributed innovations with standard deviation  $\sigma_s$ .

### C. Dynamics of the Classical Equilibrium

Letting the superscript  $c$  denote values at the classical equilibrium, a few steps of algebra show that output and labor:

$$(17) \quad y_t^c = a_t + \Xi [g_t + \gamma_t / (\gamma - 1) + \nu_t / (\nu - 1)],$$

$$(18) \quad l_t^c = (y_t^c - a_t)/\beta,$$

where  $\Xi = \beta\psi/(1 + \psi)$ . Output inherits a stochastic trend from productivity, while hours are stationary, a result of assuming King-Plosser-Rebelo preferences. Both output growth and hours are independent of the monetary shocks, hours are independent of productivity shocks, and the autoregressive roots of output growth are just the roots of the exogenous shocks. This monetary neutrality, absence of technology-driven labor market fluctuations, and lack of internal persistence are some of the main problems the classical model has facing the facts.<sup>2</sup>

Real wages and inflation are:

$$(19) \quad (w_t - p_t)^c = y_t^c - l_t^c + \frac{\nu_t}{\nu - 1},$$

$$(20) \quad \Delta p_t^c = \sum_{j=0}^{\infty} \varphi_p^{-j-1} E_t(\Delta y_{t+1+j}^c - \Delta g_{t+1+j} + \varepsilon_{t+j}).$$

According to the model, real wages will tend to be as volatile as output per hour, and the response of inflation to a monetary shock is higher on impact and decays at the same rate as the shock. These two predictions are also at odds with the conventional wisdom.

#### D. Sticky Information

In response to the mismatch between the classical model's predictions and the data, researchers have introduced different forms of rigidities. One approach assumes that there are fixed costs of acquiring, absorbing, and processing information, so that agents optimally choose to update their information sporadically (Reis 2006a, 2006b). This is the model of inattentiveness, and, in principle, it leads to a rich distribution of agents updating their information on different dates and at different frequencies. There are some (very strict) conditions under which this distribution of inattentiveness is exponential, and I assume that these hold. In the log-linearized world, it is then, as if every period a constant fraction of agents update their information and write plans into the future that they revise only when they obtain information again. This is the model of sticky information, where information disseminates slowly throughout the population.

In the context of the general equilibrium model presented so far, there is sticky information in all three markets. While consumers and workers share a household, in the sense of having the same utility function and facing the same budget constraint, and the household owns the firms, these three agents may have different information. When the consumer updates his information, he learns about what the worker in his household has been up to and about the firms' pricing plans, and then

<sup>2</sup>Extensions of the model that include capital accumulation to generate internal persistence, or different preferences to explain the dynamic of hours worked, also typically fail to match the facts (e.g., Timothy Cogley and James M. Nason 1995; Robert Shimer 2009).



makes his own choice of a consumption plan. This model, where inattentiveness is pervasive in all markets, is the sticky information in general equilibrium model (SIGE).<sup>3</sup>

In the goods' markets, firms update their information at rate  $\lambda$ , so there are  $\lambda$  firms with current information,  $\lambda(1 - \lambda)$  with one-period old information,  $\lambda(1 - \lambda)^2$  with two-period old information, and so on. Letting the index  $i$  denote the group of firms that last updated their information  $i$  periods ago, then it will set its price for date  $t$  equal to what it expected its desired price would be,  $p_{t,i} = E_{t-i}(p_t^*)$ .<sup>4</sup> The sticky information Phillips curve then is

$$(21) \quad p_t = \lambda \sum_{i=0}^{\infty} (1 - \lambda)^i E_{t-i} \left[ p_t + \frac{\beta(w_t - p_t) + (1 - \beta)y_t - a_t}{\beta + \nu(1 - \beta)} - \frac{\beta \nu_t}{(\nu - 1)[\beta + \nu(1 - \beta)]} \right].$$

In the savings market, there is sticky information on the part of the consumers, who update their information at rate  $\delta$ , so that a share  $\delta(1 - \delta)^j$  of consumers last updated their information  $s$  periods ago. After iterating the Euler equation for desired consumption forward, and defining a measure of wealth  $y_\infty^c = \lim_{\tau \rightarrow \infty} E_t(y_{t+\tau})$ , and the long real interest rate  $R_t = E_t \sum_{\tau=0}^{\infty} (i_{t+\tau} - \Delta p_{t+1+\tau})$ , we obtain the sticky information IS curve:

$$(22) \quad y_t = \delta \sum_{j=0}^{\infty} (1 - \delta)^j E_{t-j} (y_\infty^c - R_t) + g_t.$$

Finally, in the labor market, there is sticky information on the part of workers, who update their information at rate  $\omega$ . Following similar steps, as in the consumption case, the sticky information wage curve is

$$(23) \quad w_t = \omega \sum_{k=0}^{\infty} (1 - \omega)^k E_{t-k} \left[ p_t + \frac{\gamma(w_t - p_t)}{\gamma + \psi} + \frac{l_t}{\gamma + \psi} + \frac{\psi(y_\infty^c - R_t)}{\gamma + \psi} - \frac{\psi \gamma_t}{(\gamma + \psi)(\gamma - 1)} \right].$$

These three equations, together with the production function (12) and the policy rule (16), and together with the relevant initial conditions, define the SIGE equilibrium.

<sup>3</sup> Reis (2009) presents the microfoundations of this model in more detail. A few important notes are that: (i) the parameters describing the share of agents that update at any data map one-to-one to resource costs of planning and are constant as long as the variances of all variables is constant; (ii) while there is inattentiveness in all markets, not all agents are inattentive, so that there is still a monopolistic-competition equilibrium in which all markets clear.

<sup>4</sup> This follows because, up to a first-order approximation, certainty equivalence holds.



## II. Dynamics and Optimal Policy with Sticky Information

Making the model useful for policy analysis requires picking a set of parameters that make it mimic some features of the data, then understanding its dynamic properties, and, finally, performing counterfactual policy experiments.

### A. Data and Prior Parameters

The model assumed a closed economy with an unchanged monetary policy rule and unchanged variances so that the fractions of agents adjusting was constant. These features lead me to focus on seasonally adjusted quarterly data for a large economy, the United States, from the third quarter of 1986 to the first quarter of 2006. The starting date coincides with the start of Alan Greenspan's term as chairman of the Federal Open Market Committee (FOMC) and comes after the reduction in macroeconomic volatility in the early 1980s (Olivier J. Blanchard and John Simon 2001). The data series are: the change in the log of the output deflator, real output growth per capita, growth in total real compensation per hour, hours per capita (all in the nonfarm business sector), and the effective federal funds rate.

The model has 19 parameters:  $\theta = \{\psi, \nu, \gamma, \beta, \rho_{\Delta a}, \sigma_{\Delta a}, \rho_{\varepsilon}, \sigma_{\varepsilon}, \rho_g, \sigma_g, \rho_\nu, \sigma_\nu, \rho_\gamma, \sigma_\gamma, \varphi_p, \varphi_y, \delta, \omega, \lambda\}$ . Starting with the preference parameters, the elasticity of labor supply  $\psi$  is set to two, a large number as is traditionally assumed in business cycle models. The elasticities of substitution across goods' and labor varieties,  $\nu$  and  $\gamma$ , are set at 11, following Susanto Basu and John G. Fernald (1997), to imply a steady-state markup of 10 percent. Finally,  $\beta$  is set at  $\frac{2}{3}$ , roughly the value of the labor share in the data.

Turning to the shock parameters, given the aggregate production function (12) and the data on output and employment, one can back out a series for productivity and by least-squares regression estimate  $\rho_{\Delta a}$  and  $\sigma_{\Delta a}$  to be (0.03, 0.66). The remaining four serial correlation parameters are set to 0.9, so that the half-life of the shocks is approximately 6 quarters, in line with what is typically assumed, and the standard deviations are set to 0.5, close to the value for the technology shock.<sup>5</sup>

Next, the monetary policy parameters  $\varphi_p$  and  $\varphi_y$  are set to the values estimated by Glenn D. Rudebusch (2002) on US data,  $\varphi_p = 1.24$  and  $\varphi_y = 0.33$ . Finally, the inattentiveness parameters  $\delta, \omega, \lambda$  are set to 0.5 to imply an average length of inattentiveness of 2 quarters. Traditionally, models with sticky information have chosen an average inattentiveness of four quarters, while in a classical model all are attentive. The midpoint between these two cases is two quarters.

### B. Dynamics with Sticky Information

Figure 1 shows the impulse responses of inflation, nominal interest rates, hours, and the output gap to a one-standard deviation monetary shock. A large effort has gone into measuring this moment (see Christiano, Eichenbaum, and Evans (1999)

<sup>5</sup> For the markups, the value for the standard deviation is multiplied by ten, the elasticities of substitution minus one, to counteract the multiplier that is visible in equations (21) and (23).

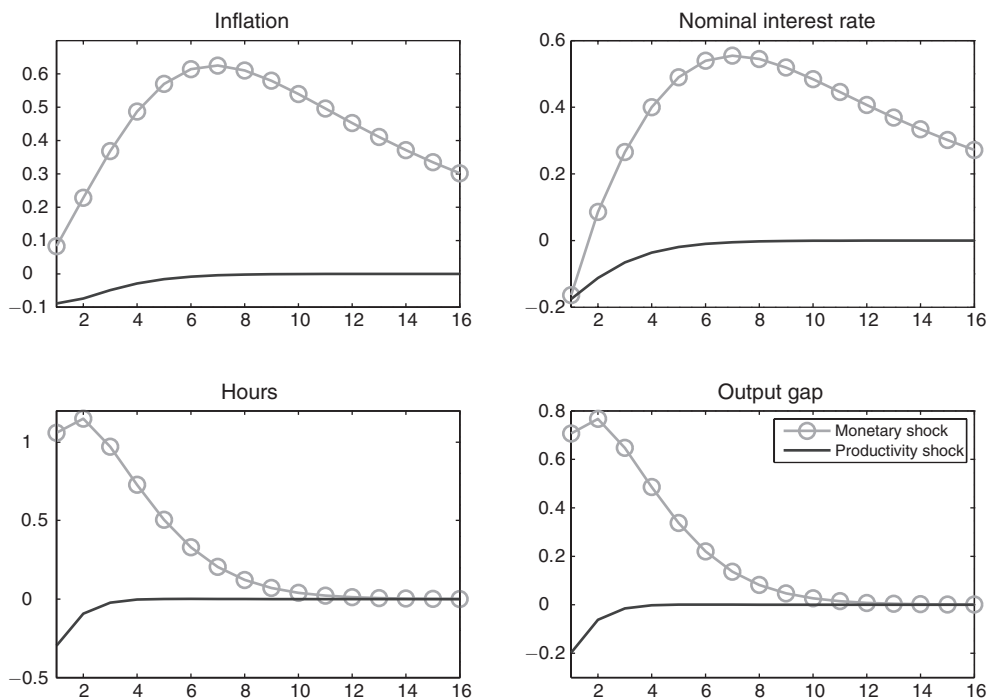


FIGURE 1. IMPULSE RESPONSE FUNCTIONS AT PRIOR PARAMETERS

for a survey) leading to the consensus that the responses of inflation and the output gap are delayed and hump-shaped, with the response for inflation peaking after that for output. At the prior parameter values, the SIGE model matches this description.

Figure 1 also shows the response to a productivity shock. Consistent with the results of Jordi Galí (1999) and Basu, Fernald, and Miles S. Kimball (2006) for the United States, boosts to productivity raise output but lower hours on impact. Moreover, the impact of productivity shocks on inflation is faster than that of monetary shocks, overcoming the challenge posed by Bill Dupor, Jing Han, and Yi Chan Tsai (2007).

The literature has also focused on the ability (or lack thereof) of models with nominal rigidities to generate enough persistence of inflation and output (see Taylor 1999 for a survey). In the post-1986 US data, the serial correlation of inflation and output growth are 0.57 and 0.11, respectively. At the prior parameters, the SIGE model predicts that the serial correlation of inflation is 0.98 and that of output growth is 0.17, so it has no problem generating persistence.

A final empirical fact is the accelerationist Phillips curve, the positive correlation between the change in inflation and the deviation of output from trend.<sup>6</sup> The classical model predicts that this moment is very close to 0, while it is 0.29 in the data. The

<sup>6</sup> For the models, I compute this moment by taking 1,000 sequences of draws of each shock of the same length as the data, using the model to generate series for output and inflation, and then calculating  $\text{Corr}(\Delta p_{t+2} - \Delta p_{t-2}, y_t - y_t^{\text{trend}})$ , where  $y_t^{\text{trend}}$  is the HP-filter trend.

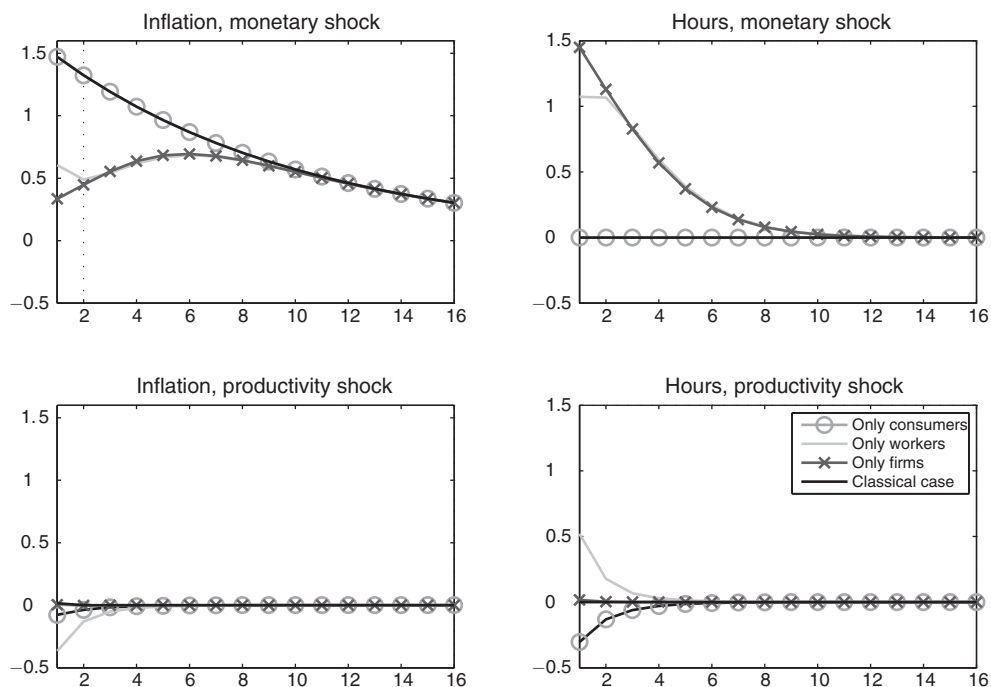


FIGURE 2. IMPULSE RESPONSE FUNCTIONS WITH SINGLE-STICKINESS

SIGE model at the prior parameters predicts that the accelerationist Phillips curve correlation is 0.63.

All things considered, the SIGE model does a good job of matching the key facts from the conventional wisdom on macroeconomic dynamics. Figure 2 tries to understand why, by examining the role of sticky information if only consumers, only workers, or only firms are inattentive. If only consumers are inattentive, then the firm and workers react instantly to a monetary shock, so there are no nominal rigidities in prices or wages. As a result, the monetary shock is neutral with respect to hours and output, leading to a zero Phillips correlation. If, instead, only workers are inattentive, a positive technology shock raises hours instead of lowering them, against the US evidence. The intuition is that, with rigid wages but flexible prices, as productivity increases, firms see their marginal costs (wages) rise less than the increase in productivity. They, therefore, choose to expand production and hire more labor. Finally, if only firms are inattentive, the main divergence from the data is that the serial correlation of output growth becomes  $-0.05$ . As Figure 2 shows, output responds almost exactly one-to-one to the technology shock, thus inheriting its unit root, while the response to a monetary shock (equal to  $\beta$  times the response of hours in the figure) declines smoothly inducing a negative serial correlation on output growth.<sup>7</sup>

<sup>7</sup> Mankiw and Reis (2006) emphasize another problem of the model with inattentive firms only. Because workers have wages over adjusting to shocks in response to the sluggishness of price, real wage growth is much

Repeating the same exercise when only one sector is fully attentive produces impulse responses (not reported for brevity) that are qualitatively close to the model with pervasive stickiness. The main flaws of these dual-stickiness models are in their quantitative predictions for second moments. As before, and for the same reason, as long as consumers are attentive, then the model predicts a negative serial correlation of output growth. With attentive workers, it is the serial correlation of wage growth that becomes negative ( $-0.07$ ), even though it is positive in the data ( $0.27$ ). Finally, with attentive firms, the model deviates from the stylized facts in two ways: it predicts an increase in hours in response to an improvement in productivity, and it predicts that real wage growth is more volatile than productivity growth, when the opposite is true in the data.

To conclude, stickiness of information plays a role in all three markets in moving the predictions of the model from their classical benchmark closer to the US evidence. Inattentiveness of firms and workers setting prices and wages is required to have real effects of monetary shocks, and if only one of the two is inattentive, then real wages become too volatile and technology shocks counterfactually raise hours. Inattentiveness of consumers is required so there is positive serial correlation in the growth rate of output.

### C. Optimal Policy Rules

With the model and parameters picked, there is a “laboratory” in place in which to ask policy questions. To compare the performance of different policies, I focus on a utilitarian measure of social welfare—the percentage increase in steady-state consumption under the prior policy rule that would lead to the same unconditionally expected utility as in the alternative policy being considered.<sup>8</sup>

I focus on two policy rules that have dominated the literature, and typically yield outcomes robustly close to the first best. The first is the Taylor (1993) rule,

$$(24) \quad i_t = \varphi_p \Delta p_t + \varphi_y (y_t - y_t^c),$$

with no monetary shocks, since in the SIGE model these lead to inefficient fluctuations. In reality, the policy shocks may be due to policy reacting to macroeconomic and financial news other than inflation and the output gap, or to the exercise of judgement and discretion, or simply to policy mistakes, but in the model policy shocks are errors that unambiguously lower welfare. The second rule is a price-level targeting rule,

$$(25) \quad p_t = K_t - \varphi (y_t - y_t^{PO}),$$

---

more volatile than productivity. In the post-1986 US data, the standard deviations of real wage growth and output per hour are almost the same, while in the model with only inattentive firms, the former is 2.32 times higher than the latter.

<sup>8</sup> Reis (2009) has the analytical expressions to calculate this measure of welfare.

TABLE 1—OPTIMAL POLICY RULES AT THE PRIOR PARAMETERS

Policy rule	Parameters	Welfare gains
<i>Panel A: SIGE economy</i>		
Taylor rule	$i_t = 1.15\Delta p_t + 0.73(y_t - y_t^c)$	0.570
Price-target rule	$p_t = -2.78(y_t - y_t^{PO})$	0.528
No policy errors	$i_t = 1.24\Delta p_t + 0.33(y_t - y_t^c)$	0.569
<i>Panel B: Single-stickiness</i>		
Firms only		
Taylor rule	$i_t = 10\Delta p_t + 10(y_t - y_t^c)$	0.571
Price-target rule	$p_t = -0.06(y_t - y_t^{PO})$	0.572
Workers only		
Taylor rule	$i_t = 10\Delta p_t + 1.28(y_t - y_t^c)$	0.570
Price-target rule	$p_t = -0.15(y_t - y_t^{PO})$	0.494

Note: There was an upper bound of ten on the search for optimal rule coefficients.

that keeps the price level close to a deterministic target  $K_t$ , allowing for deviations in response to deviations of output from its Pareto optimal level  $y_t^{PO}$ .<sup>9</sup> In an economy with sticky information only on the side of firms, Ball, Mankiw, and Reis (2005) showed that this “elastic price standard” is optimal. More generally, Lars E. O. Svensson (2003) argued that targeting rules may be superior in general to the Taylor rule.

Table 1 shows the optimal rule coefficients and welfare gains in the SIGE economy.<sup>10</sup> Both rules respond strongly to output deviations. In particular, the optimal  $\varphi_y$  is 2.2 times higher than its prior value. This reveals an important feature of SIGE economies that holds for many parameter values. Fluctuations in real activity are considerably more costly than fluctuations in inflation, so policy is particularly concerned with real stabilization.<sup>11</sup> Both rules reach significant welfare gains, most of which come from eliminating the inefficient monetary policy shocks, as shown in the third row.

To understand better what drives optimal policy in the SIGE model, panel B in Table 1 shows the optimal policy coefficients and welfare gains if there is sticky information in only one market. If only consumers are inattentive, there are no nominal rigidities since they choose real consumption. Monetary policy is neutral, so any monetary policy rule is as good as another.

If only firms are inattentive, we are in the setup considered by Ball, Mankiw, and Reis (2005), in which case the price-level target dominates the Taylor rule.

<sup>9</sup> Because  $K_t$  is common knowledge to all, it is neutral with respect to quantities and welfare. The Pareto-optimal output level differs from the classical level  $y^c$  as long as there are shocks to the markups. The discrepancy between the measure of the output gap in the two rules arises because  $y^c$  is the usual choice in the Taylor rule literature, whereas  $y^{PO}$  appears in Ball, Mankiw, and Reis (2005). Results (not reported) using Taylor rules with  $y^{PO}$  in (24) were almost identical, whereas using  $y^c$  on (25) hurt its welfare performance slightly.

<sup>10</sup> I look numerically in a grid for the optimal coefficients. There is an upper bound of ten for each coefficient. Raising it to 20 or 30 still led to hitting the bound with no change in welfare to the fourth significant digit. Moreover, in the three cases in which the bound is hit, lowering the coefficient to six changes welfare by less than one basis point.

<sup>11</sup> Real stabilization is, as usual, understood as stabilizing the output gap, not the level of output.

Intuitively, keeping the price level on target reduces the mistakes that firms make with their price plans due to outdated information. In response to temporary shocks to markups inducing inefficient fluctuations in real quantities, however, it is best to let prices deviate from the target so as to attenuate the real fluctuations. The optimal price-targeting rule balances these two forces. In contrast, because the Taylor rule responds to inflation, it creates base drift in the price level. Price setters with information older than the shock therefore continue making incorrect forecasts of prices into the future. Being constrained to follow a Taylor rule, policy reacts very strongly to the output gap, since this reduces the extent of base drift and comes closer to the optimal price-level targeting rule.

If only workers are inattentive, the Taylor rule does better. The reason is that, while workers have to forecast the price level to set their plans for wages, they also have to forecast inflation (via the long-run interest rate) in order to assess how much to intertemporally substitute their supply of labor. Targeting inflation, at least partially, becomes legitimate and the Taylor rule performs as well as the price-level target.

### III. Application to the United States

The previous section characterized macrodynamics and optimal policy in the SIGE model for a particular choice of parameters based on prior information. This section uses the five US data series described in Section IIA to choose a new set of parameters and updates the conclusions on dynamics and policy for this empirically realistic case.

#### A. Comparing Model and Data Using Estimates

Starting from the prior parameters from other studies that were used in the previous section, I take a Bayesian approach to combine them with data, taking uncertainty into account. Given the data  $\mathbf{Y}$ , this consists of assigning prior uncertainty to the parameters in the previous section via a joint probability density  $p(\theta)$ , assuming that the five shocks are independently normally distributed to derive the likelihood function  $\mathcal{L}(\mathbf{Y}|\theta)$ , and then obtaining the posterior density for the parameters  $p(\theta|\mathbf{Y})$ . This is done numerically, using Markov Chain Monte Carlo simulations.<sup>12</sup>

The prior density  $p(\theta)$  follows the convention in the DSGE literature (e.g., Sungbae An and Frank Schorfheide 2007) for most parameters. The first section of Table 2 displays the choices. Each parameter is treated independently, and is assigned a particular distribution with a mean equal to the choices in the previous section and a relatively large variance. The prior for the adjustment parameters is flat in the unit interval.

The second section of Table 2 shows the posterior parameter estimates. Starting with the preference and production parameters, the elasticities of substitution across varieties are roughly similar to the priors. The elasticity of labor supply, however, is more than twice as large as the prior, and even though the 95 percent credible set is wide, all values in it are quite large. Such an elastic labor supply is consistent

<sup>12</sup> A companion paper, Reis (2009), describes the simulation procedure in more detail and examines the sensitivity of the results to different prior specifications.

TABLE 2—PRIOR AND POSTERIOR DISTRIBUTION

	Prior		Posterior	
	Mean	95% set	Mean	95% set
Preference and production				
$\beta$	2/3	—	2/3	—
$\psi$	2	0.05, 7.38	5.15	1.18, 10.95
$\nu$	11	5.80, 18.08	10.09	5.83, 15.93
$\gamma$	11	5.80, 18.08	9.09	4.74, 14.63
Nonpolicy shocks				
$\rho_{\Delta a}$	0.03	—	0.03	—
$\sigma_{\Delta a}$	0.66	—	0.66	—
$\rho_g$	0.9	0.23, 1.00	0.99	0.98, 1.00
$\sigma_g$	0.5	0.21, 1.02	0.83	0.59, 1.23
$\rho_\nu$	0.9	0.23, 1.00	0.28	0.08, 0.48
$\sigma_\nu$	0.5	0.21, 1.02	1.06	0.31, 2.57
$\rho_\gamma$	0.9	0.23, 1.00	0.86	0.71, 1.00
$\sigma_\gamma$	0.5	0.21, 1.02	1.23	0.48, 2.70
Monetary policy				
$\varphi_p$	1.24	1.00, 1.92	1.17	1.01, 1.60
$\varphi_y$	0.33	0.03, 0.97	0.06	0.01, 0.14
$\rho_\varepsilon$	0.9	0.23, 1.00	0.29	0.07, 0.52
$\sigma_\varepsilon$	0.5	0.21, 1.02	0.44	0.30, 0.65
Inattentiveness				
$\delta$	0.5	0.03, 0.98	0.08	0.03, 0.16
$\omega$	0.5	0.03, 0.98	0.74	0.34, 0.98
$\lambda$	0.5	0.03, 0.98	0.52	0.28, 0.94

Notes: The prior densities are: the gamma for  $\nu + 1$ ,  $\gamma + 1$ ,  $\varphi_p + 1$ , and  $\varphi_y$ ; the beta for all the  $\rho_s$ ; the inverse gamma for all the  $\sigma_s^2$ ; and the uniform for  $\delta$ ,  $\omega$ , and  $\lambda$ . The posterior moments reflect 450,000 draws from 5 independent chains of 1,000,000 draws each, discarding the first 100,000 draws and keeping every tenth draw to save memory space.

with the typical assumption in business cycle models, but it goes against estimates using microeconomic data.<sup>13</sup> Another parameter, where there is a large difference between priors and posterior means, is the response of nominal interest rates to real activity, which is considerably lower in the estimates than in the prior assumptions. The estimates of the persistence of monetary policy shocks are also lower than in the prior, with only 29 percent of a shock remaining after one period.

Turning to the more interesting inattentiveness parameters, firms are estimated to, on average, be inattentive for 6 months, workers are estimated to be inattentive for 4 months, and consumers are estimated to be inattentive for 36 months. The fact that consumers are very inattentive is not too shocking since, as Reis (2006a) showed, a consumer that is inattentive forever would optimally choose to live hand-to-mouth, consuming his income every period, and between 20 and 50 percent of the US population seems to live this way.<sup>14</sup> More puzzling is the discrepancy between consumers and workers. Broadly interpreted, these estimates point to US wages being quicker to adjust to news than US consumption choices. Narrowly interpreted, they imply that workers are more attentive than consumers. Perhaps this is due to the flexibility of

<sup>13</sup> Richard Rogerson and Johanna Wallenius (2007) provide a recent restatement of the disparity between micro and macro elasticities, and propose a resolution.

<sup>14</sup> See John Y. Campbell and Mankiw (1989), Erik Hurst (2003), Reis (2006a), and the references therein.



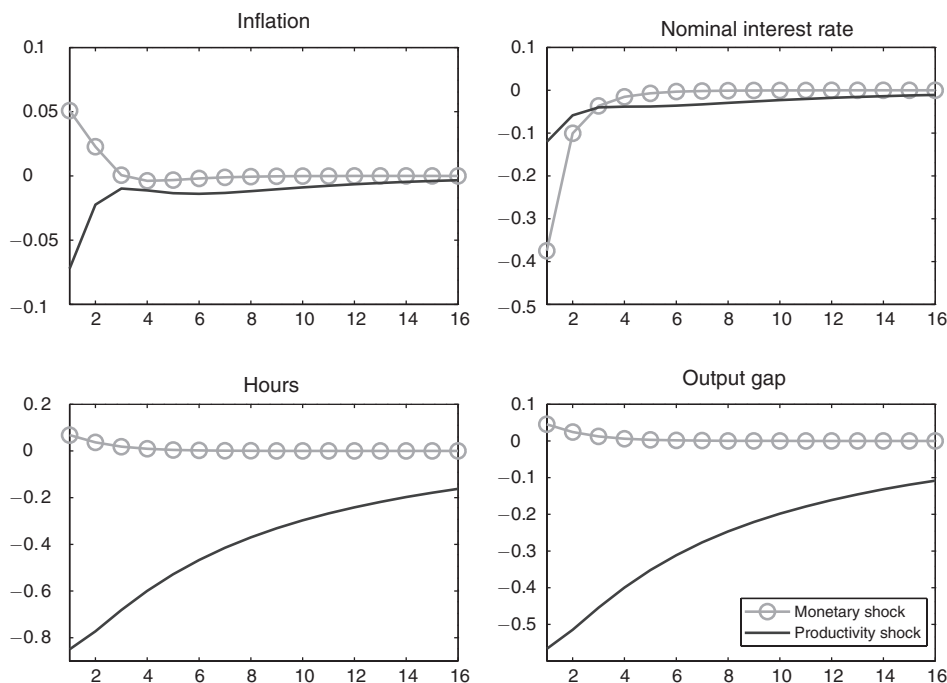


FIGURE 3. IMPULSE RESPONSE FUNCTIONS AT POSTERIOR PARAMETERS

the US labor market, or to frequent adjustments in margins of compensation beyond wages, but it is hard to know for sure.<sup>15</sup>

Figure 3 shows the impulse responses to monetary and productivity shocks at the mean posterior parameters. The response to productivity shocks is larger and faster than at the priors, but qualitatively the shapes are similar. In response to monetary shocks though, all variables move faster than at the prior parameters, without any hump shapes. This fast reaction of macroeconomic variables to policy shocks is consistent with the findings of Jean Boivin and Marc P. Giannoni (2006). They note that while much of the evidence for delayed and hump-shaped responses to monetary policy shocks comes from looking at the post-war US, in the United States post mid-1980s, the impact of monetary shocks has become much faster according to VARs. The source of the prior used for Figure 1 comes from studies looking at post-war data, whereas the posteriors in Figure 3 use post-1988 data. The contrast between these two figures is in line with the VAR evidence.

To understand what is driving it in the SIGE model, Figure 4 shows the same impulse response for three sets of parameters. Across all sets, the nonpolicy parameters are the same and equal to the mean of the posterior distribution.<sup>16</sup> They differ

<sup>15</sup> These suggestions are informed by the fact that the gap between worker and consumer inattentiveness is much smaller in the Euro area, and re-estimating the model using US nominal wages instead of the total compensation series reduces the gap.

<sup>16</sup> Setting the parameters at the prior values leads to similar results.

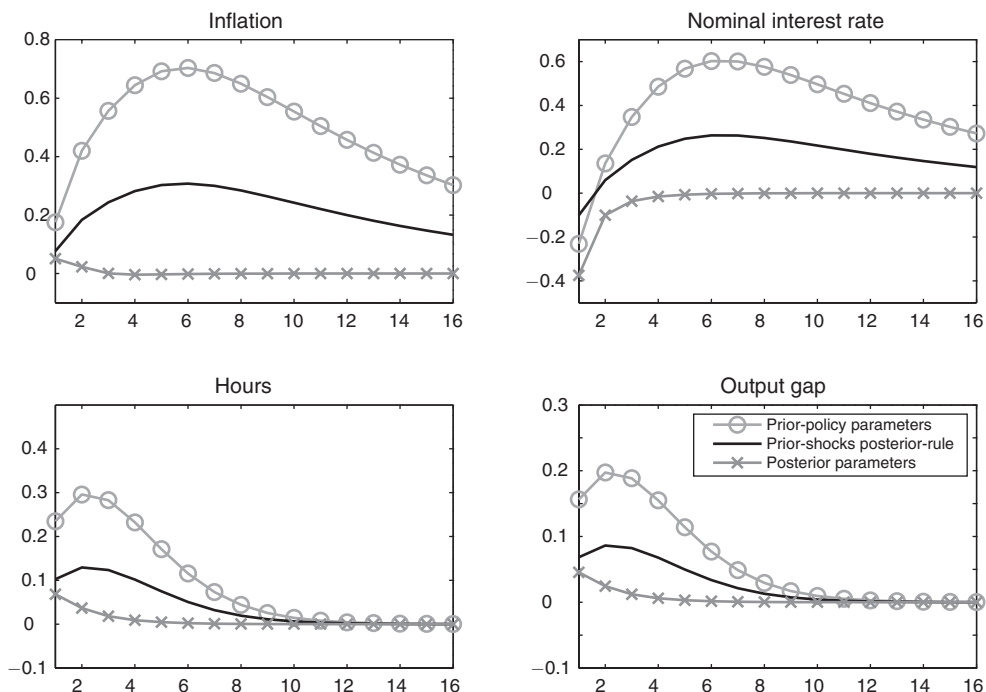


FIGURE 4. IMPULSE RESPONSE FUNCTIONS FOR DIFFERENT POLICY PARAMETERS

in the policy parameters, as in one case, both policy-rule parameters ( $\varphi_p$  and  $\varphi_y$ ) and policy-shock parameters ( $\rho_\varepsilon, \sigma_\varepsilon$ ) are kept at the prior parameter values. In the second case, the policy-rule parameters are updated but the policy-shock parameters are not. In the third case, all parameters are at the mean posterior (as in Figure 3). Figure 4 makes clear that the qualitative differences between the dynamics at the prior and posterior are not due to a difference in the monetary transmission mechanism. Rather, monetary policy has quick effects with no hump shapes at the posterior exclusively because the persistence of the shocks is much smaller at the posterior than at the prior.<sup>17</sup>

Table 3 has the predicted variance decompositions at an infinite horizon. Using VARs, Christiano, Eichenbaum, and Evans (1999) and Ben S. Bernanke, Boivin, and Piotr Elias (2005) find that monetary policy shocks in the United States play a small role in all variables except the nominal interest rate. The SIGE model is consistent with these predictions. Productivity shocks play a significant role for the US output gap, while aggregate demand shocks are important especially to explain hours. Finally, wage-markup shocks are quite important, while price-markup shocks are less so. Table 4 shows the predicted serial correlations and the accelerationist

<sup>17</sup> Oliver Coibion (2006) also finds a large role of the persistence of monetary shocks on their impact on inflation and output in a simpler sticky information model. It is a virtue of sticky information models that whether inflation responds quickly or sluggishly to shocks depends on the policy regime, instead of being built-in as in models of price indexation.

TABLE 3—PREDICTED VARIANCE DECOMPOSITIONS

Variable	Monetary	Aggregate productivity	Shock		
			Aggregate demand	Goods markup	Labor markup
Inflation	1	2	2	9	86
Interest rate	21	4	2	8	65
Output gap	0	39	12	11	38
Hours	0	5	94	0	1

Notes: All numbers are in percentage units. Rows do not add up to one due to rounding.

TABLE 4—PREDICTED MOMENTS

Moment	US data	SIGE predictions	
		Median	95% set
Serial correlations			
Inflation	0.57	0.82	0.60, 0.93
Interest rate	0.98	0.67	0.38, 0.84
Output growth	0.11	0.00	-0.23, 0.22
Hours	0.98	0.90	0.73, 0.97
Real wages	0.28	0.18	-0.05, 0.38
Phillips curve correlation	0.29	0.06	-0.32, 0.42

Notes: The median and 95 percent is  $\text{Corr}(\Delta p_{t+2} - \Delta p_{t-2}, y_t - y_t^{\text{trend}})$ , where the output trend comes from an HP-filter with smoothing parameter 1600.

TABLE 5—OPTIMAL POLICY RULES AT THE POSTERIOR PARAMETERS

Policy rule	Change in variance				Welfare gains	Indifference intervals
	Inflation	Interest rate	Hours	Gap		
Taylor rule $i_t = 2.69\Delta p_t + 0.37(y_t - y_t^c)$	-86.1	-8.3	-0.4	-12.7	0.06	1.32, 7.62 0.10, 0.65
Price-target rule $p_t = -0.06(y_t - y_t^{po})$	-99.6	448.4	-0.6	-17.2	-0.03	-0.15, 0.03
No policy errors $i_t = 1.17\Delta p_t + 0.06(y_t - y_t^c)$	-0.9	-21.1	0.0	-0.1	0.01	—
Ignoring real activity $i_t = 1.17\Delta p_t + \varepsilon_t$ and $\varepsilon_t = 0.29\varepsilon_t + 0.44z_t$	45.8	12.7	0.4	4.2	-0.03	—

Notes: All numbers are in percentage units, and the welfare gains are the percentage change in steady-state consumption relative to the status quo. The indifference intervals are the ranges for the parameters where the change in welfare is less than 0.01 percent.

Phillips correlation. As expected, taking the data and uncertainty into account move the predictions closer to the data, although taking the uncertainty in the parameters into account, the model's predictions are imprecisely estimated.

Because wage-markup shocks are so important, Figure 5 plots the impulse response to them at the posterior parameters. A positive shock corresponds to a fall in the desired markup. Therefore, hours rise as wages fall, but because of inattention, firms do not expand production by as much as they would with full information, so

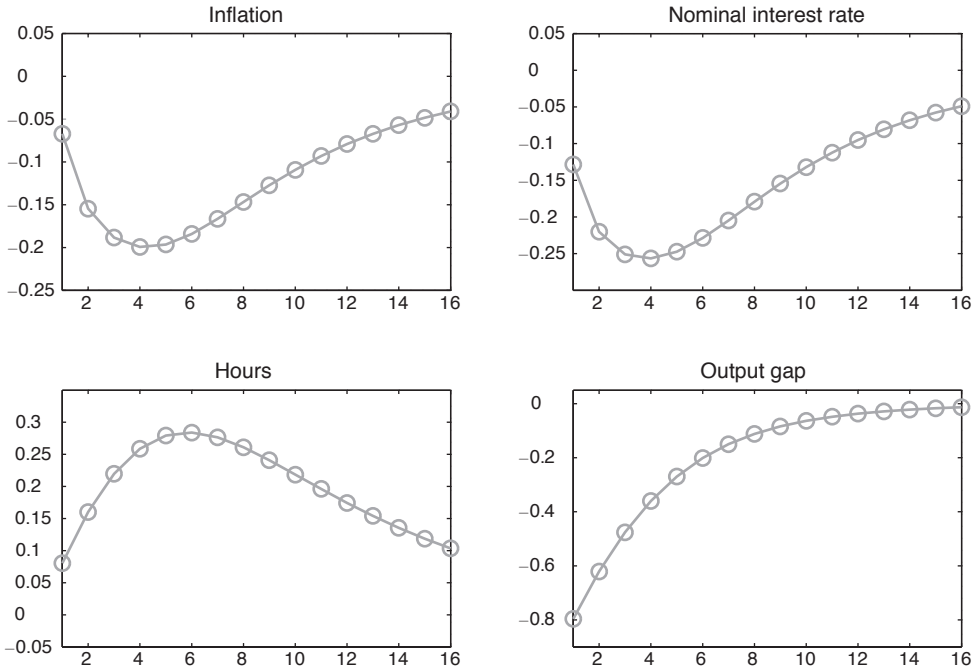


FIGURE 5. IMPULSE RESPONSE FUNCTIONS TO WAGE-MARKUP SHOCK

that a negative output gap results. The fall in wages induces a fall in prices, so inflation falls. Noticeably, the responses of inflation and hours are both hump-shaped and delayed. This is particularly important because it largely explains why the model is able to match the Phillips correlation. In response to these shocks (that explain a large part of the variance of inflation and the output gap), for the first few periods, the change in inflation is negative, while the output gap is large and negative, so the correlation between the two is positive.

### B. The Optimal Taylor and Price-Targeting Rules

Table 5 shows the Taylor rule that maximizes social welfare, as well as its impact on the variance of a few variables, and “indifference intervals” calculated as the range within which each parameter can change without changing welfare by more than one basis point (bp). Noticeably, policy optimally responds by more to inflation than in the estimated status quo. Moreover, the indifference intervals for  $\varphi_p$  are asymmetric, showing that as long as the response to inflation is sufficiently large, the exact value of  $\varphi_p$  is not very important for welfare. According to SIGE, policy should be quite sensitive to the output gap and the welfare benefits from this rule relative to the status quo would be 6 bp.

To understand better these results, note that contrary to the case at the prior parameters, eliminating policy errors has a negligible impact on variability and welfare. This is due to the small estimate for the volatility of monetary policy shocks in the US economy since 1986, and it is the reason why the welfare gains are smaller in

Table 5 than they were in Table 1. Moreover, Table 5 shows, again, that stabilization policy is very valuable in the SIGE model. Even though the estimated  $\varphi_y$  is small, setting it equal to zero produces a large increase in volatility and significantly lower welfare.

Turning to the optimal price-level standard, it is essentially inelastic. The rule performs quite well from the perspective of stabilizing the output gap and inflation, but, in terms of social welfare, it does not improve over the status quo. Because, in the estimates, price-setters are more inattentive than wage-setters, this rule is close to the one that we calculated earlier for an economy with only inattentive firms.

### C. Alternative Rules

Over the past decade, a variety of different interest rate rules have been proposed as an alternative to Taylor's suggestion. Athanasios Orphanides (2003) noted that the output gap is hard to estimate in real time and mistakes about its value can lead policy astray. An alternative interest rate rule that safeguards against this danger might respond, instead, to hours worked as the measure of real activity. Orphanides and John C. Williams (2002) and Carl E. Walsh (2003), instead, argued in favor of replacing the level of the output gap with its growth rate in the Taylor rule (a "speed limit" rule). Table 6 shows that these policy rules do quite well in terms of welfare, although this comes at the expense of a large increase in the volatility for nominal variables.

Woodford (2003b) noted that sticky-price models provide a reason for interest rate inertia as a form of policy commitment inducing firms to adjust their prices faster to shocks today. In the SIGE model, because firms can set future prices different from current prices in their plans, this motive is absent, so the welfare benefits from inertia are insignificant. Table 6 shows that responding to wage rather than price inflation, as argued in Christopher J. Erceg, Dale W. Henderson, and Andrew T. Levin (2000), leads to extremely volatile price inflation and nominal interest rates, in return for a modest reduction in the volatility of hours and the output gap. As a result, it does worse than either the employment or speed limit rules.

Table 6 also looks at modifications of the price-level targeting rule that mimic these modifications of the Taylor rule. The best performing rule is an elastic wage-level target, in which wages are allowed to rise above target in a boom. In response to a shock that leads to a positive output gap, the policymaker wants to induce a disinflation to contract the economy. However, if firms are more inattentive than workers (as in the case of the United States), then by committing to raise nominal wages in response to a shock, the policymaker ensures that real wages rise, inducing firms to cut production and stabilize real activity.

## IV. Robustness of the Conclusions

I inspect the robustness of the conclusions to the parameters in two ways: by computing robustly-optimal policy rules for the United States, and by repeating the analysis for a different but similar economy, the Euro area post-Maastricht.

TABLE 6—ALTERNATIVE POLICY RULES AT THE POSTERIOR PARAMETERS

Policy rule	Change in variance				Welfare gains	Indifference intervals	
	Inflation	Interest rate	Hours	Gap			
<i>Panel A: Interest-rate rules</i>							
Employment rule $i_t = 4.68\Delta p_t + 0.69l_t$	580.2	313.2	-2.2	-14.2	0.12	0.40, 3.11,	1.01, 7.87
Speed-limit rule $i_t = 17.72\Delta p_t + 5.37\Delta(y_t - y_t^c)$	155.1	718.0	-1.0	-22.0	0.24	4.03, 13.08,	6.82, 20
Inertial rule $i_t = 5.87\Delta p_t + 0.78(y_t - y_t^c) + 0.41i_{t-1}$	-86.6	35.3	-0.3	-12.5	0.07	0.30, 2.79,	1.30, 12.97
Wage-inflation rule $i_t = 1.01\Delta w_t + 0.52(y_t - y_t^c)$	11,207	5,127	-1.2	-3.6	0.11	1.00, 0.45,	1.01, 0.60
<i>Panel B: Price-targeting rules</i>							
Employment rule $p_t = -0.10l_t$	-95.1	661.6	-1.4	-19.3	0.04	-0.15,	-0.06
Speed limit rule $p_t = -0.07\Delta(y_t - y_t^{PO})$	-98.9	475.4	-0.5	-16.9	-0.03	-0.17,	0.01
Inertial rule $p_t = -0.06(y_t - y_t^{PO}) - 0.16p_{t-1}$	-99.6	451.6	-0.6	-17.1	-0.03	-0.15,	0.02
Wage rule $w_t = 0.19(y_t - y_t^{PO})$	-92.8	402.2	-0.7	-15.3	0.08	-0.33,	0.65

TABLE 7—ROBUSTLY OPTIMAL POLICY RULES

Policy rule	Welfare gains from status quo			Welfare gains from optimal
	Mean	95 percent set		
SIGE				
Taylor rule $i_t = 4.90\Delta p_t + 0.48(y_t - y_t^c)$	0.10	0.00	0.54	0.00
Elastic price standard $p_t = -0.11(y_t - y_t^c)$	0.01	-0.53	0.45	0.01

Notes: The first set of welfare gains is relative to the status quo policy rule. The second set is relative to the rules at the optimal parameter in Table 4. The 95 percent set shows the 2.5 and 97.5 percentile of welfare gains with the robust rules.

### A. Robustness to Parameter Uncertainty

The calculations, so far, evaluated optimal welfare at the mean parameter estimates. Splitting the parameter vector  $\theta$  into two vectors, one with the policy parameters  $\theta^p$  and another with the nonpolicy parameters  $\theta^{np}$ , and writing the unconditional expectation of social welfare as  $\mathcal{W}(\theta^p, \theta^{np})$ , the optimal policy rules chose  $\theta^p$  to maximize

$$(26) \quad \mathcal{W}(\theta^p, \int \theta^{np} dp(\theta^{np} | \mathbf{Y})),$$

where  $p(\theta^{np} | \mathbf{Y})$  was the posterior distribution.

By taking the parameters at their mean, this approach ignores the uncertainty in the estimates. One approach to take it into account is to focus, instead, on maximizing *integrated social welfare*:

$$(27) \quad \int \mathcal{W}(\boldsymbol{\theta}^p, \boldsymbol{\theta}^{np}) dp(\boldsymbol{\theta}^{np} | \mathbf{Y}).$$

Levin et al. (2006) and Rochelle M. Edge, Thomas Laubach, and Williams (2007) call the policies that maximize this criteria “robustly” optimal in the sense that they are the best after averaging over the different models that correspond to each  $\boldsymbol{\theta}^{np}$ . Christopher A. Sims (2001) defends this Bayesian model-averaging as an alternative to “min-max” analysis.

Table 7 shows the robustly-optimal Taylor rules and elastic price-level standards according to integrated welfare.<sup>18</sup> The Taylor rules are more aggressive in their response to inflation and output, and the price-level standards are more elastic.<sup>19</sup> Relative to the status quo, the robustly-optimal Taylor rule performs quite well, on average, as well as in most circumstances, since more than 95 percent of the time it leads to outcomes no worse than the current ones. Compared, instead, to the optimal Taylor rule that ignored parameter uncertainty, the benefits from taking robustness into account are small.

Turning to the elastic price-targeting rules, they are more elastic when uncertainty is taken into account, and the gains in welfare are 7 bp. However, there is a sense in which this price-level standard is not very robust. More than 5 percent of the time it leads to welfare losses of half a percentage point in consumption units.

Comparing the two types of rules more directly, the Taylor rule performs better than the elastic price standard 82 percent of the time in the United States. Moreover, while the worst scenarios under the robust policy rule lead to welfare losses of 10 bp, under the robust price-level standard, for some parameter values, the welfare losses can be as high as 90 bp. Thus, while “robustness,” in this section, was interpreted as model-averaging, a “min-max” perspective would also lead to preferring interest rate rules over price-targeting rules.

### B. *Are the Conclusions for the Euro Area Different?*

The Euro area post-Maastricht treaty (1993:Q4–2005:Q4) is the closest region in the world to the United States post-1986 in terms of size, structure of the economy, and monetary policy regime. Checking whether the policy conclusions for this area agree with those for the United States provides an alternative check on their robustness.

<sup>18</sup> To find these optima, I averaged over 10,000 draws from the posterior density to approximate the integral, and maximized over sequence of grids with jumps of size 1, 0.1, and 0.01 successively.

<sup>19</sup> Taking a min-max perspective in a sticky-price model, Giannoni (2007) finds that a concern for robustness leads to more responsive interest rate responses.



TABLE 8—POSTERIOR DISTRIBUTIONS FOR THE EURO AREA

	Mean	95% set			Mean	95% set
Preference and production				Inattentiveness		
$\psi$	2.70	1.92, 3.46		$\delta$	0.21	0.10, 0.52
$\nu$	8.16	5.94, 10.80		$\omega$	0.32	0.15, 0.93
$\gamma$	7.11	5.49, 8.34		$\lambda$	0.58	0.26, 0.79
Nonpolicy shocks				Monetary policy		
$\rho_g$	0.99	0.95, 1.00		$\varphi_p$	1.06	1.00, 1.35
$\sigma_g$	0.37	0.22, 0.62		$\varphi_y$	0.07	0.01, 0.24
$\rho_v$	0.70	0.31, 0.98		$\rho_\varepsilon$	0.51	0.27, 0.66
$\sigma_v$	0.82	0.33, 1.98		$\sigma_\varepsilon$	0.46	0.30, 0.75
$\rho_\gamma$	0.37	0.09, 0.62				
$\sigma_\gamma$	1.93	0.77, 4.12				

TABLE 9—POLICY EXERCISES IN THE EURO AREA

Policy rule	Change in variance				Welfare gains	Indifference intervals
	Inflation	Interest rate	Hours	Gap		
<i>Panel A: Optimal rules</i>						
Optimal Taylor rule $i_t = 1.18\Delta p_t + 1.25(y_t - y_t^c)$	-63.0	469.1	6.4	-51.4	0.09	1.00, 2.68 0.60, 2.29
Elastic rule $p_t = -1.25(y_t - y_t^{PO})$	-61.7	-12.8	-11.5	-15.2	0.00	-4.71, -0.47
<i>Panel B: Interest rate rules</i>						
Employment rule $i_t = 3.74\Delta p_t + 0.12l_t$	-62.9	69.1	-10.2	-16.7	0.02	-0.21, 0.60 1.39, 8.52
Speed limit rule $i_t = 1.75\Delta p_t + 0.24\Delta(y_t - y_t^c)$	-39.0	3.3	9.7	-27.5	0.06	0.11, 0.40 1.27, 3.35
Inertial rule $i_t = 1.27\Delta p_t + 1.69(y_t - y_t^c) + 0.15i_{t-1}$	-53.2	574	6.6	-53.2	0.09	0.99, 2.80 1.00, 3.37 -0.08, 0.30
Wage-inflation rule $i_t = 2.74\Delta w_t + 6.47(y_t - y_t^c)$	2,270	1,137	7.2	-8.3	-0.01	1.90, 4.36 4.50, 9.79
<i>Panel C: Price-targeting rules</i>						
Employment rule $p_t = -0.60l_t$	-66.0	112.0	-14.1	-17.9	0.00	-1.36, -0.27
Speed limit rule $p_t = -20.7\Delta(y_t - y_t^{PO})$	124.0	66.0	-18.7	2.7	0.02	-40.00, -8.11
Inertial rule $p_t = -0.55(y_t - y_t^{PO}) + 0.83p_{t-1}$	-69.0	231.6	-9.6	-21.9	0.01	-1.35, -0.28 0.31, 1.00
Wage rule $w_t = -1.46(y_t - y_t^{PO})$	-65.8	345.6	-7.0	-25.9	0.05	-3.48, -0.53

Table 8 shows the posterior parameters from performing the same estimation exercise using the Euro area data (the priors are the same as in Table 2). Most estimates are relatively similar to those for the United States, including the policy rule and the inattentiveness of European firms. The main exception is the inattentiveness of workers and consumers. In Europe, consumers update their information, on average, every 15 months, while workers do so every 9 months, and the two 95 percent

credible sets have a large overlapping range. The Euro area data is consistent with the two members of the household updating at the same time, so that consumption and wage-setting decisions are made in tandem.<sup>20</sup>

Table 9 provides the counterpart to Table 5 and Table 6 for the Euro area. Most of the conclusions on the desirability of different rules hold up for the Euro area, with three significant exceptions. First, the welfare benefits of moving policy from the status quo to optimal alternatives are usually about twice as large for the Euro area as for the United States. While I cannot be sure what drives this difference, altering the Euro area parameters one by one to match the US parameters gives a clue. Much of the difference in the size of welfare benefits seems to be due to the elasticity of labor supply  $\psi$  being half as large in the Euro area as in the United States, so that fluctuations in real variables and hours worked more generally have a higher welfare cost.

Second, the optimal Taylor rule in panel A dominates all of the interest rate rules in panel B. As with the United States though, the key feature of the optimal interest rate rules is that they respond strongly to real activity.

Third, while elastic wage targeting is also the best targeting policy for the Euro area, the sign of the coefficient is the opposite of that for the United States. This discrepancy is likely due to the difference in the relative inattentiveness of workers vis-à-vis firms in the two economies. Unlike in the United States, in the Euro area, workers are more inattentive than firms. By committing to induce a fall in nominal wages in a boom, the policymaker encourages workers to cut hours worked, stabilizing real activity.

### *C. Relation to Optimal Policy with Sticky Actions*

There is a large literature studying optimal monetary policy in new Keynesian general equilibrium models (see Galí 2008 for a selective survey). The adequate comparison group for the results in this paper is formed by studies of monetary policy in models that account for at least the dynamics of three variables, and that were estimated to fit the US data. In this group, there are three main studies, all of which use variants of the Christiano, Eichenbaum, and Evans (2005) model. This model assumes that there are costs of adjusting actions, not information, so that agents choose plans that are not only based on outdated information but must also be constant over time. At the same time, in this model, a series of indexation clauses allow actions to respond (albeit mechanically) to current news.

Schmitt-Grohé and Uribe (2007) calculate the optimal coefficients in an inertial interest rate rule that responds to inflation, wage growth, and output growth. Consistent with the results for the SIGE model, they find that interest rate inertia is modest and has a small impact on welfare, that optimal policy is quite aggressive in its response to inflation, and that it is more important to focus on wage rather than price inflation. Unlike the results for the SIGE model though, they find that it is best for interest rates to not respond to any measure of real activity.

<sup>20</sup> Curiously, Mankiw and Reis (2007) found this was also the case for the post-war US data. The discrepancy between workers and consumers' inattentiveness seems to be specific to the recent US data.

In turn, Juillard et al. (2006) find that optimal policy tends to generate quite volatile inflation and nominal interest rates, similar to what was found in this paper. However, the volatility of inflation that is tolerable with little impact on welfare is much higher here than in their work.

Finally, Levin et al. (2007) find that a simple rule that focuses solely on wage inflation performs very well and is quite robust to parameter uncertainty. The surprising robustness of optimized interest rate rules to parameter uncertainty is also true in the SIGE model, although I found that this is less true of targeting rules. The SIGE model also confirms a desire to focus on wage inflation, although taking into account real activity is very important here, but not in their work.

Combining the comparisons with these three papers, it seems that in models with sticky information, inflation is not as much of a policy concern as in sticky-actions models. In SIGE, optimal policy is more responsive to measures of real activity and more tolerant of inflation volatility. While this difference has many roots, a key one is, perhaps, that firms and workers that set time-varying plans for prices and wages can more flexibly accommodate to inflation than agents constrained to set the same price and wage over time.

## V. Policy Conclusions

Starting from a baseline classical model at the core of most DSGE monetary models, this paper introduced rigidities by assuming sticky information instead of the more popular assumption of sticky actions. The estimates show that imperfect information is pervasive across all markets, and similar between the United States and the Euro area, with the exception of American workers being more attentive than their European counterparts. Despite being so parsimonious, the model can match several empirical facts: sluggish or quick adjustments of inflation and output to monetary policy shocks depending on the policy regime, a quick adjustment of inflation to technology shocks, and the high serial correlations of inflation and output, as well as the accelerationist Phillips correlation between changes in inflation and de-trended output. The fit to the US data was promisingly good, although before the SIGE model can be used for detailed policy advice, it must incorporate features like capital accumulation and an open economy.

The paper analyzed a few counterfactual policy experiments that, while probably infeasible in the real world, could be studied within the laboratory provided by the SIGE model. These experiments led to a few concrete lessons for applied monetary policy:

- interest rates should respond more aggressively to inflation than they have;
- interest rates should respond to some measure of real activity, but the best measure may be the output gap, the level of employment, or the change in the output gap;
- the optimal targeting rules are on the wage level, but these typically perform worse than interest rate rules;

- a concern for robustness leads to more aggressive policy rules, and interest rate rules are quite robust to parameter uncertainty, while targeting rules are less so;
- relative to conventional sticky-action models, the sticky-information model puts a stronger emphasis on stabilizing real activity, with larger policy coefficients on real activity and smaller relative variance of output versus inflation.

Finally, note that the optimal policy rules typically led to gains of around 0.10 percent of steady-state consumption. In the United States in 2006, this would be worth \$9,240 millions. This may not seem like a large amount but, by comparison, recent estimates of the costs of fluctuations are only five to ten times higher.<sup>21</sup> Another relevant comparison is with the total expenses of the Federal Reserve Banks, which were \$3,264 millions in 2006. If the scope for improving monetary policy can reach gains that are almost three times as large as the budget of the central bank, this is a tempting area for policy improvement.

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<sup>21</sup> See Fernando Alvarez and Urban J. Jermann (2004) and Reis (forthcoming) for recent estimates of the costs of fluctuations.

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