Sticky Price and Sticky Information Price Setting Models: What is the Difference?*

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Abstract

Using a partial equilibrium framework, Mankiw and Reis [2002] show that a sticky information model can generate a lagged and gradual inflation response after a monetary policy shock, whereas a sticky price model cannot. Our paper demonstrates that that finding is sensitive to their model's parameterization. To determine a plausible parameterization, we specify a general equilibrium model with sticky information. In that model, we find that inflation peaks only one period after a monetary disturbance. A sensitivity analysis of our results reveals that the inflation peak is delayed by including real rigidities when the monetary policy instrument is money growth, whereas inflation peaks immediately when the policy instrument is the nominal interest rate.

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1 Introduction

Empirical studies suggest that inflation adjusts gradually after a monetary policy shock with the peak occurring several quarters later.[1] Most theoretical models, however, generate an inflation response that peaks on impact. Nelson [1998] finds that even the introduction of sticky prices does not help solve that problem. Mankiw and Reis [2002] argue that the key to generating a substantial lag in the peak inflation response is the introduction of sticky information, not sticky prices, in a model.

The premise in Mankiw and Reis [2002] is that the slow dissemination of information on macroeconomic conditions is responsible for the sluggish adjustment in inflation. In their paper, the gradual flow of information is incorporated into a partial equilibrium model via a Fischer [1977] style price setting rule.[2] That rule assumes that every firm adjusts its price each period, but the expectations of current and future economic conditions used to set that price are updated infrequently. Hence, information and not prices tends to be sticky. Mankiw and Reis [2002] show that a sticky information model, in contrast to a standard sticky price model, can generate a substantial lag in the inflation peak after a monetary disturbance. Those results lead Mankiw and Reis [2002] to conclude that sticky information should replace sticky prices in New Keynesian models of the business cycle.

This paper begins by employing Mankiw and Reis' [2002] partial equilibrium model to reproduce their finding that inflation responds with a significant lag in a sticky information model but adjusts rapidly in a sticky price model. Uncertainty about the parameterization of one of the equations in their model, however, persuades us to examine the robustness of their results. A sensitivity analysis shows that the lagged peak in inflation occurs anywhere from one to seven periods after a monetary disturbance depending on the parameterization of the model. In order to determine a plausible parameterization for their model, we integrate a sticky information rule into a dynamic stochastic general equilibrium (DSGE) model where the monetary authority follows a money growth rule as in Mankiw and Reis [2002]. In our model, inflation peaks one period after a monetary policy shock which is consistent with a different parameterization of the partial equilibrium model than the one used by Mankiw and Reis [2002]. We then conduct a second sensitivity analysis to determine whether the

[1] See Leeper, Sims, and Zha [1996] and Christiano, Eichenbaum, and Evans [1999] for an examination of this issue.

[2] Devereux and Yetman [2003] also use Fischer [1977] style pricing contracts in a similar monetary model. Koenig [1996, 1999, 2000], in contrast, examines a monetary model with Fischer [1977] style wage contracts.

addition of more real rigidities and changes to the monetary policy rule can assist our DSGE model with sticky information in producing results consistent with Mankiw and Reis [2002].[3] Our findings demonstrate that a considerable amount of real rigidities are necessary if a DSGE model with sticky information is going to generate the seven-period lag in the peak inflation rate produced in Mankiw and Reis [2002]. When the monetary instrument is the nominal interest rate instead of the money growth rate, we show that a DSGE model with sticky information, like the standard sticky price model, produces an immediate inflation peak after a monetary policy shock. Those results suggest a sticky information model can produce more plausible inflation responses than a sticky price model if the model includes important real rigidities and a money growth policy rule. The inflation behavior in the two models, however, is similar when the policy instrument is the nominal interest rate.

The rest of the paper is arranged as follows. Section 2 introduces the partial equilibrium model used by Mankiw and Reis [2002] and replicates inflation's response to a monetary policy shock with both sticky prices and sticky information. Then, a sensitivity analysis is conducted to determine the robustness of those results to different parameterizations of both models. Section 3 examines inflation's response to a monetary policy shock when a sticky information price setting rule is incorporated into a DSGE model. Inflation's response in the DSGE model is compared with its behavior in the partial equilibrium model. Section 4 presents a sensitivity analysis of inflation's response to different parameterizations of the DSGE model. Section 5 concludes.

2 Partial Equilibrium Approach

In an influential paper, Mankiw and Reis [2002] use a partial equilibrium model to show that a sticky information model can generate a gradual inflation response that peaks several quarters after a monetary policy shock, while a sticky price model produces an inflation response that peaks on impact. That result leads Mankiw and Reis [2002] to conclude that New Keynesian business cycle models should be specified routinely with a sticky information rule, as opposed to a sticky price rule. Given the potential implications of such a conclusion, we begin by examining the robustness of Mankiw and Reis' [2002] inflation responses in their sticky price and sticky information models.

[3]Following the terminology in Ball and Romer [1990], real rigidities are features that make relative prices less responsive to changes in economic activity.

2.1 The Model

The sticky price and sticky information models employed by Mankiw and Reis [2002] comprise five equations. Of those five equations, four are common to both models while only the price setting equation is unique to each model. Since the models share most of the same equations, we present one common model but specify it with a sticky price and a sticky information price setting rule.

In every period t, each firm prefers to set a price, $P^*_{t,}$, that is a function of the price level, P_t, and output, y_t:

$$\log(P^*_t/P^*) = \log(P_t/P) + \gamma \log(y_t/y), \tag{1}$$

where $\gamma > 0$ is the sensitivity of a firm's price to output and a variable without a time subscript represents a steady state value. Although (1) is not determined by solving a profit maximizing problem, a similar equation can be derived using the Dixit and Stiglitz [1977] methodology of monopolistically competitive firms. The difference between the pricing rule in Mankiw and Reis [2002] and a rule derived by solving a profit maximizing problem is that in a profit maximizing framework $P^*_{t,}$ depends on marginal cost and not output. Mankiw and Reis [2002], however, argue that output is a sufficient proxy for marginal cost because the demand pressures for additional output cause marginal cost to rise. While output and marginal cost move together over the business cycle, the relative volatility of marginal cost to output influences the similarity between those two pricing rules.[4] That distinction is important because firm pricing decisions directly influence inflation's response to a monetary policy shock. A comparison of the impact of those two pricing rules on inflation will be discussed in more detail in Section 3.

Sticky price and sticky information models differ by the method in which firms set their prices. In the sticky price model, a fraction of the firms each period can select a new price, $X_{t,0}$, while the remaining firms can only adjust their price by the steady state inflation rate. Hence, the price charged by a firm that last selected a new price j periods ago is $X_{t,j} = \pi^j X_{t-j,0}$, where π is the gross steady state inflation rate. Based on Calvo [1983], the conditional probability that a firm can pick a new price in any period is η, while the conditional probability it must adjust its price by the steady state inflation rate is $(1-\eta)$. Since price selecting opportunities are infrequent, a price changing firm sets a price equal to

[4]The positive movement between real marginal cost and output assumes that business cycle movements are caused by aggregate demand shocks.

the weighted average of its optimal prices until its next expected pricing opportunity:

$$\log(X_{t,0}/X) = \eta \sum_{j=0}^{\infty}(1-\eta)^j E_t[\log(P^*_{t+j}/(\pi^j P^*))]. \tag{2}$$

In the sticky information model, every firm can adjust its price each period but the expectations used to set that price is updated sporadically. Utilizing Calvo's [1983] model of random adjustment, each firm's conditional probability that it can adjust its expectations is η, while the remaining fraction of firms, $(1-\eta)$, must set their prices based on expectations last adjusted j periods ago. Hence, each firm sets its price, $P^*_{t,j}$, equal to its expectation of the optimal price formed j periods ago:

$$\log(X_{t,j}/X) = E_{t-j}[\log(P^*_t/P^*)]. \tag{3}$$

A common characteristic of sticky price and sticky information models is that the adjustment rate in prices or expectations, η, is constant. Thus, the fraction of firms that last adjusted their prices or expectations j periods ago is $\eta(1-\eta)^j$. The calculation of the price level, which is the average of all prices in the economy, then is identical for both models:

$$\log(P_t/P) = \eta \sum_{j=0}^{\infty}(1-\eta)^j \log(X_{t,j}/X). \tag{4}$$

To complete the model, we identify an aggregate demand equation and a monetary policy rule. A simple equation of exchange is specified for aggregate demand:

$$\log(y_t/y) + \log(P_t/P) = \log(M_t/M), \tag{5}$$

where M_t is nominal money balances and log velocity is assumed to be zero and constant.[5] The monetary authority conducts policy via a money growth rule. According to the rule, money growth follows a first-order autoregressive process:

$$\Delta \log(M_t/M) = \rho_M \Delta \log(M_{t-1}/M) + \varepsilon_{M,t}, \tag{6}$$

where $0 \leq \rho_M < 1$ and $\varepsilon_{M,t} \sim N(0, \sigma^2_M)$. Hence, a monetary policy shock permanently adjusts the money stock, but only temporarily changes the money growth rate.

[5] Mankiw and Reis [2002] also argue that M_t can be considered as a variable encompassing other factors that shift aggregate demand. Another alternative view is that the monetary authority targets the level of nominal aggregate demand. Under that view, the Mankiw and Reis [2002] model is really just examining the lag between a change in nominal aggregate demand and a change in the price level after a monetary policy shock.

2.2 Parameterizing the Model

A system of five equations log-linearized around their nonstochastic steady states characterizes the sticky price and the sticky information models. Specifically, equations (1), (2), (4), (5), and (6) describe the sticky price model's equilibrium, while equations (1), (3), (4), (5), and (6) characterize the sticky information model's equilibrium. Since the system of equations in both models are log-linearized around their nonstochastic steady state, the rational expectations solutions can be obtained easily by using the methodology of King and Watson [1998, 2002].

The parameter values chosen for both models are the same values used by Mankiw and Reis [2002]. Parameter η, which represents the conditional probability of adjustment in prices or expectations, is set to 0.25. That value is consistent with Rotemberg and Woodford's [1997] survey on the frequency of price adjustment by firms and with Carroll's [2001] estimate on the dissemination of information on inflation in the economy. The autoregressive coefficient in the monetary policy rule, ρ_M, is set to 0.5. Christiano, Eichenbaum, and Evans (CEE) [1998] find that that parameterization reasonably approximates exogenous M2 money growth. The steady state inflation rate is set to zero so that π equals 1. The results for both the sticky price and sticky information pricing rules are unchanged for positive steady state inflation rates. Finally, the sensitivity of a firm's optimal price to output, γ, is set to 0.10. Although Mankiw and Reis [2002] do not fully explain why the appropriate parameterization for γ is 0.10, they argue that a small value of γ is consistent with a considerable level of real rigidity or a significant degree of strategic complementarity. Given the uncertainty about the appropriate value of γ, we examine the sensitivity of our results to various parameterizations of γ in both the sticky price and the sticky information models.

2.3 Results

Figure 1 displays inflation's response to a 1% expansionary monetary policy shock in the sticky price and the sticky information models.[6] Our results show that inflation responds differently in the sticky price model than in the sticky information model. In the sticky price model, price adjusting firms substantially raise their prices immediately after a monetary policy shock. That is true because each firm confronts the possibility that it may not

[6] These results are identical to Mankiw and Reis' [2002] inflation response in Figure IV of their paper, except that they examine the impact of a one-standard deviation contractionary monetary policy shock.

have another price adjustment opportunity for a number of periods. Thus, inflation peaks immediately after a monetary disturbance, which is inconsistent with empirical evidence. In the sticky information model, expectations adjusting firms only modestly raise their prices immediately after a monetary policy shock, since each firm can set a new price in subsequent periods. The sluggish pricing response enables the sticky information model to produce a hump-shaped inflation response that peaks seven periods after a monetary disturbance. That result, Mankiw and Reis [2002] argue, suggests that a sticky information model is better than a sticky price model at generating a long lag between monetary policy actions and inflation.

A key factor driving the speed of price adjustment in both models is the responsiveness of a firm's price to changes in output. Specifically, the value of γ measures the response of a firm's price to an expected deviation in output from its steady state. Since uncertainty exists as to the appropriate value of γ, we examine the robustness of the results in Figure 1 to different parameterizations of γ.

Figure 2 presents inflation's response in the sticky price and the sticky information models to a 1% expansionary monetary policy shock when γ equals 0.10, 0.25, 0.50, and 1.00. As expected, larger values of γ speed up price adjustment in both models, which causes the initial inflation response to be stronger. Price adjusting firms in the sticky price model aggressively increase their prices, which results in an immediate peak in the inflation rate after a monetary disturbance, regardless of the value of γ. In contrast, the parameterization of γ in a sticky information model has a significant impact on when inflation peaks. For example, when γ is large, expectations adjusting firms set prices higher in response to the monetary induced increase in output. While the benchmark specification ($\gamma = 0.10$) of the sticky information model produces a peak inflation response seven periods after a monetary policy shock, its peak inflation response is reduced to three, two, and one periods following a monetary disturbance when γ equals 0.25, 0.50, and 1.00, respectively. Those results suggest that the ability of a sticky information model to produce a long delay in the peak inflation response depends critically on the parameterization of γ. In order to determine a plausible value for γ, we incorporate a sticky information rule into a general equilibrium model in the next section.

3 General Equilibrium Approach

This section outlines a conventional DSGE model where prices are set following a sticky information rule. We restrict our analysis to the performance of a DSGE model with sticky information for two reasons. One, the results generated from the partial equilibrium model indicate that the timing of the peak inflation response after a monetary policy shock is sensitive to the parameterization of the sticky information model, whereas inflation immediately peaks in the sticky price model regardless of its parameterization. Two, Nelson [1998] notes that most sticky price models are unable to produce a lagged and gradual inflation response after a monetary disturbance.[7] Hence, our analysis is limited to determining whether sticky information models can account for the following key business cycle fact missed by most sticky price models: the inflation rate peaks several quarters after a monetary policy shock.

3.1 The Model

The model comprises three distinct sectors: households, firms, and the monetary authority. Households are utility maximizing agents that purchase output and supply labor and capital services to firms. Firms are monopolistically competitive producers of goods that set prices according to a sticky information rule. Finally, the monetary authority conducts monetary policy via either a money growth rule or a nominal interest rate rule.

Households begin period t with initial levels of money, M_{t-1}, bonds, B_{t-1}, and capital, k_t. At the start of the period, households obtain funds from their maturing bonds, $R_{t-1}B_{t-1}$, where R_t is the gross nominal interest rate. They receive a payment of $W_t n_t + P_t q_t k_t^s$ during the period for labor, n_t, and capital services, k_t^s, supplied to firms, where W_t is the nominal wage rate, P_t is the aggregate price level, and q_t is the real rental rate of capital services. In addition, households receive a dividend payment, D_t, from firms and a transfer, T_t, from the monetary authority. Those resources are used by households to fund consumption and investment purchases, $P_t c_t$ and $P_t i_t$, and acquire bonds, M_t, and money, B_t, that will be carried over to the next period. The flow of funds is described formally by the following budget constraint:

$$M_t + B_t + P_t(c_t + i_t) = W_t n_t + P_t q_t k_t^s + D_t + T_t + M_{t-1} + R_{t-1}B_{t-1}. \qquad (7)$$

[7]Nelson [1998] finds that only Fuhrer and Moore's [1995] inflation persistence model is able to generate a lagged peak in the inflation rate after a monetary disturbance. The price setting rule in that model, however, is not based on microfoundations as are DSGE models.

Households' demand for money balances is equal to the sum of its nominal consumption and investment purchases:

$$P_t(c_t + i_t) = M_t. \tag{8}$$

Households also accumulate capital according to the following equation:

$$k_{t+1} - k_t = \phi(i_t/k_t)k_t - \delta(u_t)k_t, \tag{9}$$

where $\phi(\cdot)$ is the functional form for the capital adjustment costs, u_t is the capital utilization rate, and $\delta(\cdot)$ is the functional form for the depreciation rate. Specifically, the function $\phi(\cdot)$ represents a Hayashi [1982] style capital adjustment costs specification, where $i_t - \phi(i_t/k_t)k_t$ is the resources lost in the conversion of investment to capital. Those lost resources are increasing and convex, which implies that $\phi(\cdot)$ is an increasing and concave function in i/k ($\phi'(\cdot) > 0$, $\phi''(\cdot) < 0$). The function $\delta(\cdot)$ describes the depreciation rate as an increasing and convex function of the capital utilization rate ($\delta'(\cdot) > 0$, $\delta''(\cdot) > 0$). The supply of capital services provided by households to firms is

$$k_t^s = u_t k_t. \tag{10}$$

Therefore, households can supply additional capital services to firms by increasing their capital utilization, but it comes at the cost of a higher depreciation rate.[8]

Households are infinitely lived agents who seek to maximize their expected utility from consumption and their expected disutility from labor. The dynamic utility maximizing problem of households can be described as:

$$\max\left(E_0\left[\sum_{t=0}^{\infty}\beta^t\left(\ln(c_t - bc_{t-1}) - \theta\frac{{n_t}^{1+\zeta}}{1+\zeta}\right)\right]\right) \tag{11}$$

subject to (7), (9), and (10). In (11), the discount factor is $0 < \beta < 1$, habit formation in consumption preferences is present when $b > 0$, the weight on the disutility of labor is $\theta > 0$, and the labor supply elasticity is $1/\zeta$.

Purchases of consumption and investment goods by households make up aggregate output, y_t:

$$y_t = c_t + i_t.$$

Households' preferences for y_t is a Dixit and Stiglitz [1977] aggregate of a continuum of many goods ($y_t(z)$, $z \in [0,1]$) such that:

$$y_t = \left[\int_0^1 y_t(z)^{(\epsilon-1)/\epsilon}dz\right]^{\epsilon/(\epsilon-1)},$$

[8]Efficient capital utilization by households implies that $q_t = \delta'(u_t)$.

where $-\epsilon$ is the price elasticity of demand for $y_t(z)$. Cost minimization by households yields the following demand for product $y_t(z)$:

$$y_t(z) = \left(\frac{P_t(z)}{P_t}\right)^{-\varepsilon} y_t, \tag{12}$$

where P_t is a nonlinear price index such that:

$$P_t = \left[\int_0^1 P_t(z)^{1-\varepsilon} dz\right]^{1/(1-\varepsilon)}.$$

Firms are monopolistically competitive producers of differentiated goods. Each firm z hires labor, $n_t(z)$, and rents capital services, $k_t^s(z)$, from households to produce its output, $y_t(z)$, according to a Cobb-Douglas production function:

$$y_t(z) = k_t^s(z)^{\alpha} n_t(z)^{1-\alpha}, \tag{13}$$

where $0 < \alpha < 1$. Each period, every firm chooses a combination of $k_t^s(z)$ and $n_t(z)$ that minimizes its costs given its production function in (13), the real wage rate, and the real rental rate of capital services. That cost minimization yields the following two factor demand equations:

$$\psi_t \alpha [n_t(z)/k_t^s(z)]^{1-\alpha} = q_t, \tag{14}$$

$$\psi_t (1-\alpha)[k_t^s(z)/n_t(z)]^{\alpha} = W_t/P_t, \tag{15}$$

where ψ_t is the Lagrangian multiplier from the production function, interpreted as the real marginal cost of output. By combining (14) and (15), we see that ψ_t is identical for all firms:

$$\psi_t = \left(\frac{1}{1-\alpha}\right)^{1-\alpha} \left(\frac{1}{\alpha}\right)^{\alpha} (q_t)^{\alpha} \left(\frac{W_t}{P_t}\right)^{1-\alpha}.$$

In the monopolistically competitive goods market, each firm z must satisfy all of the demand for its product at the price, $P_t(z)$, it sets. The sticky information price setting rule followed by firms is similar to the wage contracting rule developed in Fischer [1977]. That is, each firm can change its price every period but its expectations of current and future economic conditions, which it uses to determine that price, are updated sporadically. The decision rule to determine whether or not a firm is able to adjust its expectations is based on Calvo's [1983] model of random adjustment. Specifically, the probability that a firm can adjust its expectations before it sets a new price is η, and the probability that a firm must set its new price using expectations last updated j periods ago is $(1-\eta)$.

Since firms update their information sets infrequently, the price set by a firm depends on the number of periods j since that firm last adjusted its expectations. Firm z, which last modified its expectations j periods ago, seeks to maximize its profits:

$$\max\left(E_{t-j}\left[P_t(z)y_t(z) - W_t n_t(z) - P_t q_t k_t^s(z)\right]\right)$$

subject to the firm's demand schedule, (12), and the input factor demands, (14) and (15). Therefore, the optimal price, $X_{t,j}$, for the zth firm that last adjusted its expectations j periods ago is

$$X_{t,j} = E_{t-j}\left[\frac{\varepsilon}{(\varepsilon-1)}P_t\psi_t\right]. \tag{16}$$

The monetary authority conducts monetary policy by changing either the money growth rate, $\mu_t = M_t/M_{t-1}$, or the nominal interest rate. When money is the monetary instrument, the monetary authority sets the money growth rate according to the following rule:

$$\ln(\mu_t/\mu) = \rho_\mu \ln(\mu_{t-1}/\mu) + \varepsilon_{M,t}, \tag{17}$$

where μ is the steady state value of μ_t, $0 \le \rho_\mu < 1$, and $\varepsilon_{M,t} \sim N(0, \sigma_M^2)$. Alternatively, the monetary authority sets the nominal interest rate using a variation of the rule proposed by Clarida, Gali, and Gertler [2000]:

$$\ln(R_t/R) = \omega \ln(R_{t-1}/R) + (1-\omega)\ln(R_t^*/R^*), \tag{18}$$

where R_t^* is the target nominal interest rate, R and R^* are the respective steady state values of R_t and R_t^*, and $0 \le \omega \le 1$. The target nominal interest rate then is set based on a Taylor [1993] style rule such that:

$$\ln(R_t^*/R^*) = \rho_\pi \ln(\pi_t/\pi) + \rho_Y \ln(y_t/y) + \varepsilon_{R,t}, \tag{19}$$

where $\pi_t = P_t/P_{t-1}$ is the inflation rate, π and y are the respective steady state values of π_t and y_t, and $\varepsilon_{R,t} \sim N(0, \sigma_R^2)$.

3.2 Parameterizing the Model

The households' and firms' first-order conditions, the identity equations, and the law of motion for the monetary authority's policy rule form a system of difference equations describing the model's equilibrium. Since a long-run increase in the money supply growth rate causes

P_t to grow over time, the nominal variables of M_t, B_t, W_t, D_t, T_t, and $P_t(z)$ are divided by P_t to induce stationarity. That transformation in the absence of stochastic shocks allows the model to converge to a steady state equilibrium. By log-linearizing the system around its steady state, the rational expectations solution for the model can be solved using the methodology of King and Watson [1998, 2002].

The parameter values employed in the model are consistent with those used in the literature. In the household sector, the discount factor, β, is set to 0.99, while the preference parameter θ is set so that the nonstochastic steady state labor supply, n, is 0.2. Christiano and Eichenbaum [1992] estimate that labor supply elasticity, $1/\zeta$, is 5.0, so ζ is set to 0.2. Initially, households do not exhibit habit formation in consumption preferences ($b = 0$) but that assumption is lifted in Section 4. It is not necessary to specify explicit functional forms for the capital adjustment costs, $\phi(\cdot)$, and the depreciation rate, $\delta(\cdot)$, since the model is linearized around its steady state. Instead, we identify certain values for the average, marginal, and second-derivative values of $\phi(\cdot)$, $\delta(\cdot)$, and u_t. The average and marginal capital adjustment costs around their steady state are assumed to be zero ($\phi(\cdot) = i/k$ and $\phi'(\cdot) = 1$), while the elasticity of the investment-capital ratio to Tobin's q, $\chi = [-(i/k)\varphi''(\cdot)/\varphi'(\cdot)]^{-1}$, is set to 1.[9] As for $\delta(\cdot)$, the steady state depreciation rate, δ, is assumed to be 0.025, which implies an annual depreciation rate of 10%, while the steady state capital utilization rate, u, is set to 0.82. Elasticity of the marginal depreciation rate to the capital utilization rate, $\xi = [u \cdot \delta''(\cdot)/\delta'(\cdot)]$, initially is set to ∞. That value implies that the capital utilization rate is fixed, as is the case in most DSGE models. The impact of variable capital utilization is examined in Section 4.

In the firm sector, capital's share of output, α, is 0.33. The elasticity of demand, ϵ, is 6, which implies an average mark-up of price over marginal cost of 20%. That parameterization is consistent with Rotemberg and Woodford's [1992] survey of empirical studies. The conditional probability that a firm can adjust its expectations, η, is set to 0.25. That value is the same parameterization used by Mankiw and Reis [2002] and is consistent with Carroll's [2001] estimates on the dissemination of information about inflation in the economy. As for the monetary policy rule, we initially assume that the monetary authority adheres to the money supply growth rule specified in (17). Following CEE's [1998] analysis of the behavior of exogenous M2 money growth, the autoregressive coefficient in the policy rule, ρ_μ, equals 0.5. The impact of a nominal interest rate rule on the performance of our model is considered

[9]Our parameterization of $\chi = 1$ is consistent with Chirinko's [1993] empirical examination of investment functions.

in detail in Section 4. Finally, the steady state gross money growth rate is set to 1.01, which is consistent with a 4% annual inflation rate.

3.3 Results

Figure 3 presents the impulse responses for inflation, marginal cost, and output to a 1% expansionary monetary policy shock in a DSGE model with sticky information. Unlike in Mankiw and Reis' [2002] partial equilibrium model with sticky information, the peak inflation response in our model occurs only one quarter after the monetary policy shock. Therefore, the inflation response in a DSGE model with sticky information resembles inflation's behavior in most sticky price models, rather than Mankiw and Reis' [2002] sticky information model. The result indicates that Mankiw and Reis' [2002] finding of a lagged peak in inflation after a monetary policy shock is not robust when sticky information is incorporated into a general equilibrium model.

The inconsistency between the inflation responses in the partial and the general equilibrium models with sticky information can be traced to the firms' pricing rules in each model. In the partial equilibrium model, substitution of (1) into (3) enables us to specify the price set by a firm that last adjusted its expectations j periods ago, $X_{t,j}$, as a function of the price level and output:

$$\log(X_{t,j}/X) = E_{t-j}[\log(P_t/P) + \gamma \log(y_t/y)], \tag{20}$$

where $\gamma = 0.10$ is the sensitivity of a firm's price to deviations in output. Output is used as a proxy for real marginal cost, since the partial equilibrium model does not include any measure of firm costs.

In the general equilibrium model, the log-linearization of the price setting rule in (16) indicates that $X_{t,j}$ is a function of the price level and real marginal cost:

$$\log(X_{t,j}/X) = E_{t-j}[\log(P_t/P) + \log(\psi_t/\psi)]. \tag{21}$$

The price setting rules for the partial and the general equilibrium models, (20) and (21), are identical when:

$$E_{t-j}[\gamma \log(y_t/y)] = E_{t-j}[\log(\psi_t/\psi)].$$

Price setting firms that adjusted their expectations since the last monetary policy shock have perfect expectations of y_t and ψ_t. Those firms set the same prices in both models only if $\gamma \log(y_t/y) = \log(\psi_t/\psi)$. Dotsey and King [2006] derive an explicit equation for γ

in a general equilibrium framework with fixed capital. The derivation for γ is drastically complicated by the presence of capital investment, so we instead implicitly calculate a value for γ. Our impulse responses from the general equilibrium model in Figure 3 show that the magnitude of marginal cost's response, $\log(\psi_t/\psi)$, to a monetary policy shock exceeds that of output, $\log(y_t/y)$. The result suggests that the optimal parameterization of γ in the partial equilibrium model is greater than 1.00.[10] Recall, in Figure 2 when $\gamma = 1.00$, inflation peaks one period after the monetary policy shock, which is identical to inflation's behavior in the general equilibrium model. Thus, the partial equilibrium model with sticky information fails to generate a long lag between monetary policy actions and the peak inflation response when γ is set to a value implied by a simple general equilibrium model.

4 Robustness of the General Equilibrium Results

The response of inflation to a monetary policy shock depends on current and future pricing decisions. In a DSGE model with sticky information, those pricing decisions are influenced by real rigidities (i.e., factors that affect the elasticity of marginal cost with respect to output) and the conduct of monetary policy. Real rigidities influence firm pricing decisions and as a result, inflation dynamics by either enhancing or dampening marginal cost's response to a monetary policy shock. Persistent expansionary monetary policy also impacts inflation dynamics by persuading firms to set higher prices in the future. Since those features can influence the ability of a DSGE model with sticky information to generate a lagged and gradual inflation response, this section analyzes the robustness of the results in Section 3 to various parameterizations of our sticky information model. We analyze the impact of real rigidities such as variable capital utilization, infinite labor supply elasticity, capital adjustment costs, and habit persistence in consumption. The effect of increased money growth persistence on the behavior of inflation also is investigated. Finally, we examine inflation's response in our DSGE model when the monetary authority follows a nominal interest rate rule instead of a money growth rule.

[10] Using a DSGE model with sticky prices, Chari, Kehoe, and McGrattan [2000] also find that γ is above 1.00.

4.1 Real Rigidities

Our benchmark sticky information model is modified easily to incorporate various real rigidities. We begin by examining individually the impact of variable capital utilization, infinite labor supply elasticity, capital adjustment costs, and habit persistence in consumption on inflation's response after a monetary disturbance. An important interaction between capital adjustment costs and habit persistence in consumption that affects inflation's response is then observed. Finally, the ideal sticky information model is specified with all of the real features that generate the slowest response in inflation, so that the maximum lag in peak inflation can be determined. Figure 4 illustrates the impact of those features on inflation's response after a 1% expansionary monetary policy shock.

CEE [2005] and Dotsey and King [2006] note that variability in capital utilization reduces price movements after a monetary policy shock when prices are sticky. The top left graph of Figure 4 reveals that variable capital utilization (i.e., $\xi = 1$) also slows inflation's response in a sticky information model.[11] In particular, the ability to intensify capital utilization gives firms another way to raise output and limit price increases in the short run. While an increase in capital utilization raises the marginal depreciation rate, the corresponding rise in marginal cost is less pronounced than when firms are unable to change their capital utilization rate. As a result, firms dampen their price increases which causes a smaller rise in inflation.

Price movements after a monetary disturbance also can be eased by incorporating infinite labor supply elasticity into our model. That result is illustrated by the top right graph of Figure 4. To understand how that assumption impacts marginal cost and inflation, we revisit the households' utility maximization problem in (11). Combining the first-order conditions for c_t and n_t from (11) and log-linearizing the resulting efficiency condition yields the following relationship between labor, consumption, and the real wage:

$$\zeta \log(n_t/n) + \log(c_t/c) = \log(W_t/W) - \log(P_t/P),$$

where $(1/\zeta)$ is the labor supply elasticity.[12] Accordingly, the upward pressure on the real wage and marginal cost caused by an expansionary monetary policy shock is minimized when

[11] This calibration of the elasticity of the marginal depreciation rate with respect to the utilization rate, $\xi = [u \cdot \delta''(\cdot)/\delta'(\cdot)]$, is consistent with estimates by Basu and Kimball [1997].

[12] The assumption of habit persistence in consumption slightly modifies this log-linearized efficiency condition, but that change does not affect the response of the real wage to movements in labor supply.

the labor supply elasticity is infinite (i.e., $\zeta = 0$). That sluggish response in marginal cost then constrains the rise in prices and inflation.

Capital adjustment costs are another factor that influences inflation dynamics. The left graph of the middle row of Figure 4 shows that inflation responds slower to an expansionary monetary disturbance when capital adjustment costs are eliminated from our benchmark model (i.e., $\chi = \infty$). Capital adjustment costs dampen investment's response by imposing a cost on the conversion of investment to capital. Those costs also push down the real interest rate which stimulates consumption. The acceleration in consumption, however, only partially offsets the slowdown in investment, so output's response is more restrained. That sluggishness in output reduces the rise in money demand which forces the price level to increase more to clear the money market. Our result differs from models, such as CEE [2005], where money demand depends on consumption as opposed to output. In those models, higher consumption caused by capital adjustment costs raises money demand which slows down price adjustment.

An additional feature that impacts inflation's response to a monetary policy shock is habit persistence in consumption. The right graph of the middle row of Figure 4 reveals that inflation initially rises more in the model with habit persistence ($b = 0.6$).[13] Households that exhibit habit persistence in consumption prefer to adjust slowly their consumption, which limits its increase after a monetary disturbance. That sluggishness dampens the rise in output. As a result, money demand increases less and the price level must rise more to clear the money market. Our finding is reversed if money demand is very elastic to nominal interest rate changes. Specifically, habit persistence in consumption puts downward pressure on both the nominal and real interest rates after a monetary policy shock, which pushes up money demand. If the positive influence of the nominal interest rate outweighs the negative influence of output, then money demand will rise more following an expansionary monetary disturbance. Therefore, the upward pressure on the price level is dampened in a model with habit persistence.[14]

The impact of habit persistence on inflation's response to a monetary policy shock depends on whether or not there are capital adjustment costs. The bottom left graph of Figure 4 reveals that in a model without capital adjustment costs the introduction of habit persistence has no effect on inflation's behavior. (Note: The impulse response for the model

[13]Our calibrated value of 0.6 for the habit persistence parameter, b, is consistent with estimates in CEE [2005].

[14]CEE [2005] generate that result in their model.

"with habit persistence" overlays the impulse response for the model "without habit persistence.") That result is caused by the interaction between capital adjustment costs and habit persistence. In a sticky information model, an expansionary monetary policy shock essentially creates a temporary rise in real wealth. Since households desire a fairly constant consumption path, they prefer to save most of their increased wealth as capital. Without capital adjustment costs, the conversion of investment to capital is costless, so investment spikes while consumption barely adjusts. The fact that consumption hardly changes leads to a smooth household consumption path without habit persistence. Thus, the moderation in consumption caused by introducing habit persistence is so small in the absence of capital adjustment costs that its introduction has virtually no effect on the economy.

We denote the ideal sticky information specification as the model that produces the longest lag in the peak inflation rate following a monetary disturbance. For our paper, that model includes variable capital utilization, infinite labor supply elasticity, no capital adjustment costs, and no habit persistence. The bottom right graph of Figure 4 compares inflation's response to an expansionary monetary policy shock in our benchmark and ideal models. Introducing those real rigidities into our sticky information specification increases the lag inflation peak from only one period in the benchmark model to three periods in the ideal model. The ideal model's response, however, is still substantially less than the seven-period lagged inflation peak produced in Mankiw and Reis' [2002] sticky information model and the approximate ten-period lag generated in CEE's [2005] sticky price and sticky wage model. To generate additional lags in peak inflation, a DSGE model with sticky information also should include features, such as decreasing elasticity of demand for goods and the existence of intermediate inputs, that further reduce the elasticity of marginal cost with respect to output. Therefore, we conclude that numerous real rigidities are necessary if a sticky information model is going to generate a substantial lag in the peak inflation response after a money growth shock. Note that our result is consistent with Ball and Romer's [1990] finding that a combination of real and nominal rigidities are needed to produce substantial effects from nominal rigidities in New Keynesian models.

An additional feature that has assisted sticky information models in generating a lagged inflation response is the assumption that firms draw labor inputs from firm specific labor markets instead of a single common labor market. Using a DSGE framework similar to Woodford [2003], Trabandt [2005] shows that a sticky information model with firm specific labor markets can generate the substantial lagged peak in inflation produced in Mankiw and Reis [2002]. His specification of firm specific labor markets, however, assumes firms are price setters and not price takers in their respective labor markets. Specifically, a higher firm price causes the firm's product demand and labor demand to fall, which reduces its marginal cost. The lower marginal cost encourages the firm to dampen its price increase, which assists the model in producing a lagged peak in inflation. Dotsey and King [2003] eliminate that price setting behavior in firm specific labor markets by assuming firms pool their labor supply risks, so that each firm pays the average aggregate marginal cost, instead of their individual firm marginal cost. If labor supply elasticity is greater than one, then a model with that style of firm specific labor markets has a lower elasticity of marginal cost with respect to output than a model with a common labor market. When the labor supply elasticity is infinity, the elasticity of marginal cost with respect to output is minimized and identical in both models with firm specific labor markets and models with a common labor market. Therefore, if we assume firms are price takers in the labor market, then a model with a common labor market and an infinite labor supply elasticity generates a lagged peak in inflation that is as large or larger than a model with firm specific labor markets.

4.2 Money Growth Persistence

The degree of money growth persistence in the monetary policy rule is another factor that influences the timing of the peak in inflation after a monetary disturbance. When firms set prices according to a sticky information rule, only the current money supply affects the current period price set by an expectations adjusting firm. As a result, the amount of money growth persistence does not initially influence the inflation rate. Higher money growth persistence and consequently, a larger money stock does in subsequent periods, however, put upward pressure on the prices set by firms that have adjusted their expectations since the monetary disturbance. Thus, the inflation rate is higher in subsequent periods when the increase in the money growth rate is more persistent. That result implies that higher money growth persistence can lead to a longer lag in the peak inflation response following a monetary disturbance.

Standard sticky price models, such as CEE [2005], respond differently than sticky information models to changes in the degree of money growth persistence. Price setting firms in a sticky price model choose a price that is a positive function of current and expected future price levels. Higher degrees of money growth persistence raise expected future price levels. Sticky price firms, unlike sticky information firms, respond to greater money growth persistence by setting prices higher immediately following a monetary policy shock. As a result, a sticky price model's initial inflation response is greater and the time between a monetary disturbance and the peak inflation response can be shorter than in a sticky information model.

Figure 5 examines the impact of a 1% positive money growth shock on inflation in four sticky information models. The baseline model has fixed capital utilization, finite labor supply elasticity, capital adjustment costs, and no habit persistence. Our second model contains variable capital utilization, finite labor supply elasticity, capital adjustment costs, and habit persistence and is closest in structure to CEE [2005].[15] The third model is identical to the second model, except that it assumes infinite labor supply elasticity. Our ideal model has variable capital utilization, infinite labor supply elasticity, no capital adjustment costs, and habit persistence.[16] The inflation response for each model is examined when $\rho_\mu = 0.50$, 0.80, and 0.95. Those values are selected because $\rho_\mu = 0.50$ is the benchmark parameterization, $\rho_\mu = 0.80$ is one of the largest values estimated for ρ_μ in the literature, and $\rho_\mu = 0.95$ is an unrealistically high value for ρ_μ that provides an upper bound on the impact of money growth persistence.[17]

Our results show that raising the amount of money growth persistence in the monetary policy rule increases the lag in the peak inflation response. For the first three models, increasing the value of ρ_μ from 0.50 to 0.80 only changes the lagged inflation peak from zero or one period after a monetary policy shock to one or two periods. It is only when the level of money growth persistence is at an unrealistically high level of $\rho_\mu = 0.95$ that those same models generate a modest three to four period lag in the peak inflation response. In the ideal model, a rise in the value of ρ_μ from 0.50 to 0.80 shifts the peak inflation response from three to five periods following a monetary disturbance. That model also can generate the seven-period inflation lag produced in Mankiw and Reis' [2002] partial equilibrium model, but to do so requires an implausibly high value of $\rho_\mu = 0.95$.

[15] A key difference between the models is that CEE [2005] contains nominal labor market frictions while our model does not.

[16] This model includes habit persistence because it allows for an easy comparison with the third model and without capital adjustment costs, the inclusion of habit persistence has virtually no effect on inflation dynamics.

[17] Using the monetary base as the measure of money, Christiano [1991] estimates $\rho_\mu = 0.80$ over the sample period 1952:Q2-1984:Q1. Christiano [1991] acknowledges that the high value of ρ_μ is being driven by the strong upward trend in the monetary base over the 1950's and 1960's.

4.3 Nominal Interest Rate Rule

A number of researchers contend that monetary policy is represented better by a nominal interest rate rule than a money growth rule. Bernanke and Blinder [1992], using a vector autogression model, find that a short-term nominal interest rate is the best indicator of monetary policy. Goodfriend [1993] argues that historically the principle tool of the Federal Reserve has been a short-term nominal interest rate. Strongin [1995] and Bernanke and Mihov [1998] claim that money growth rates often are corrupted by the accommodation of non-policy shocks, such as money demand shocks, by the Federal Reserve. Given those arguments, we examine inflation's response to a monetary policy shock in our DSGE model with sticky information when the monetary authority follows a nominal interest rate rule.

We assume that the monetary authority now adheres to the nominal interest rate rule specified in (18) and (19). Following Taylor [1993], the parameter values measuring the responsiveness of the nominal interest rate to output, ρ_y, and inflation, ρ_π, are set to 0.5 and 1.5, respectively.[18] Uncertainty, however, exists about the appropriate value of the coefficient on the lagged interest rate, ω. We know that as the value of ω increases, monetary policy becomes more persistent, which results in a larger long-run change in prices. Hence, inflation's response to a monetary disturbance is examined for a range of values of ω in our sticky information model.

Figure 6 examines the impact of a 1% expansionary nominal interest rate shock on inflation in the following four models: a fixed capital utilization, finite labor supply elasticity, and capital adjustment costs, and no habit persistence model; a variable capital utilization, finite labor supply elasticity, capital adjustment costs, and habit persistence model; a variable capital utilization, infinite labor supply elasticity, capital adjustment costs, and habit persistence model; and a variable capital utilization, infinite labor supply elasticity, no capital adjustment costs, and habit persistence model. The inflation response for each model is analyzed when $\omega = 0.00$, 0.50, and 0.95. Those values are chosen because $\omega = 0.00$ is consistent with Taylor's [1993] nominal interest rate rule, $\omega = 0.50$ is in the range of values for ω estimated in the literature, and $\omega = 0.95$ is an upper bound on the persistence of the nominal interest rate. Our results show that inflation peaks immediately after the monetary policy shock regardless of the model or the value of ω.

The absence of any lagged inflation peak in the model with a nominal interest rate

[18] Any plausible calibration of ρ_y does not change our results.

rule clearly differs from sticky information models, such as Mankiw and Reis [2002], where money is the monetary instrument. Under a nominal interest rate rule, monetary policy's endogenous response to the inflation rate reduces the persistence of money growth changes after a monetary policy shock. That lack of persistence dampens future price increases which causes an immediate peak in inflation. CEE [2005] also examine the impact of specifying monetary policy via a Taylor [1983] style nominal interest rate rule. Unlike our sticky information model, CEE's [2005] sticky price and sticky wage model produces comparable inflation responses under both a nominal interest rate rule and a money growth rule. That result suggests that sticky information models may have to include nominal wage frictions, such as Koenig's [1996, 1999, 2000] sticky information wages, in order to generate similar inflation dynamics under both monetary policy rules. Although further investigation is needed on the impact of nominal interest rate rules, our results indicate that a DSGE model with sticky information prices, like the standard sticky price model, generates an immediate peak in inflation when the monetary authority follows a nominal interest rate rule.

5 Conclusion

Most monetary models, including those with sticky prices, are unable to produce a lagged and gradual response in the inflation rate after a monetary policy shock. In a recent paper, Mankiw and Reis [2002] contend that inflation's response to a monetary policy shock is sluggish because information on macroeconomic conditions disseminates slowly through the economy. To account for the informational problem, Mankiw and Reis [2002] specify a Fischer [1977] style price-setting rule (sticky information) in their model. That rule permits firms to set their prices every period but adjust their expectations used in setting those prices infrequently. Based on the results from a partial equilibrium model, Mankiw and Reis [2002] conclude that New Keynesian models should be specified routinely with sticky information rather than sticky prices.

This paper analyzes inflation's response to a monetary policy shock in both Mankiw and Reis' [2002] partial equilibrium model with sticky information and in a DSGE model with sticky information. Our results show that the finding of a substantial lag between a monetary policy action and the subsequent inflation peak in Mankiw and Reis' [2002] sticky information model is sensitive to the parameterization of the optimal price equation. Under some parameterizations of that equation, the peak inflation response occurs only one period after the monetary disturbance. That immediate rise in inflation is consistent with findings from our DSGE model with sticky information, where the peak inflation response occurs in the period immediately following the monetary policy shock. A sensitivity analysis of our DSGE model reveals that the peak inflation response can be delayed by introducing a number of real rigidities into the model when money is the monetary instrument. That sensitivity analysis, however, demonstrates that inflation peaks immediately after a monetary policy shock when the nominal interest rate is the monetary instrument.

Our results enable us to examine the differences between sticky price models and sticky information models of price setting. In sticky price models, inflation peaks immediately following a monetary policy shock regardless of whether money or the nominal interest rate is the instrument of monetary policy. In our sticky information model, inflation also peaks immediately when the nominal interest rate is the target of monetary policy, but can be delayed when money is the monetary instrument by introducing a number of real rigidities into the model. Therefore, we conclude that the differences between inflation behavior in sticky price and sticky information models depend critically on the instrument of monetary policy and on the presence of significant real rigidities.

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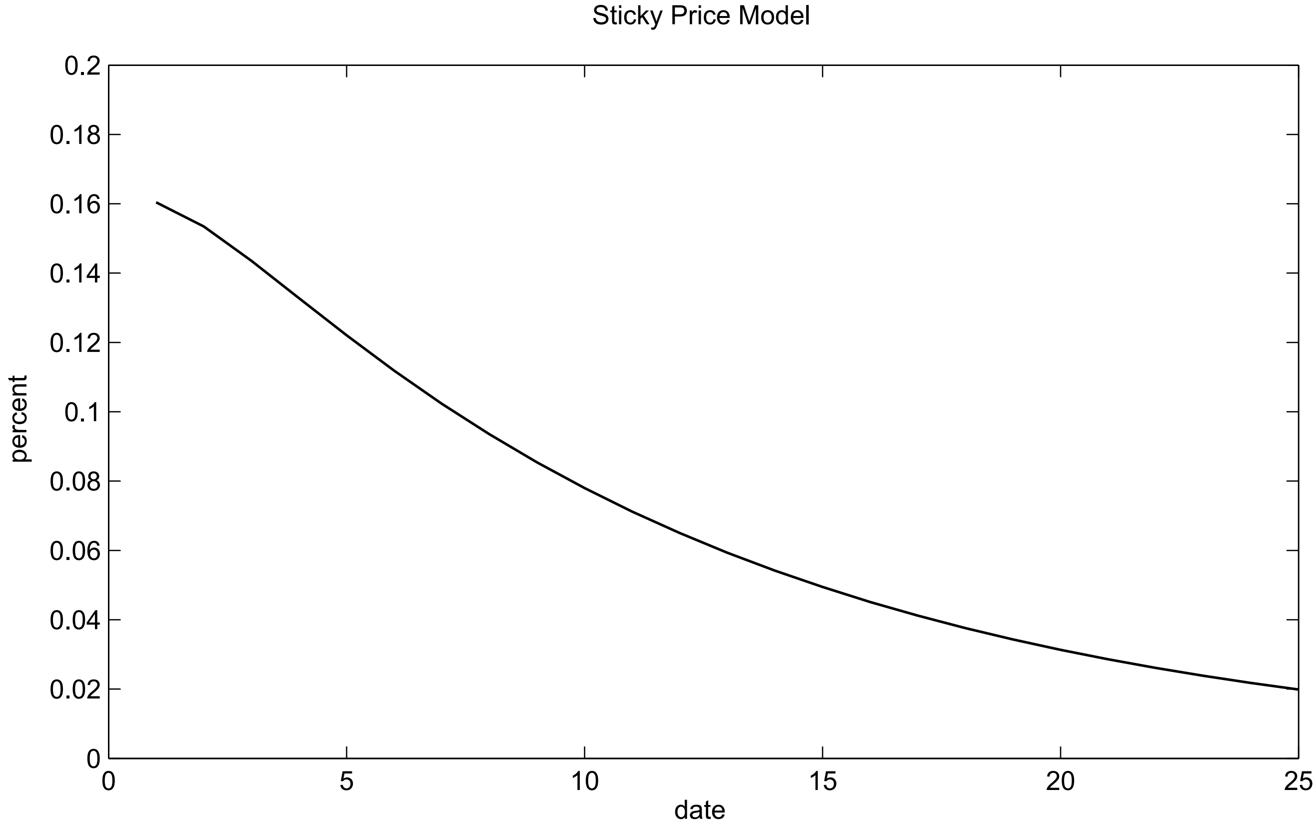
Figure 1: Inflation`s Response in a Partial Equilibrium Model



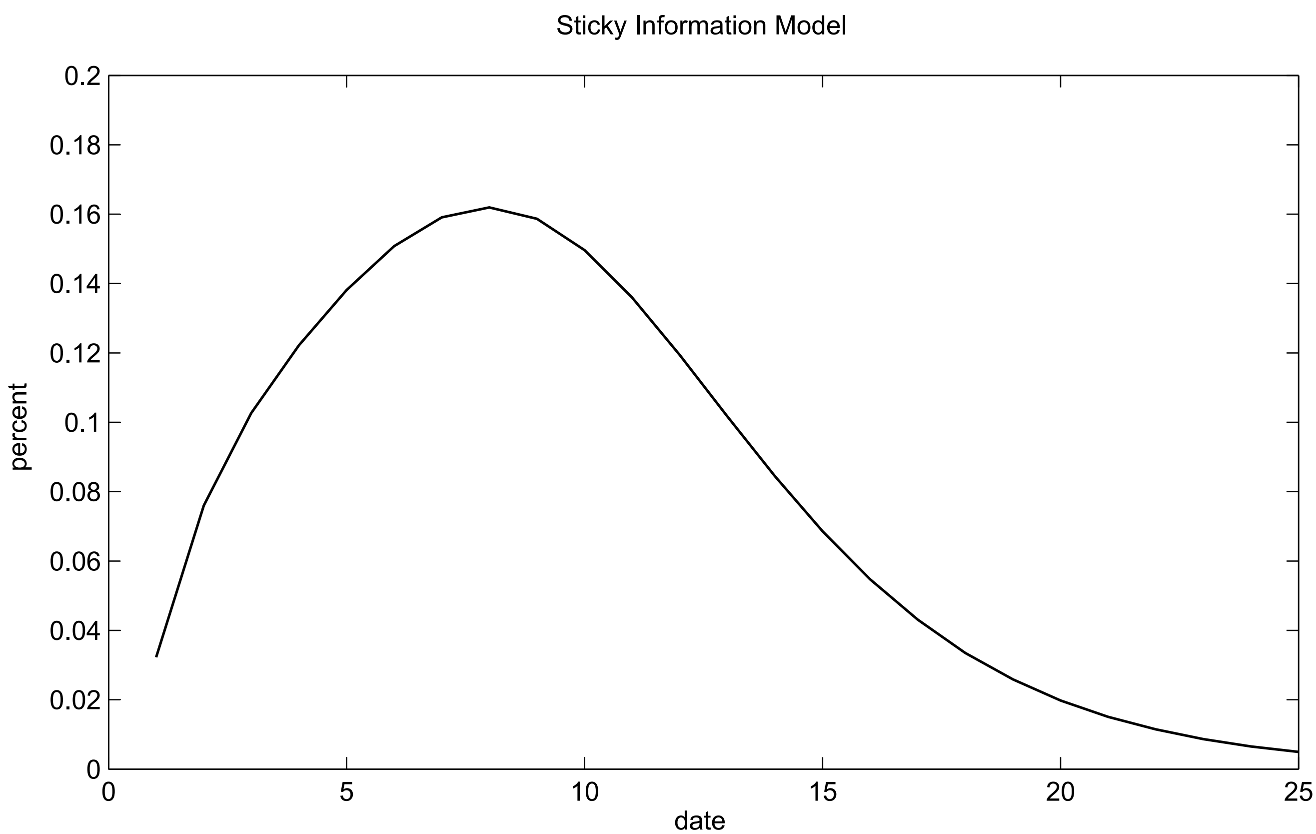
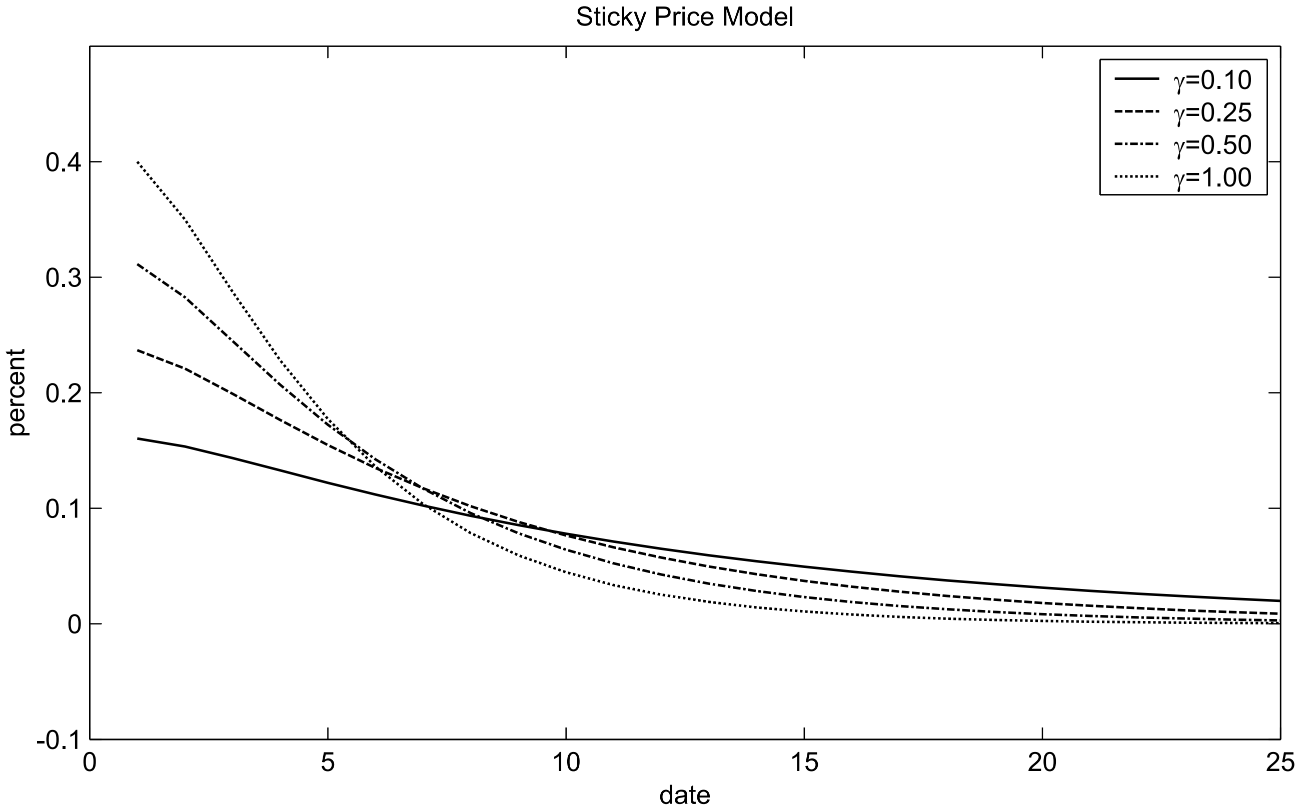


Figure 2: Inflation`s Response in a Partial Equilibrium Model: A Sensitivity Analysis



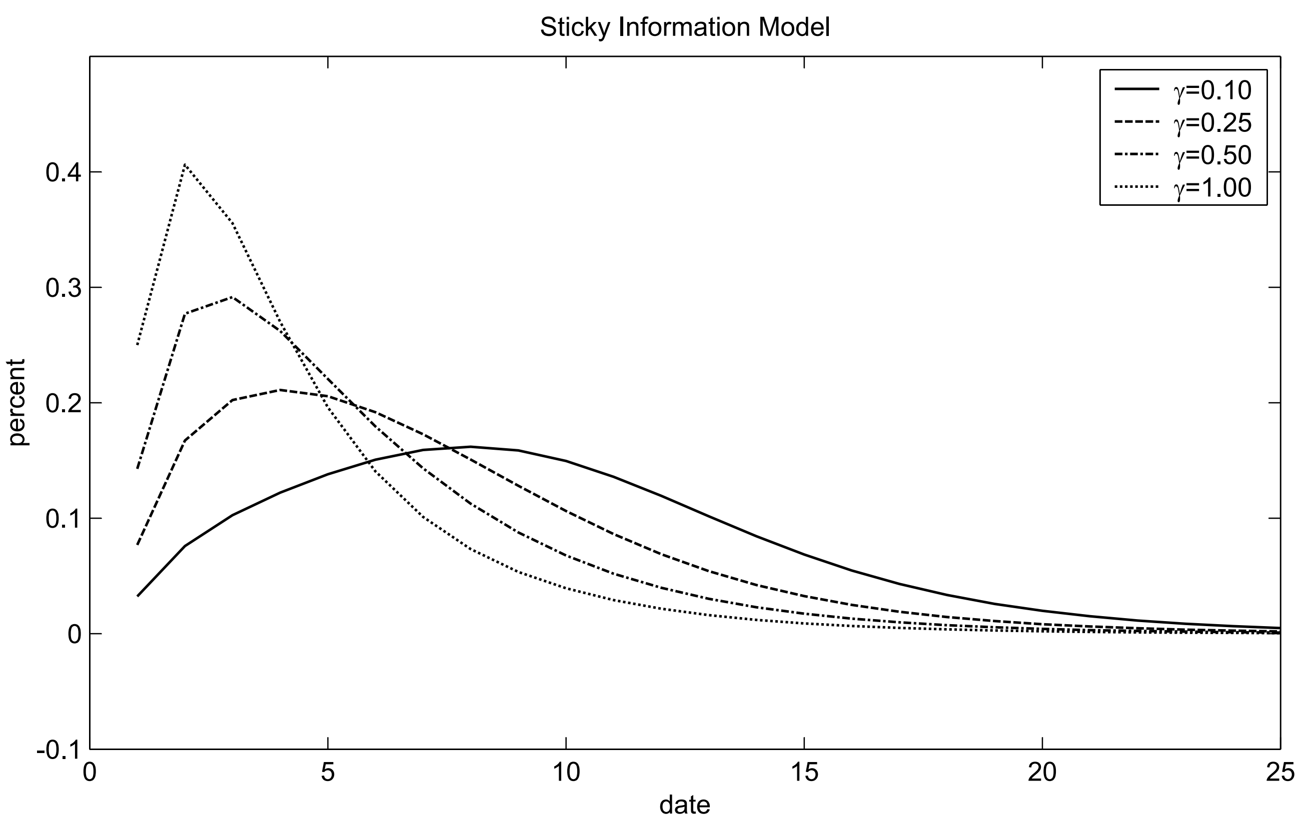
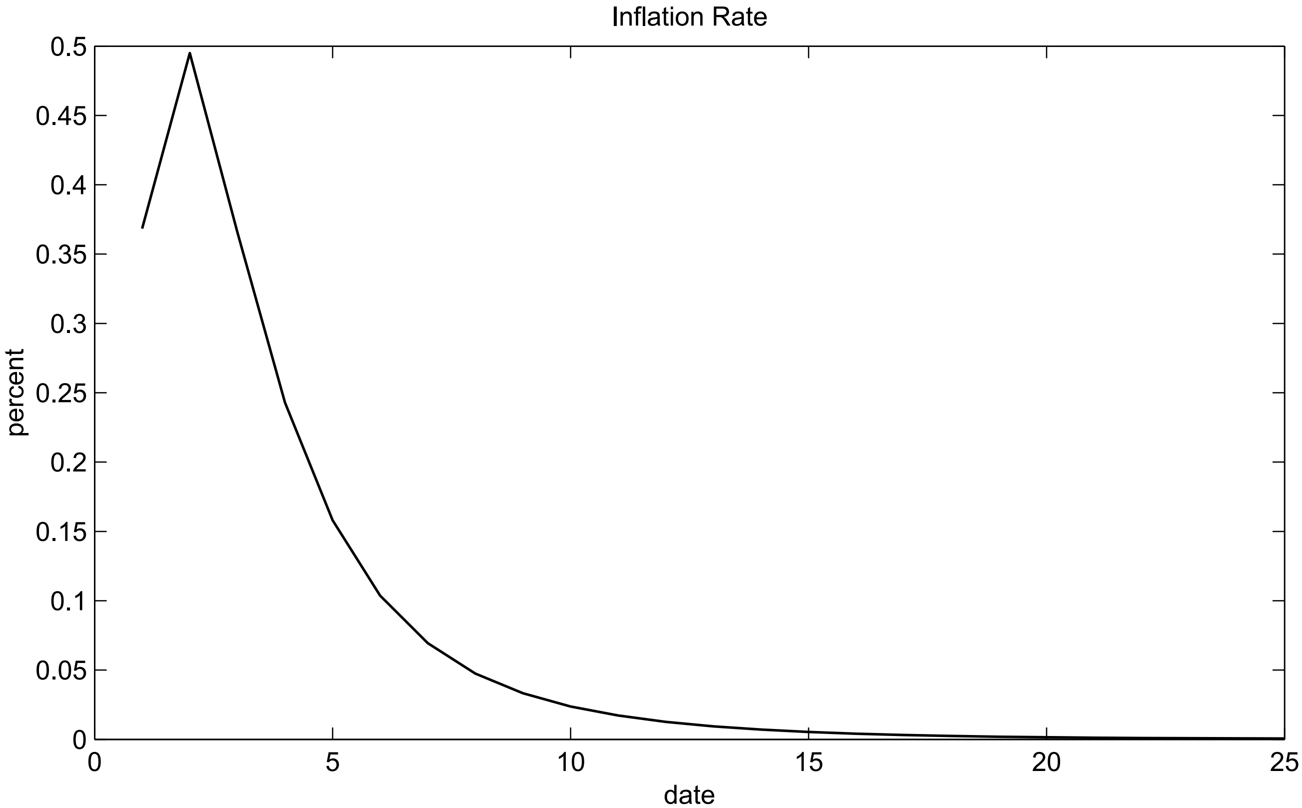


Figure 3: Inflation's, Marginal Cost's, and Output's Responses in a General Equilibrium Model



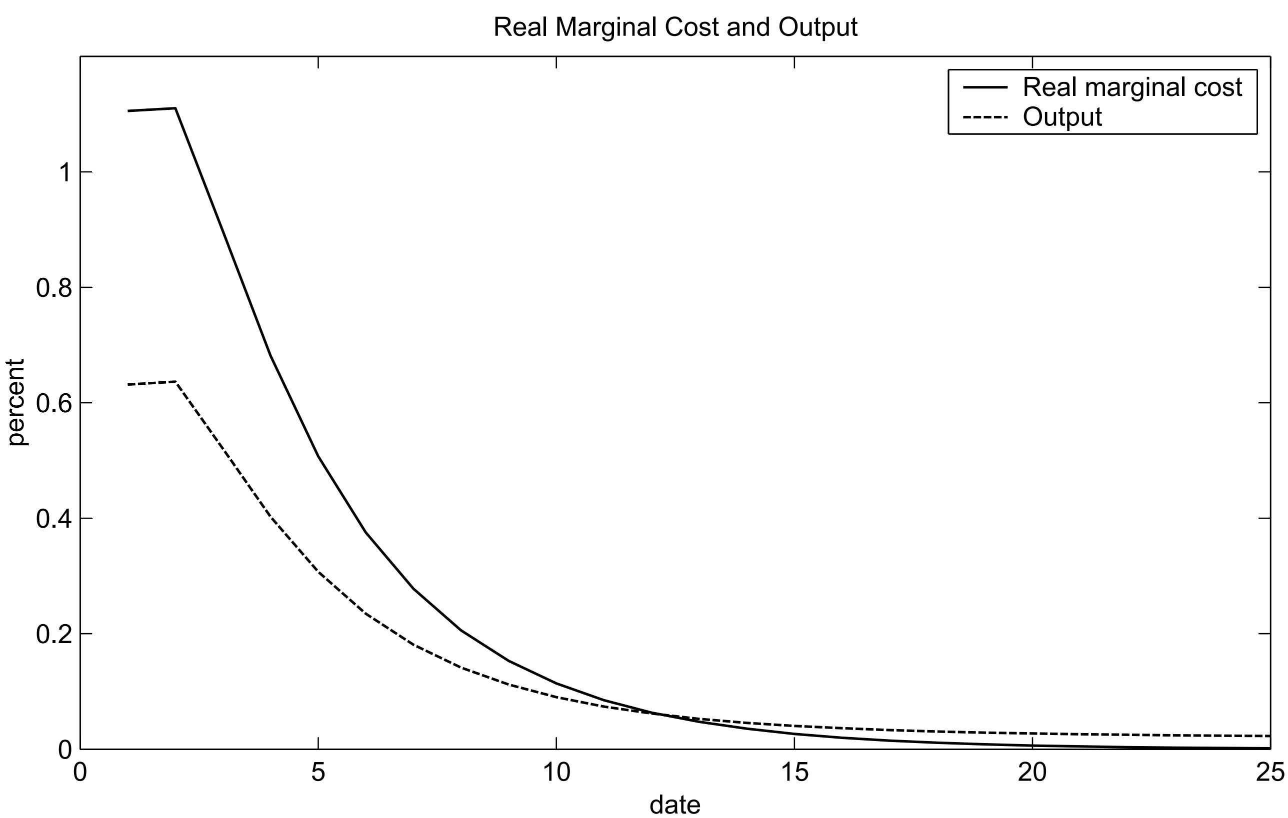


Figure 4: Inflation`s Response: The Impact of Real Rigidities

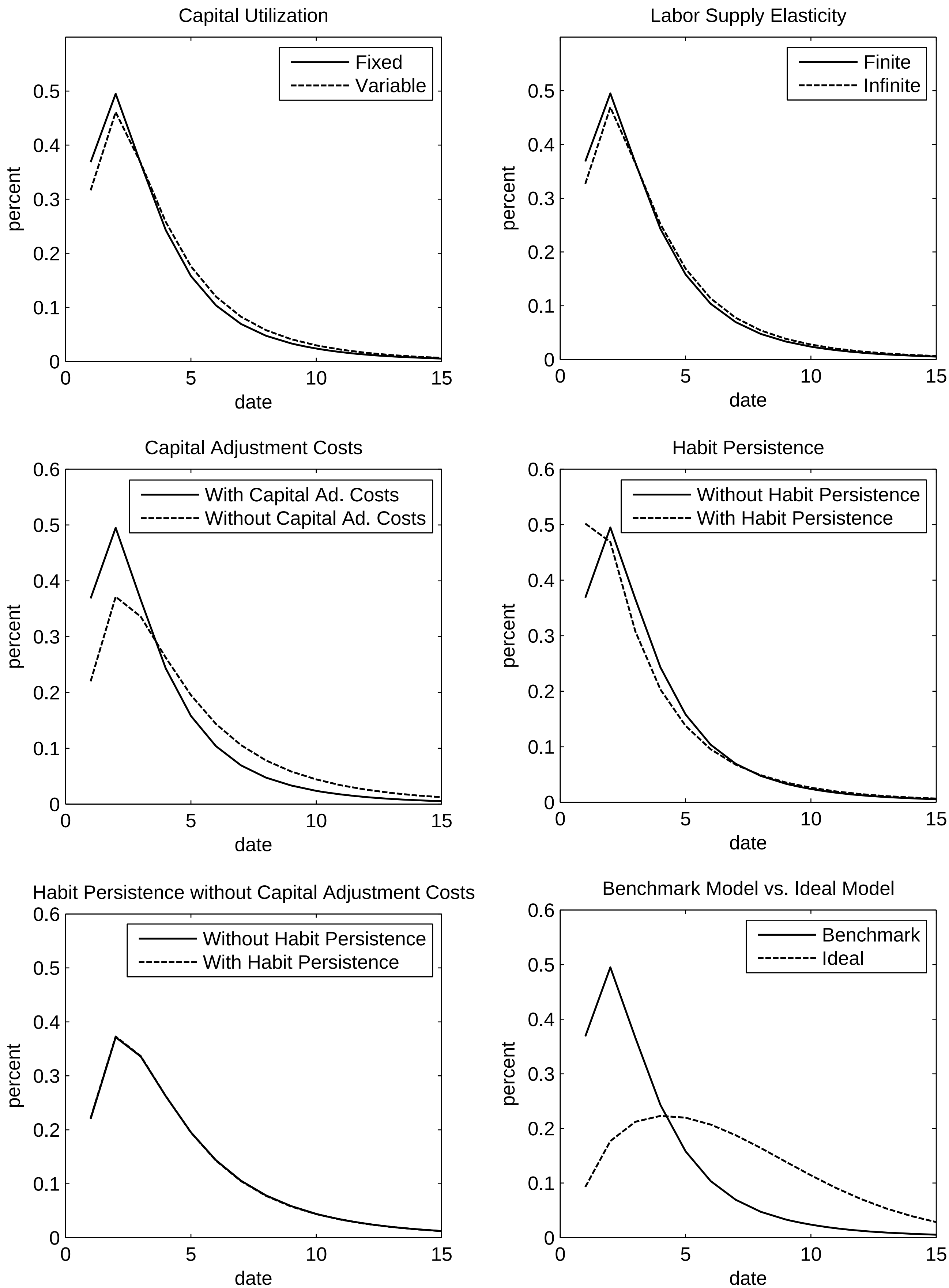


Figure 5: Inflation`s Response: The Impact of Money Growth Persistence

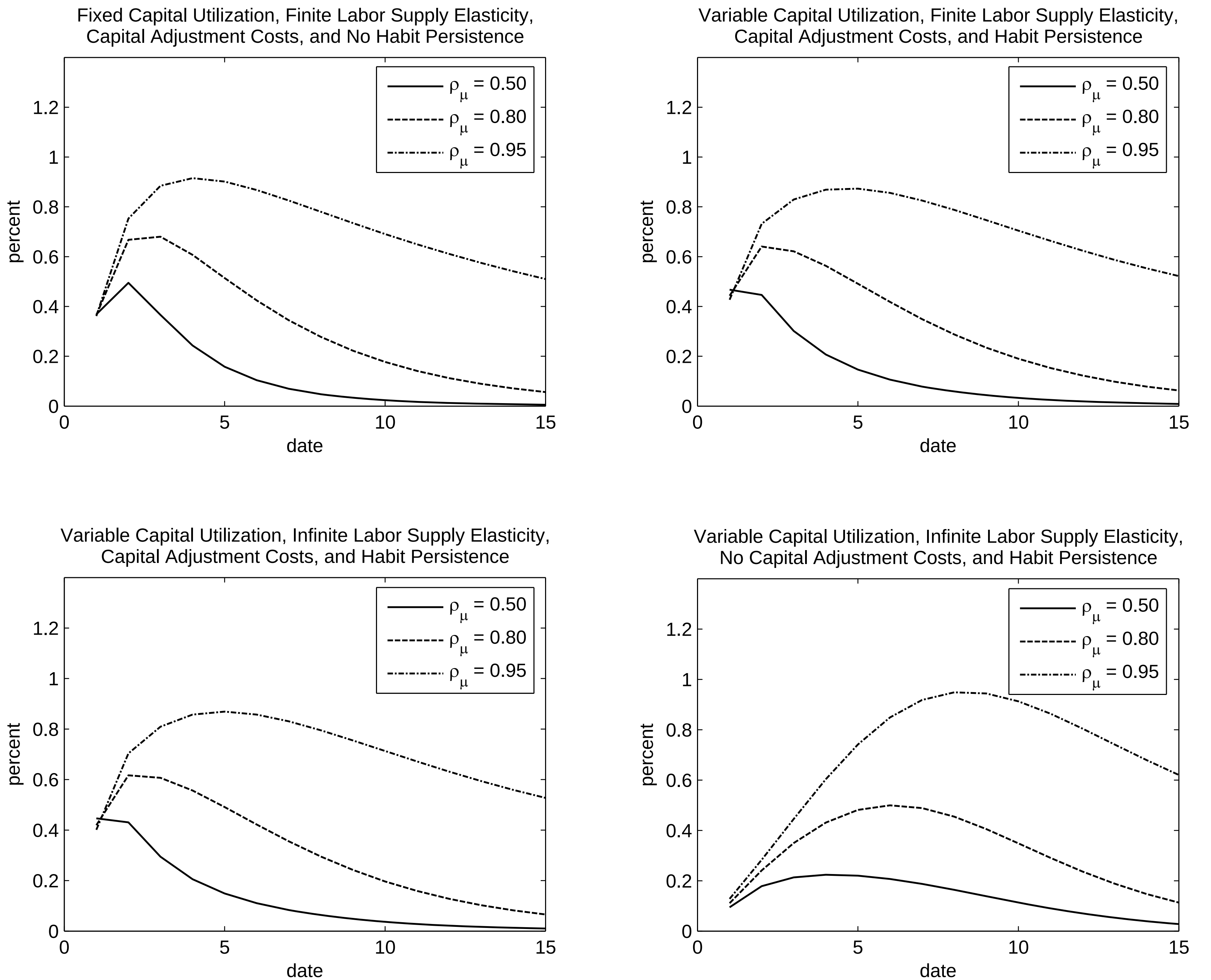


Figure 6: Inflation`s Response: The Impact of a Nominal Interest Rate Rule