

# Output, Inflation, and Interest Rates in an Estimated Optimizing Model of Monetary Policy\*

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## Abstract

This paper examines the impact of sticky prices and financial market frictions, both separately and combined, in a dynamic stochastic general equilibrium model. Using U.S. data on output, inflation, interest rates, money growth, and investment, maximum likelihood estimates reveal that the data prefers a model with both structural features. Our results also show that the combined model mimics many important features of the business cycle. In particular, the model generates reasonable impulse responses and only a modest amount of the variability in output and inflation is due to monetary policy shocks.

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# 1 Introduction

In recent years, macroeconomists have sought to develop a plausible structural model of the monetary transmission mechanism. At a minimum, such a model should be able to account for the empirically observed fall in output, persistent decline in inflation, and rise in the nominal interest rate after a contractionary monetary policy shock. While such a simple experiment enables macroeconomists to reject many models outright, the decision to reject or not to reject other models depends critically on the values assigned to certain parameters. Macroeconomists, however, are often uncertain about the actual values of some of those parameters. The problem suggests that statistical procedures are needed to estimate the parameters directly. This paper uses the formal econometric method of maximum likelihood to estimate our model's parameters.

Interest in modeling the effects of monetary policy has generated numerous competing dynamic stochastic general equilibrium (DSGE) models, each stressing different structural features. Two of the most popular structural features used in monetary models are price stickiness and financial market frictions.<sup>1</sup> King and Watson [1996] document that sticky price models, such as King [1991] and Kimball [1995], are unable to generate the liquidity effect (i.e., the rise in the nominal interest rate after a contractionary monetary disturbance), while limited participation models, such as Christiano and Eichenbaum [1992, 1995], are unable to account for the output and inflation effects after a monetary policy shock. Keen [2003] builds on the research of King and Watson [1996] by specifying a DSGE model with both sticky prices and financial market frictions and finds that the model can generate the correct qualitative responses for output, inflation, and the nominal interest rate. Those results, however, are sensitive to parameterization of the degree of price stickiness, time adjustment costs, capital adjustment costs, and monetary policy rule.<sup>2</sup>

This paper constructs and estimates the parameters by maximum likelihood of three DSGE models: a sticky price model, a limited participation model, and a sticky price and limited participation model. Those parameters are estimated using quarterly U.S. data on output, inflation, money growth, nominal interest rate, and investment under the assumption that those data series provide the best information on the actual values for the degree of price stickiness, time adjustment costs, capital adjustment costs, and monetary policy rule. Analysis of our models using likelihood ratio tests indicates that the data prefers a sticky price and limited participation model as opposed to the other models. When evaluated at its estimated parameter values, only our sticky price and limited participation model is able to account simultaneously for the output, inflation, and liquidity effects after a monetary disturbance. The estimated model also is able to generate other key business cycle facts observed in the data. For example, monetary policy shocks account for a modest portion of

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<sup>1</sup>Models with financial market frictions are often called limited participation models.

<sup>2</sup>Time adjustment costs are a style of financial market frictions.

the variability in output and inflation. The ability of a sticky price and limited participation model to replicate those key features, at the very least, suggests that the model is a reasonable benchmark for the development of future monetary models.

The remainder of the paper is structured as follows. Section 2 discusses existing models of the business cycle. Section 3 outlines our model. Section 4 describes the model's solution and the estimation procedure. Section 5 presents the maximum likelihood estimates and assesses the quantitative and qualitative properties of the model. Section 6 serves as the conclusion.

## 2 Existing Models of the Business Cycle

A plausible model of the monetary transmission mechanism should produce qualitative responses after a monetary policy shock that are consistent with those responses observed in the data. After analyzing the results from many different vector autoregression (VAR) models, Christiano, Eichenbaum, and Evans (CEE) [1999] conclude that a monetary model should generate a reduction in output, a persistent decline in inflation, and a rise in the nominal interest rate after a contractionary monetary policy shock. This section briefly describes the successes and failures of sticky price models and limited participation models in producing those outcomes. We then summarize findings that suggest that a model with both sticky prices and financial market frictions can generate all of those key qualitative effects of a monetary policy shock.

Sticky price models, such as King and Wolman [1996] and Ireland [1997], introduce methods to enable prices to adjust gradually after a monetary policy shock. In those models, the price stickiness causes output to fall temporarily in response to a contractionary monetary disturbance. The temporary decline in output prompts the representative household to decrease its savings in order to smooth out its consumption. Furthermore, the lower output demand in subsequent periods decreases the demand for investment. The response of the real interest rate to the monetary policy shock depends on the relative magnitude of the decreases in investment demand and savings. Price stickiness, however, dampens inflationary expectations which puts downward pressure on the nominal interest rate. Those lower inflationary expectations are usually strong enough to dominate any rise in the real interest rate. As a result, the nominal interest rate in a sticky price model usually falls instead of rises after a contractionary monetary disturbance.

Limited participation models, such as Christiano and Eichenbaum [1992, 1995] and Dotsey and Ireland [1995], assume that the representative household begins with an initial level of money balances, which it must allocate between consumption spending and savings. Financial market frictions then prevent the representative household from completely adjusting its savings to a contractionary monetary disturbance. That slow adjustment of savings decreases the resources available for investment, which leads to a rise in both the nominal and real interest rates. The lack of any price rigidities in a limited participation model enables all firms to adjust their price.

As a result, most of the change in prices occurs immediately, which causes a one-time drop in the inflation rate and prevents a large decrease in output. While the limited participation model succeeds in generating the liquidity effect, it fails in producing a large real effect on output or a persistent decline in the inflation rate.

Based on the results from the sticky price model and the limited participation model, the natural conjecture is to combine both of those structural features into one model. Keen [2003] finds that a combined sticky price and limited participation model can produce a decline in output, a persistent reduction in inflation, and an increase in the nominal interest rate after a contractionary monetary policy shock. Introducing financial market frictions into a sticky price model enables the model to produce the liquidity effect by further reducing savings after a negative monetary disturbance. That reduction then leads to more upward pressure on both nominal and real interest rates. Keen [2003] indicates that the ability of a sticky price and limited participation model to generate the output, inflation, and nominal interest rate effects depends on the parameter values assigned to the degree of price stickiness, time adjustment costs, capital adjustment costs, and monetary policy rule. The literature, however, has not converged on a uniform set of values for those features. Therefore, this paper estimates directly the parameters of a sticky price and limited participation model using maximum likelihood to determine if our model can account for the qualitative effects of a monetary policy shock.

### 3 The Model

The model developed here extends the sticky price and limited participation model developed in Keen [2003] in two ways. One, this model, motivated by Bernanke and Blinder [1992] and Taylor [1993], specifies the nominal interest rate instead of the money growth rate as the target of monetary policy. Two, our model specifies four non-policy exogenous shocks to capture the effects of production technology, money demand, aggregate demand, and investment technology.

The model comprises a representative household, monopolistically competitive firms, a capital supplier, banks, and a monetary authority. The representative household purchases consumption goods from the firms. A fraction of those consumption purchases must be paid in advance out of existing money balances. Remaining money balances are deposited at the banks. Firms produce output with labor supplied by the household and capital rented from the capital supplier. The capital supplier invests in capital and rents it to the firms. Each period, the capital supplier finances a fraction of its investment purchases, which must be paid in advance by borrowing funds from the banks. The banks facilitate beginning of the period lending and end of the period repayment of loans between the household and the capital supplier. Finally, the monetary authority targets the nominal interest rate via monetary transfers to the banks.

### 3.1 The Representative Household

The representative household is an infinitely lived agent who has a preference for consumption,  $c_t$ , and leisure,  $l_t$ . Following Blanchard and Kiyotaki [1987], the consumption good,  $c_t$ , is a Dixit and Stiglitz [1977] aggregate of a continuum of differentiated goods ( $c_t(z)$ ,  $z \in [0, 1]$ ):

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

where  $-\epsilon$  is the price elasticity of demand for good  $c_t(z)$ . The differentiated good  $c_t(z)$  sells at a price  $P_t(z)$ . Cost minimization on the part of the representative household implies that the demand for  $c_t(z)$  is a decreasing function of its relative price:

$$c_t(z) = \left( \frac{P_t(z)}{P_t} \right)^{-\epsilon} c_t, \quad (2)$$

where  $P_t$  is the aggregate price index. Substituting (2) into (1),  $P_t$  is specified as a nonlinear index of prices of a continuum of differentiated goods:

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

Each period, the representative household allocates  $S_t$  of its beginning of the period money stock,  $M_{t-1}$ , for consumption purchases and saves the remaining amount,  $M_{t-1} - S_t$ , at the banks. The household is required to pay for a fraction,  $v_t$ , of its consumption purchases at the beginning of the period and the remaining fraction,  $1 - v_t$ , at the end of the period.<sup>3</sup> That restriction leads to the following cash constraint:

$$v_t P_t c_t = S_t, \quad (3)$$

where  $0 < v_t < 1$ .<sup>4</sup> The random variable  $v_t$  is a money demand shock that follows an autoregressive process:

$$\ln(v_t) = \rho_v \ln(v_{t-1}) + (1 - \rho_v) \ln(v) + \varepsilon_{vt},$$

where  $0 < v < 1$ ,  $0 < \rho_v < 1$ , and  $\varepsilon_{vt} \sim N(0, \sigma_v^2)$ .

The limited participation friction is integrated into this model by imposing time costs on adjusting  $S_t$  similar to those employed by Christiano and Eichenbaum [1992], King and Watson [1996], and Christiano and Gust [1999]. Like Dotsey and Ireland

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<sup>3</sup>Christiano and Gust [1999] specify a similar money demand shock, but their model assumes firms must finance  $v_t$  of the current wage bill in advance.

<sup>4</sup>It is shown later that  $v_t$  is the inverse of the velocity of money.

[1995], those time costs allow partial but not complete adjustment of  $S_t$  to an unexpected shock. Specifically, the household incurs time costs to adjust  $S_t$  of the form:

$$h_t = \frac{\gamma}{2} \left( \frac{S_t}{\mu S_{t-1}} - 1 \right)^2,$$

where  $\gamma > 0$  is the magnitude of the time adjustment costs and  $\mu$  is the steady state money growth rate. Time spent by the household adjusting its portfolio cuts into its leisure time according to the following time constraint:

$$n_t + l_t + h_t = 1, \quad (4)$$

where  $n_t$  denotes the fraction of time worked.

The household supplies labor to the firms and holds a claim to the profits of the firms, the capital supplier, and the banks. At the end of each period, the representative household receives income for labor services, savings with interest, and profits from the firms,  $D_t^f$ , the capital supplier,  $D_t^c$ , and the banks,  $R_t X_t$ . At the same time, the household pays for the remainder of its consumption purchases,  $(1 - v_t)P_t c_t$ . At the end of the period, money balances,  $M_t$ , held by the household are

$$M_t = W_t n_t + R_t(M_{t-1} - S_t) + D_t^f + D_t^c + R_t X_t - (1 - v_t)P_t c_t, \quad (5)$$

where  $W_t$  is the nominal wage rate and  $R_t$  is the gross nominal interest rate. In the next period, the household will spend the money on consumption purchases or save it at the banks.

The representative household has preferences for consumption and leisure. Each period, the representative household maximizes the expected value of the sum of instantaneous utilities at time  $t$ :

$$E_t \left[ \sum_{j=0}^{\infty} \beta^j a_{t+j} \frac{(c_{t+j}^{\theta_2} l_{t+j}^{1-\theta_2})^{1-\theta_1}}{1 - \theta_1} \right] \quad (6)$$

subject to (3), (4), and (5). The utility function is a constant relative risk aversion transformation of a Cobb-Douglas function of consumption and leisure, where  $\theta_1 > 0$  and  $0 < \theta_2 < 1$ .  $E_t$  is the expectational operator at time  $t$ , while  $0 < \beta < 1$  is the discount factor. Finally, the preference parameter,  $a_t$ , resembles an aggregate demand shock and follows an autoregressive process:

$$\ln(a_t) = \rho_a \ln(a_{t-1}) + \varepsilon_{at},$$

where  $0 < \rho_a < 1$  and  $\varepsilon_{at} \sim N(0, \sigma_a^2)$ . McCallum and Nelson [1999] show that  $a_t$  is similar to a preference shock to the IS curve in traditional Keynesian economics.<sup>5</sup>

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<sup>5</sup>In a model without time adjustment costs, changes in  $a_t$  are linked exactly to consumption growth and the interest rate, which resembles an IS shock. When the model includes small time adjustment costs, however, changes in  $a_t$  should approximate closely the behavior of an IS shock.

### 3.2 Firms

The firms are monopolistically competitive producers of differentiated goods,  $y_t(z)$ , that are owned by the representative household. Each firm hires labor,  $n_t(z)$ , from the representative household and rents capital,  $k_t(z)$ , from the capital supplier to produce  $y_t(z)$  according to the following production function:

$$y_t(z) = Z_t(k_t(z))^\alpha(n_t(z))^{1-\alpha}. \quad (7)$$

The production technology parameter,  $Z_t$ , follows an autoregressive process:

$$\ln(Z_t) = \rho_Z \ln(Z_{t-1}) + (1 - \rho_Z) \ln(Z) + \varepsilon_{Zt},$$

where  $Z > 0$ ,  $0 < \rho_Z < 1$ , and  $\varepsilon_{Zt} \sim N(0, \sigma_Z^2)$ . Labor and capital inputs used in (7) are supplied by perfectly competitive markets. The capital stock is predetermined in the aggregate, but profit maximizing implies efficient allocation of capital across firms. Cost minimization on the part of the  $z$ th firm yields the following input factor demands:

$$\begin{aligned} \psi_t \alpha Z_t [n_t(z)/k_t(z)]^{1-\alpha} &= q_t, \\ \psi_t (1 - \alpha) Z_t [k_t(z)/n_t(z)]^\alpha &= W_t/P_t, \end{aligned}$$

where  $q_t$  is the real user cost of capital and  $\psi_t$  is the real marginal cost.

Each period, a fraction of the firms,  $\eta$ , are randomly allocated the opportunity to adjust their price. The remaining fraction of the firms,  $(1 - \eta)$ , cannot change their price and must satisfy all demand at their previously set price. That rule, based on Calvo [1983], allows each firm to have its own specific opportunities to adjust its price.<sup>6</sup> An advantage of the pricing rule is that it closely replicates economic conditions by allowing the timing and magnitude of price changes to vary across firms.

Staggered price setting behavior by firms makes their profit maximization problem dynamic. The price adjusting firm seeks to set a price,  $P_t(z)$ , that maximizes the present value of expected future profits to households:

$$E_t \left[ \sum_{j=0}^{\infty} \beta^j (1 - \eta)^j \lambda_{t+j} [P_t(z) y_{t+j}(z) - W_{t+j} n_{t+j}(z) - P_{t+j} q_{t+j} k_{t+j}(z)] \right], \quad (8)$$

where  $\lambda_t$  measures the marginal utility value of an additional dollar of profits to the household:

$$\lambda_t = U_l(c_t, l_t)/W_t.^7$$

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<sup>6</sup>Keen [2003] specifies a Levin [1991] pricing rule but parameterizes it equivalent to the Calvo [1983] pricing rule used here. The pricing rule in this paper is specified directly as a Calvo [1983] rule to simplify calculation of the likelihood function.

<sup>7</sup>If the value of profits to the representative household is expressed in terms of the marginal

Determining the optimal price involves maximizing current and expected future profits. To make the profit maximization problem a function of only  $P_t(z)$ ,  $P_{t+j}$ ,  $\lambda_{t+j}$ , and  $y_{t+j}$ , the demand schedule and the cost minimizing quantities of factor inputs are substituted into (8).<sup>8</sup> Solving that profit maximization problem yields the optimal price for an adjusting firm,  $P_t(z)$ , which can be written as:

$$P_t(z) = \frac{\varepsilon}{\varepsilon - 1} \frac{\sum_{j=0}^{\infty} \beta^j E_t[(1 - \eta)^j \lambda_{t+j} \psi_{t+j} P_{t+j}^{1+\varepsilon} y_{t+j}]}{\sum_{j=0}^{\infty} \beta^j E_t[(1 - \eta)^j \lambda_{t+j} P_{t+j}^{\varepsilon} y_{t+j}]}.$$
 (9)

Given that there are no firm-specific factors influencing pricing decisions in (9), all adjusting firms in period  $t$  set the same profit maximizing price,  $P_t(z)$ .

### 3.3 Capital Supplier

The capital supplier owns all of the capital in the economy. At the beginning of a period, the capital supplier rents capital to the firms but must wait until the end of that same period to receive its rental income. The firms require the capital supplier to pay for a fraction,  $v_t$ , of its capital investment at the beginning of the period. To finance the advance payment, the capital supplier must borrow  $v_t P_t i_t$  from the banking sector. At the end of a period, the remaining balance of  $(1 - v_t) P_t i_t$  on the capital investment is paid to the firms and the loans are paid in full with interest. Consequently, the cost of capital investment is  $(1 - v_t + v_t R_t) P_t i_t$ .

In our model, the capital supplier incurs costs to adjust the capital stock. Dow [1995], Kimball [1995], King and Watson [1996], Kim [2000], and Ireland [2001] find that capital adjustment costs help explain interest rate movements over the business cycle. The capital adjustment costs denoted as  $i_t - \varphi(i_t/k_t)k_t$  in this model are resources lost in the conversion of investment to capital. We assume that incorporating new capital at slower rates rather than at higher rates is less costly, so that  $\varphi' > 0$  and  $\varphi'' < 0$ . Adjustment costs are modeled as described in Hayashi [1982], which means that capital accumulates as follows:

$$k_{t+1} - k_t = J_t \varphi(i_t/k_t) k_t - \delta k_t.$$
 (10)

$J_t > 0$  is an investment technology parameter that follows the autoregressive process:

$$\ln(J_t) = \rho_J \ln(J_{t-1}) + \varepsilon_{Jt},$$

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utility of consumption,  $\lambda_t$  is affected by the lost interest and time costs associated with the decline in savings needed to fund the additional consumption. In that case,  $\lambda_t$  is expressed as:

$$\lambda_t = \frac{U_c(c_t, l_t)/P_t - v_t h'_t U_l(c_t, l_t)/(\mu S_{t-1}) + \beta E_t[v_t h'_{t+1} S_{t+1} U_l(c_{t+1}, l_{t+1})/(\mu S_t)^2]}{[(1 - v_t) + v_t R_t]}.$$

<sup>8</sup>Cost minimization on the part of the household and the capital supplier yields the following demand schedule for the  $z$ th firm:  $y_t(z) = [P_t(z)/P_t]^{-\varepsilon} y_t$ .

where  $0 < \rho_J < 1$  and  $\varepsilon_{Jt} \sim N(0, \sigma_J^2)$ . Greenwood, Hercowitz, and Huffman [1988] argue that  $J_t$  resembles a shock to the productivity of investment.

The capital supplier seeks to maximize the value of the discounted stream of dividend payments to the household. The value of dividends to the household is the additional utility gained from leisure divided by the nominal wage rate. Therefore, the capital supplier maximizes the following equation:

$$E_t \left[ \sum_{j=0}^{\infty} \beta^j \lambda_{t+j} [P_{t+j} q_{t+j} k_{t+j} - P_{t+j} (1 - v_{t+j} + v_{t+j} R_{t+j}) i_{t+j}] \right]$$

subject to (10).

### 3.4 Banks

Banks facilitate lending between the household and the capital supplier. Each period, banks receive household deposits,  $S_t$ , and lump-sum injections from the monetary authority,  $X_t = M_t - M_{t-1}$ . Banks lend those funds to the capital supplier to finance the fraction,  $v_t$ , of its capital purchases,  $P_t i_t$ , that must be paid in advance. A gross interest rate,  $R_t$ , is paid to the household and charged to the capital supplier to clear the loan market:

$$v_t P_t i_t = [M_{t-1} - S_t + X_t]. \quad (11)$$

At the end of the period, the capital supplier repays its loan interest,  $R_t v_t P_t i_t$ , the households receive their savings plus interest,  $R_t (M_t - S_t)$ , and the banks pay dividends,  $R_t X_t$ , to their owner, the representative household.

Combining the loan market clearing condition, (11), with the household's cash constraint, (3), yields the quantity equation of money:

$$P_t y_t = M_t (1/v_t). \quad (12)$$

Thus, the money demand variable,  $v_t$ , is interpreted as the inverse of money velocity.

### 3.5 The Monetary Authority

In this model, the monetary authority targets the nominal interest rate instead of the money growth rate. There are several reasons for identifying monetary policy in that way. First, Taylor [1993] finds that a variation of the nominal interest rate rule, proposed here, does a good job of describing Federal Reserve behavior under Chairman Alan Greenspan. Second, Bernanke and Blinder [1992], using a VAR model, find that the short-term nominal interest rate is the best indicator of monetary policy.<sup>9</sup> Third,

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<sup>9</sup>CEE [1996] suggest that a narrow measure of money, non-borrowed reserves, is the best indicator of monetary policy. Bernanke and Mihov [1998], however, find that the best indicator of monetary policy over the last 30 years is the federal funds rate.

Bernanke and Mihov [1998] and Strongin [1995] argue that money growth rates are often influenced by non-policy shocks accommodated by the Federal Reserve. Fourth, Goodfriend [1993] claims that the nominal interest rate, the federal funds rate, or its equivalent, historically has been the primary policy instrument of the Federal Reserve.

The interest rate reaction function employed here is identical to that used in Ireland [2001]. The monetary authority adjusts the nominal interest rate in response to changes in output,  $y_t$ , inflation,  $\pi_t = P_t/P_{t-1}$ , and money growth,  $\mu_t = M_t/M_{t-1}$ , such that:

$$\ln(R_t/R) = \phi_y \ln(y_t/y) + \phi_\pi \ln(\pi_t/\pi) + \phi_\mu \ln(\mu_t/\mu) + \varepsilon_{Rt}, \quad (13)$$

where  $\varepsilon_{Rt} \sim N(0, \sigma_R^2)$ .

## 4 Equilibrium and Estimation Procedure

The first-order conditions, identity equations, and exogenous shocks form a system of difference equations describing the systematic equilibrium of the model. In equilibrium, the existence of a steady state rate of inflation,  $\pi$ , causes the nominal variables in the model to grow at a deterministic trend. To induce stationarity, the nominal variables,  $P_t$ ,  $P_t(z)$ ,  $W_t$ ,  $S_t$ ,  $M_t$ ,  $D_t^c$ , and  $D_t^f$  are divided by  $\pi^t$ . In the absence of any exogenous shocks, that stationary-inducing transformation allows the model to converge to a steady state equilibrium.

A log-linear approximation of the model's system of difference equations around its nonstochastic steady state can be solved using the techniques of King and Watson [1998, 2002].<sup>10</sup> The solution of the model is easily transformed into the following state space form:

$$\mathbf{s}_t = \mathbf{M}\mathbf{s}_{t-1} + \boldsymbol{\varepsilon}_t, \quad (14)$$

$$\mathbf{Y}_t = \mathbf{\Pi}\mathbf{s}_t, \quad (15)$$

where  $\mathbf{Y}_t$  is a vector of observed variables,  $\mathbf{s}_t$  is a vector of observed and unobserved variables, and  $\boldsymbol{\varepsilon}_t$  is a vector of innovations. Each variable included in vectors  $\mathbf{s}_t$  and  $\mathbf{Y}_t$  is specified as the percent deviation of that variable from its steady state. The matrices  $\mathbf{M}$  and  $\mathbf{\Pi}$  comprise the underlying parameters of the model. The vector of innovations,  $\boldsymbol{\varepsilon}_t$ , contains five independent innovations  $\varepsilon_{at}$ ,  $\varepsilon_{vt}$ ,  $\varepsilon_{Zt}$ ,  $\varepsilon_{Jt}$ , and  $\varepsilon_{Rt}$  present in the model. Given the specification of the exogenous shocks in the model,  $\boldsymbol{\varepsilon}_t$  is normally distributed with a covariance matrix  $E[\boldsymbol{\varepsilon}_t\boldsymbol{\varepsilon}_t'] = \boldsymbol{\Omega}$  that is diagonal.

Data on output, inflation, money growth, the nominal interest rate, and investment are incorporated into  $\mathbf{Y}_t$ . The output, inflation, money growth, and nominal interest rate variables are central to the analysis of monetary policy in both the

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<sup>10</sup>The solution methodology of King and Watson [1998, 2002] is a generalization of the methods of Blanchard and Kahn [1980].

structural VAR literature and in DSGE models. Furthermore, those variables contain valuable information needed to estimate the parameters of the monetary policy rule and the probability of price adjustment by firms. Data on investment also is included because it provides key information on the magnitude of the capital adjustment costs. Obtaining accurate parameter estimates for the monetary policy rule, probability of price adjustment, magnitude of the time adjustment costs, and size of the capital adjustment costs is important because those parameter values are critical in determining whether or not a sticky price and limited participation model can generate the output, inflation, and liquidity effects after a monetary policy shock. Finally, the specification of an equal number of observed variables,  $\mathbf{Y}_t$ , and innovations,  $\boldsymbol{\varepsilon}_t$ , eliminates the need for any measurement error in the observation equation, (15).<sup>11</sup>

The state space representation of the model solution, (14) and (15), is convenient for calculating the likelihood function via the Kalman filter. The Kalman filter generates the optimal linear projections of the observed variables,  $\mathbf{Y}_{t|t-1}$ , from (15) based on  $\ddot{\mathbf{Y}}_{t-1} \equiv (\mathbf{Y}_{t-1}, \dots, \mathbf{Y}_1)$ . The fact that  $\boldsymbol{\varepsilon}_t$  and initial state  $\mathbf{s}_1$  are assumed to be Gaussian yields a distribution of  $\mathbf{Y}_t$  conditional on  $\ddot{\mathbf{Y}}_{t-1}$  such that:

$$\mathbf{Y}_t | \ddot{\mathbf{Y}}_{t-1} \sim N(\mathbf{\Pi} \mathbf{s}_{t|t-1}, \mathbf{\Pi}' \mathbf{P}_{t|t-1} \mathbf{\Pi}),$$

where  $\mathbf{P}_{t|t-1} = E[(\mathbf{s}_t - \mathbf{s}_{t|t-1})(\mathbf{s}_t - \mathbf{s}_{t|t-1})']$ . That result makes it straightforward to create the sample log-likelihood function conditional on  $\mathbf{s}_1$ :

$$L(\Theta) = \sum_{t=2}^T \log f_{\mathbf{Y}_t | \ddot{\mathbf{Y}}_{t-1}}(\mathbf{Y}_t | \ddot{\mathbf{Y}}_{t-1}, \Theta), \quad (16)$$

where  $\Theta$  is a vector of parameters.<sup>12</sup> Since (16) is a function of  $\mathbf{\Pi}$ ,  $\mathbf{M}$ , and  $\mathbf{\Omega}$ , the model's parameters are estimated by numerically maximizing (16) with respect to  $\Theta$ .

The data used to estimate the model covers the period from 1959Q2-2003Q4. Output is real personal consumption expenditures plus real gross private domestic investment.<sup>13</sup> Investment is real gross private domestic investment. The output and investment data are expressed in per capita terms by dividing by the civilian, noninstitutional population, age 16 and over. Inflation is the percent change in the implicit GDP price deflator. The money growth rate is the percent change in the per capita M2 money stock. The nominal interest rate is the federal funds rate.

Distinct upward trends appear in the output and investment data. The model, however, assumes that those variables move around their steady states. The fact

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<sup>11</sup>Models with more variables than innovations require the presence of error terms in (15) to prevent the covariance matrix of the data from being singular.

<sup>12</sup>See Hamilton [1994, Ch. 13] for details on this technique.

<sup>13</sup>Since the model defines output as the sum of consumption and investment, we use this specification of the output data series. That same construction for the output data series also is employed in Ireland [2003].

that investment growth exceeds output growth over the sample period complicates estimation of a constant growth trend for the real variables. To avoid introducing different growth rates for the real variables in the model, the output and investment data are linearly detrended by their average quarterly growth rates of 0.00536 and 0.00646, respectively, over the sample period.

## 5 Estimation Results and Tests

### 5.1 Estimates

Some of the model's parameters need to be set prior to estimation because of weak identification or insufficient information in the data. In particular, the absence of data on employment and capital makes it difficult to estimate the preference parameter  $\theta_2$  and the depreciation rate,  $\delta$ . The value of  $\theta_2$  then is parameterized so that the nonstochastic steady state value of labor,  $\bar{n}$ , is 0.2. The depreciation rate,  $\delta$ , is fixed to 0.025, which implies that capital depreciates at an annual rate of 10%. Given that the model is linearized around its nonstochastic steady state, we do not need to identify a specific functional form for the investment adjustment cost function,  $\varphi(i_t/k_t)$ , but instead, need only to specify parameter values for  $\varphi$ ,  $\varphi'$ , and  $\varphi''$ . Identification problems prevent estimating all three of those parameters simultaneously, so it is assumed that there are no average or marginal capital adjustment costs around the steady state. Therefore,  $\varphi$  and  $\varphi'$  are set to  $i/k$  and 1, respectively. The only investment adjustment cost parameter estimated is the inverse of the elasticity of the investment-capital ratio to Tobin's  $q$ ,  $\chi = [(i/k)\varphi''/\varphi']$ . Since we use data on money growth and not the level of money, it is problematic to estimate the steady state money velocity,  $v$ , so  $v$  is set to 0.693 which is consistent with the average ratio of detrended real output to detrended real M2 balances.<sup>14</sup> Lastly, it is difficult to distinguish the price elasticity of demand,  $\epsilon$ , from the production technology parameter,  $Z$ , so  $\epsilon$  is set to 6. The value implies that the steady state mark-up of price over marginal cost is equal to 20%, which matches Rotemberg and Woodford's [1992] survey of empirical studies.

We estimate three separate DSGE models: a sticky price model (the constraint  $\gamma = 0$  is imposed), a limited participation model (the constraint  $\eta = 1$  is imposed), and a sticky price and limited participation model. There are two distinct advantages in estimating those models. One, likelihood ratio tests can be used to determine if the introduction of sticky prices and financial market frictions yields a statistically significant improvement in the ability of our combined model to fit the data. Two, the successes and failures of each model can be analyzed and compared with the other models. Tables 1-3 display the parameters' maximum likelihood estimates and their

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<sup>14</sup>Real output in this calculation is defined as real personal consumption expenditures plus real gross private domestic investment.

respective standard errors for the sticky price model, the limited participation model, and the sticky price and limited participation model, respectively. To derive the standard errors, the log-likelihood function's matrix of second derivatives is multiplied by negative one and inverted. Standard errors then are calculated as the square roots of the diagonal elements of the inverted matrix.

The ability of a DSGE model to account for the output, inflation, and liquidity effects depends on the parameter estimates affecting the degree of price stickiness,  $\eta$ , the magnitude of the time adjustment costs,  $\gamma$ , the size of the capital adjustment costs,  $\chi$ , and the behavior of the monetary policy authority,  $\phi_y$ ,  $\phi_\pi$ , and  $\phi_\mu$ . Beginning with the degree of price stickiness, the estimate of  $\eta = 0.1855$  in the sticky price model and  $\eta = 0.2178$  in the sticky price and limited participation model suggests that around 20% of all firms adjust their price in any given period. Those estimates are close to survey evidence, which finds that firms on average change their price about once a year.<sup>15</sup> In the limited participation model and the sticky price and limited participation model, the time adjustment costs estimates of  $\gamma = 0.0125$  and  $\gamma = 0.0414$ , respectively, are very small but statistically significant. The size of the capital adjustment costs measured in Tables 1-3 by the estimates of  $\chi = -0.3608$ ,  $\chi = -0.5030$ , and  $\chi = -0.2373$  is modest but also statistically significant.

In the case of the monetary policy rule, estimates in the three models of monetary policy's response to output deviations of  $\phi_y = 0.0179$ ,  $\phi_y = 6 \times 10^{-8}$ , and  $\phi_y = 0.0049$  are small and statistically insignificant, like those in Ireland [2001, 2003]. The estimated response of monetary policy to inflation is  $\phi_\pi = 0.5453$  in the sticky price model and  $\phi_\pi = 0.6707$  in the sticky price and limited participation model. In the limited participation model, the response of monetary policy to inflation,  $\phi_\pi = 1.6223$ , is much larger than in the models with sticky prices. The difference can be explained partially by the much lower estimated response of monetary policy to money growth changes,  $\phi_\mu = 0.3276$ , in the limited participation model than the estimates of  $\phi_\mu = 1.6437$  and  $\phi_\mu = 0.9951$  in the sticky price model and the sticky price and limited participation model, respectively. In fact, a higher value of  $\phi_\pi$  should be associated with a lower value of  $\phi_\mu$  because the money growth rate equals the inflation rate plus the output growth rate when velocity is constant.

We conduct likelihood ratio tests to determine if a model with both sticky prices and financial market frictions can better explain the empirical behavior of our observed variables than a model without either sticky prices or financial market frictions.<sup>16</sup> The likelihood ratio statistic is formed by doubling the difference between the unrestricted and restricted maximum values of the log likelihood function and is distributed asymptotically as a chi-square with one degree of freedom. In the sticky price and limited participation model, the maximum value of the log likelihood function is 3932. When sticky prices are excluded (the constraint  $\eta = 1$  is imposed), the

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<sup>15</sup>See Rotemberg and Woodford [1997] for a discussion of this survey evidence.

<sup>16</sup>The likelihood ratio test is utilized because, unlike the Wald test, it does not reference standard errors.

limited participation model's maximum value of the log likelihood function is 3847. Since the p-value for the null hypothesis of  $\eta = 1$  is less than 0.001, introduction of sticky prices statistically improves the ability of the model to fit the data. In the case where financial market frictions are excluded (the constraint  $\gamma = 0$  is imposed), the maximum value of the log likelihood function for the sticky price model is 3912. As a result, the p-value for the null hypothesis  $\gamma = 0$  is less than 0.001, which indicates that the model's fit to the data is improved statistically by including financial market frictions.<sup>17</sup>

## 5.2 Impulse Responses

If our estimated model is to be considered a plausible model of the monetary transmission mechanism, it must generate the dynamic responses to a monetary shock that are observed in the data. Recall, a contractionary monetary policy shock should produce a decline in real output, a persistent fall in the inflation rate, and an increase in the nominal interest rate. Figure 1 displays the impact of a temporary 1% contractionary monetary policy shock for our three estimated DSGE models.

The first column of Figure 1 shows that our estimated sticky price model generates a decline in output and a persistent fall in inflation after a contractionary monetary policy shock as observed in the data, but can generate only a trivial rise in the nominal interest rate. The nominal interest rate fails to generate a nontrivial increase because the real interest rate does not rise enough to more than compensate for the falling inflation expectations due to price stickiness. The estimated limited participation model's impulse responses for output, inflation, and the nominal interest rate are displayed in the second column of Figure 1. In that model, output and the nominal interest rate remain virtually unchanged and inflation falls for one period only to return to its previous level in the subsequent period. While the absence of plausible output and inflation effects is expected, failure to generate a rise in the nominal interest rate is related directly to our small estimate of the time adjustment costs ( $\gamma = 0.0125$ ). In fact, those costs are so small that our estimated limited participation model is essentially equivalent to a flexible price model without financial market frictions.

Column three of Figure 1 demonstrates that our estimated sticky price and limited participation model produces an empirically observed drop in output, a persistent decline in the inflation rate, and a rise in the nominal interest rate after a contractionary monetary policy shock. Price stickiness prevents all of the firms from immediately adjusting their price, so output falls and the inflation rate remains persistently lower for a period of time. The time adjustment costs, which are small ( $\gamma = 0.0414$ ) but over three times as large as in the estimated limited participation model, help push up the real interest rate. That increase in the real interest rate dominates any

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<sup>17</sup>While not examined in our paper, likelihood ratio tests in Fuhrer [2000] indicate that the data also prefers models with habit formation in consumption.

decline in inflation expectations, so that the nominal interest rate rises. A drawback of our estimated sticky price and limited participation model, and most other models with price stickiness, is that it produces an inflation response that peaks on impact instead of several quarters later as is observed in many empirical studies.

To summarize, our estimated sticky price and limited participation model produces the empirically observed drop in output, persistent decline in the inflation rate, and rise in the nominal interest rate following a contractionary monetary policy shock. Without both sticky prices and financial market frictions, our model is unable to account simultaneously for those responses. Therefore, our results confirm quantitatively that a combined sticky price and limited participation model can generate plausible dynamic responses for output, inflation, and the interest rate after a monetary disturbance.

### 5.3 Variance Decompositions

Another way to evaluate the empirical plausibility of our estimated models is to find the underlying exogenous sources of variation in the observed variables and compare them with results observed in the data. Tables 4-6 show the forecast error variance decomposition for output, the inflation rate, and the nominal interest rate in our estimated sticky price model, limited participation model, and sticky price and limited participation model, respectively. Each panel shows the percentage of a variable's variance that is attributable to the exogenous disturbances in monetary policy, production technology, aggregate demand, money demand, and investment technology. The variance decomposition for the observed variables is conducted for short- and medium-run time horizons of 1 through 4, 8, 12, and 20 quarters ahead. Note that the columns of each panel in Tables 4-6 may not add up to 100 due to rounding errors.

Medium-run changes in output are driven by supply side shocks in all three estimated DSGE models, while the primary source of short-run output movements depends on whether or not the model includes sticky prices. In particular, the production technology shock is responsible for more than 60% of output's variation in all of our estimated models when the forecast period is two years or more. The production technology shock is also responsible for the overwhelming majority of short-run output changes in the limited participation model. In the sticky price model and sticky price and limited participation model, money demand shocks are an important source of the variation in output at a forecast horizon of one year or less. Since prices cannot completely adjust in those models, output or money growth must change after a money demand shock according to the quantity equation, (12). When money growth adjusts, monetary policy responds endogenously to that change by moving the interest rate which causes output to move. It is that endogenous response of monetary policy that causes output to move after a money demand shock. Monetary policy shocks in our estimated models with sticky prices explain around 34% of output's movements at a forecast horizon of one quarter but that size decreases to

around 20% at a forecast horizon of one year. The role of monetary policy continues to decrease in those models as the forecast horizon increases. That small role for the monetary policy shock is consistent with results in the structural vector autoregressive literature. Specifically, Leeper, Sims, and Zha [1996] and CEE [1999] indicate there is broad agreement in the structural VAR literature that monetary policy shocks account for a fairly small portion of output’s variability in the actual economy.<sup>18</sup> As a result, the sticky price model and the sticky price and limited participation model succeed in replicating another important feature of the economy. Monetary policy shocks in the limited participation model, however, play virtually no role in output movements at all forecast horizons.

The inflation rate is moved primarily by the production technology, money demand, and aggregate demand shocks in the models with sticky prices, while monetary policy shocks are the main source of inflation’s movements in the limited participation model. Production technology shocks over all forecast horizons are responsible for about 45% – 55% of inflation’s movements in the sticky price model and about 30% – 40% of inflation’s variations in the sticky price and limited participation model. Aggregate demand shocks in the sticky price model account for about 8% – 16% of the changes in inflation over all time horizons, but they are responsible for nearly twice that amount in the sticky price and limited participation model. At all time horizons, money demand shocks account for about 20% – 25% of inflation’s variations in both models with sticky prices, whereas monetary policy shocks are responsible for only 13% – 16% of inflation’s variability. Such a small role for monetary policy shocks is consistent with CEE’s [1999] assertion, based on their examination of many different VAR models, that monetary disturbances account for a very modest portion of the variation in inflation. In the limited participation model, however, more than 50% of inflation’s movements over all time horizons are caused by monetary policy shocks, which is inconsistent with CEE’s [1999] results.

The nominal interest rate decompositions show that aggregate demand and investment technology shocks are responsible for most of its variability in all of our estimated models. The aggregate demand shock accounts for more than 50% of the movements in the nominal interest rate at all time horizons for our three estimated models, except at the very short-run horizons in the sticky price and limited participation model. That percentage, however, grows to over 50% in the medium-run. In the models with sticky prices, investment technology shocks explain slightly more of the nominal interest rate changes, 20% – 46%, than in the limited participation model, 12% – 21%. Monetary policy shocks, on the other hand, account for a very small amount of the nominal interest rate’s variability in all of our estimated models.

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<sup>18</sup>When using a six-variable VAR model, Faust [1998] finds weak support for the claim that monetary policy shocks contribute little to the fluctuations in output. Faust [1998], however, finds more support for that claim in the 13-variable VAR model of Leeper, Sims, and Zha [1996]. Furthermore, CEE [1999] note that this result does not deny that the endogenous component of monetary policy can play a sizable role in the variability of output.

Specifically, monetary policy shocks at all time horizons account for less than 1% of the nominal interest rate changes in the sticky price model and limited participation model, while monetary policy shocks are responsible for 5% – 8% of nominal interest rate movements in the combined sticky price and limited participation model. That minor role for the monetary policy shock means that the majority of the variation in the nominal interest rate results from systematic responses of monetary policy to economic conditions. Such a result is consistent with the behavior of the nominal interest rate observed in the data.

## 5.4 Second Moment Properties

Many researchers have documented the empirical second moment properties of key economic variables over the business cycle and then examined the ability of their DSGE models to replicate that behavior. We conduct a similar diagnostic test for our three estimated DSGE models by computing analytically the vector autocorrelation functions for detrended output, the nominal interest rate, the inflation rate, and the money growth rate and comparing them with the data. The vector autocorrelations for the data are computed using an unconstrained, fourth-order vector autoregression.<sup>19</sup>

Figures 2-4 show the vector autocorrelation functions for our three estimated models and the data. A result that is robust across all three models is their ability to closely mimic the nominal interest rate autocorrelations observed in the data. That finding occurs even though the monetary policy rule does not include an interest rate smoothing term as in Clarida, Gali, and Gertler [2000]. When it comes to other autocorrelations, however, the limited participation model performs worse than the other two models. Specifically, the limited participation models fails miserably at replicating any of the autocorrelations involving output, and it also underpredicts dramatically the degree of inflation persistence.

The autocorrelations for the sticky price model and the sticky price and limited participation model match the data quite well given the fact that the models have just 19 and 20 estimated parameters, respectively. In most cases, those models produce autocorrelations that have the same positive or negative relationship as observed in the data. One feature of business cycle models often examined is the degree of inflation persistence. In the sticky price model and the sticky price and limited participation model, the autocorrelation function for inflation indicates that both models, like most models with price stickiness, underpredicts the degree of inflation persistence.<sup>20</sup> Findings in Ireland [2001], however, suggest that the degree of inflation persistence produced by an estimated model with price stickiness appears to be sensitive to the

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<sup>19</sup>Fuhrer and Moore [1995] suggest this procedure for calculating vector autocorrelation functions in the data.

<sup>20</sup>See Fuhrer and Moore [1995] for a discussion of inflation persistence in models with price stickiness.

estimation period.<sup>21</sup> In particular, Ireland [2001] finds his sticky price model can generate the observed persistence in inflation when estimated with post-1979 data but not with pre-1979 data. Estimating our DSGE models over those sub-sample periods is a task for future research.

While similar in many cases, the autocorrelation functions for the sticky price model and the sticky price and limited participation model are different in a couple of respects. One, the output persistence produced by the sticky price and limited participation model is considerably less than that of the sticky price model and much closer to the output persistence observed in the data. Two, the sticky price model generates a negative relationship between output and the lagged nominal interest rate, but that relationship is much weaker than what is observed in the data. In the sticky price and limited participation model, the relationship is slightly positive. It is important to point out that our models' failures to generate a strong negative relationship between output and the lagged nominal interest rate is a common deficiency of most DSGE models.<sup>22</sup>

## 6 Conclusion

One of the primary long term goals in monetary economics is to develop a structural model usable for monetary policy analysis. Many previous DSGE models have been unable to generate simultaneously the output, inflation, and liquidity effects after a monetary disturbance. In models that have been successful in replicating that behavior, their results are usually sensitive to the values assigned to key parameters. Problems with those models arise because macroeconomists are often uncertain about the actual values of some of the parameters. In contrast to most other models, this paper imposes discipline on our choice of parameter values by using formal econometric methods to estimate those parameters.

Our objective in this paper is to qualitatively and quantitatively evaluate the empirical plausibility of three DSGE models: a sticky price model, a limited participation model, and a sticky price and limited participation model. Keen [2003] shows that a combined sticky price and limited participation model is able to produce simultaneously the output, inflation, and liquidity effects after a monetary disturbance, whereas the other two models cannot. The results, however, are sensitive to the calibration of certain parameter values. To alleviate the problem, we construct three DSGE models and directly estimate their parameters using maximum likelihood. When the models are evaluated at the estimated parameters, only the sticky price and limited participation model produces impulse responses for output, inflation, and the nominal interest rate after a monetary policy shock that are consistent with their qualitative

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<sup>21</sup>Ireland [2001] also indicates that the model needs to include persistent production technology and aggregate demand shocks if it is going to produce the observed persistence in inflation. The estimates in Tables 2-4 imply that those shocks are extremely persistent in our models.

<sup>22</sup>See King and Watson [1996] for a discussion of this issue.

behavior observed in the data. Furthermore, likelihood ratio tests indicate that the combined sticky price and limited participation model fits the data better than the sticky price or limited participation models. The estimated sticky price and limited participation model also accounts for the finding in many empirical VAR models that only a limited amount of the variation in output and inflation is due to monetary policy shocks.

The combination of sticky prices and financial market frictions in a DSGE model is a promising development in our overall understanding of the monetary transmission process. This paper shows that a model with those features can account for many of the empirically observed qualitative and quantitative effects from a monetary policy shock. Lucas [1980] highlights the importance of replicating key features of the economy when he states, “the more dimensions on which a model mimics the answers actual economies give to simple questions, the more we trust its answers to harder questions.” Our findings here should help guide macroeconomists in their quest to develop a structural model usable for monetary policy analysis.

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**Table 1: Maximum Likelihood Estimates and Standard Errors  
Sticky Price Model**

Parameter	Description	Estimate	Standard Error
$\alpha$	Capital's share of output	0.2263	0.0066
$\theta_1$	Preference parameter	0.9658	0.1686
$\beta$	Discount factor	0.9940	0.0010
$\pi$	Steady-state inflation rate	1.0088	0.0009
$\eta$	Probability of price adjustment	0.1855	0.0216
$\phi_y$	Policy response to output	0.0179	0.0175
$\phi_\pi$	Policy response to inflation	0.5453	0.1078
$\phi_\mu$	Policy response to money growth	1.6437	0.4476
$\gamma$	Time adjustment costs parameter	—	—
$\chi$	Degree of capital adjustment costs	-0.3608	0.0824
$Z$	Steady-state production technology	4173.6	347.92
$\rho_Z$	Persistence of production tech. shock	0.9385	0.0359
$\rho_a$	Persistence of aggregate demand shock	0.9120	0.0218
$\rho_J$	Persistence of investment tech. shock	0.8029	0.0355
$\rho_v$	Persistence of money demand shock	0.9999	0.0058
$\sigma_R$	Std. dev. of monetary policy shock	0.0150	0.0035
$\sigma_Z$	Std. dev. of production tech. shock	0.0193	0.0028
$\sigma_a$	Std. dev. of aggregate demand shock	0.0004	0.0021
$\sigma_J$	Std. dev. of investment tech. shock	0.0180	0.0038
$\sigma_v$	Std. dev. of money demand shock	0.0116	0.0006

**Table 2: Maximum Likelihood Estimates and Standard Errors  
Limited Participation Model**

Parameter	Description	Estimate	Standard Error
$\alpha$	Capital's share of output	0.2292	0.0074
$\theta_1$	Preference parameter	0.9367	0.5001
$\beta$	Discount factor	0.9939	0.0010
$\pi$	Steady-state inflation rate	1.0090	0.0043
$\eta$	Probability of price adjustment	—	—
$\phi_y$	Policy response to output	$6 \times 10^{-8}$	0.0216
$\phi_\pi$	Policy response to inflation	1.6223	0.2094
$\phi_\mu$	Policy response to money growth	0.3276	0.1188
$\gamma$	Time adjustment costs parameter	0.0125	0.0042
$\chi$	Degree of capital adjustment costs	-0.5030	0.1620
$Z$	Steady-state production technology	4520.9	832.39
$\rho_Z$	Persistence of production tech. shock	0.9995	0.0061
$\rho_a$	Persistence of aggregate demand shock	0.9077	0.0210
$\rho_J$	Persistence of investment tech. shock	0.8723	0.0333
$\rho_v$	Persistence of money demand shock	0.9999	0.0039
$\sigma_R$	Std. dev. of monetary policy shock	0.0083	0.0014
$\sigma_Z$	Std. dev. of production tech. shock	0.0082	0.0004
$\sigma_a$	Std. dev. of aggregate demand shock	0.0007	0.0060
$\sigma_J$	Std. dev. of investment tech. shock	0.0247	0.0076
$\sigma_v$	Std. dev. of money demand shock	0.0116	0.0006

**Table 3: Maximum Likelihood Estimates and Standard Errors  
Sticky Price and Limited Participation Model**

Parameter	Description	Estimate	Standard Error
$\alpha$	Capital's share of output	0.2271	0.0062
$\theta_1$	Preference parameter	0.9744	0.1229
$\beta$	Discount factor	0.9937	0.0009
$\pi$	Steady-state inflation rate	1.0092	0.0011
$\eta$	Probability of price adjustment	0.2178	0.0185
$\phi_y$	Policy response to output	0.0049	0.0092
$\phi_\pi$	Policy response to inflation	0.6707	0.0759
$\phi_\mu$	Policy response to money growth	0.9951	0.1484
$\gamma$	Time adjustment costs parameter	0.0414	0.0090
$\chi$	Degree of capital adjustment costs	-0.2373	0.0370
$Z$	Steady-state production technology	4096.1	322.61
$\rho_Z$	Persistence of production tech. shock	0.9141	0.0268
$\rho_a$	Persistence of aggregate demand shock	0.9124	0.0234
$\rho_J$	Persistence of investment tech. shock	0.9150	0.0230
$\rho_v$	Persistence of money demand shock	0.9999	0.0062
$\sigma_R$	Std. dev. of monetary policy shock	0.0103	0.0011
$\sigma_Z$	Std. dev. of production tech. shock	0.0172	0.0023
$\sigma_a$	Std. dev. of aggregate demand shock	0.0003	0.0015
$\sigma_J$	Std. dev. of investment tech. shock	0.0127	0.0019
$\sigma_v$	Std. dev. of money demand shock	0.0116	0.0006

**Table 4: Forecast Error Variance Decompositions  
Sticky Price Model**

Panel A: Output Decompositions							
	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	34.8	30.8	26.6	22.7	13.1	9.2	6.7
Production technology	8.2	17.9	28.4	38.0	62.4	72.4	79.1
Aggregate demand	0.1	0.2	0.2	0.3	0.6	0.8	1.0
Money demand	56.5	50.1	43.3	37.1	21.5	15.2	11.1
Investment technology	0.5	1.0	1.5	1.8	2.4	2.3	2.2

Panel B: Inflation Rate Decompositions							
	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	14.6	14.8	15.0	15.1	15.3	15.1	14.8
Production technology	54.0	52.4	50.9	49.6	46.3	45.3	45.5
Aggregate demand	8.4	9.3	10.2	11.1	13.5	14.7	15.2
Money demand	23.0	23.4	23.6	23.8	24.1	23.9	23.4
Investment technology	0.0	0.1	0.3	0.4	0.9	1.1	1.1

Panel C: Nominal Interest Rate Decompositions							
	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Production technology	1.8	1.8	1.8	1.8	1.7	1.6	1.5
Aggregate demand	51.5	54.2	56.7	58.8	64.5	67.3	69.2
Money demand	0.4	0.4	0.4	0.5	0.5	0.5	0.5
Investment technology	46.1	43.3	40.9	38.7	33.1	30.4	28.5

**Table 5: Forecast Error Variance Decompositions  
Limited Participation Model**

Panel A: Output Decompositions							
	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Production technology	79.7	80.5	81.2	81.9	84.4	86.3	89.3
Aggregate demand	7.4	7.1	6.7	6.4	5.3	4.4	3.3
Money demand	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Investment technology	12.8	12.5	12.1	11.7	10.4	9.2	7.4

Panel B: Inflation Rate Decompositions							
	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	64.8	62.5	60.8	59.4	56.3	55.0	54.2
Production technology	9.3	8.9	8.7	8.5	8.1	7.9	7.8
Aggregate demand	7.7	10.4	12.4	14.1	17.9	19.6	20.8
Money demand	18.3	17.6	17.1	16.7	15.9	15.5	15.3
Investment technology	0.0	0.6	1.0	1.3	1.8	1.9	1.9

Panel C: Nominal Interest Rate Decompositions							
	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Production technology	2.1	1.3	1.0	0.9	0.7	0.7	0.7
Aggregate demand	69.9	76.0	78.6	80.1	83.2	84.6	85.5
Money demand	7.0	4.1	3.1	2.6	1.8	1.6	1.5
Investment technology	21.1	18.6	17.3	16.4	14.3	13.2	12.3

**Table 6: Forecast Error Variance Decompositions  
Sticky Price and Limited Participation Model**

Panel A: Output Decompositions							
	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	33.5	27.9	22.8	18.7	10.5	7.9	6.3
Production technology	11.4	24.4	36.6	46.4	66.1	72.0	74.7
Aggregate demand	0.6	1.0	1.3	1.5	2.2	2.5	2.9
Money demand	53.4	44.9	36.9	30.4	17.2	12.9	10.4
Investment technology	1.2	1.9	2.5	3.0	4.1	4.7	5.6

Panel B: Inflation Rate Decompositions							
	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	15.6	15.7	15.7	15.5	14.5	13.8	13.2
Production technology	41.8	38.5	35.8	33.6	29.9	29.7	30.0
Aggregate demand	17.6	20.4	23.0	25.3	30.4	32.1	32.9
Money demand	24.8	25.0	24.9	24.7	23.1	21.9	21.0
Investment technology	0.2	0.4	0.7	1.0	2.0	2.6	2.9

Panel C: Nominal Interest Rate Decompositions							
	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	5.4	7.9	8.2	7.9	6.6	5.8	5.4
Production technology	20.2	12.7	9.9	8.4	6.1	5.5	5.0
Aggregate demand	32.1	45.7	51.8	55.5	62.6	65.4	67.5
Money demand	0.2	1.0	1.2	1.3	1.2	1.1	1.0
Investment technology	42.2	32.7	28.9	26.9	23.5	22.2	21.0

Figure 1: Impulse Responses of a 1% Contractionary Monetary Shock on Three DSGE Models

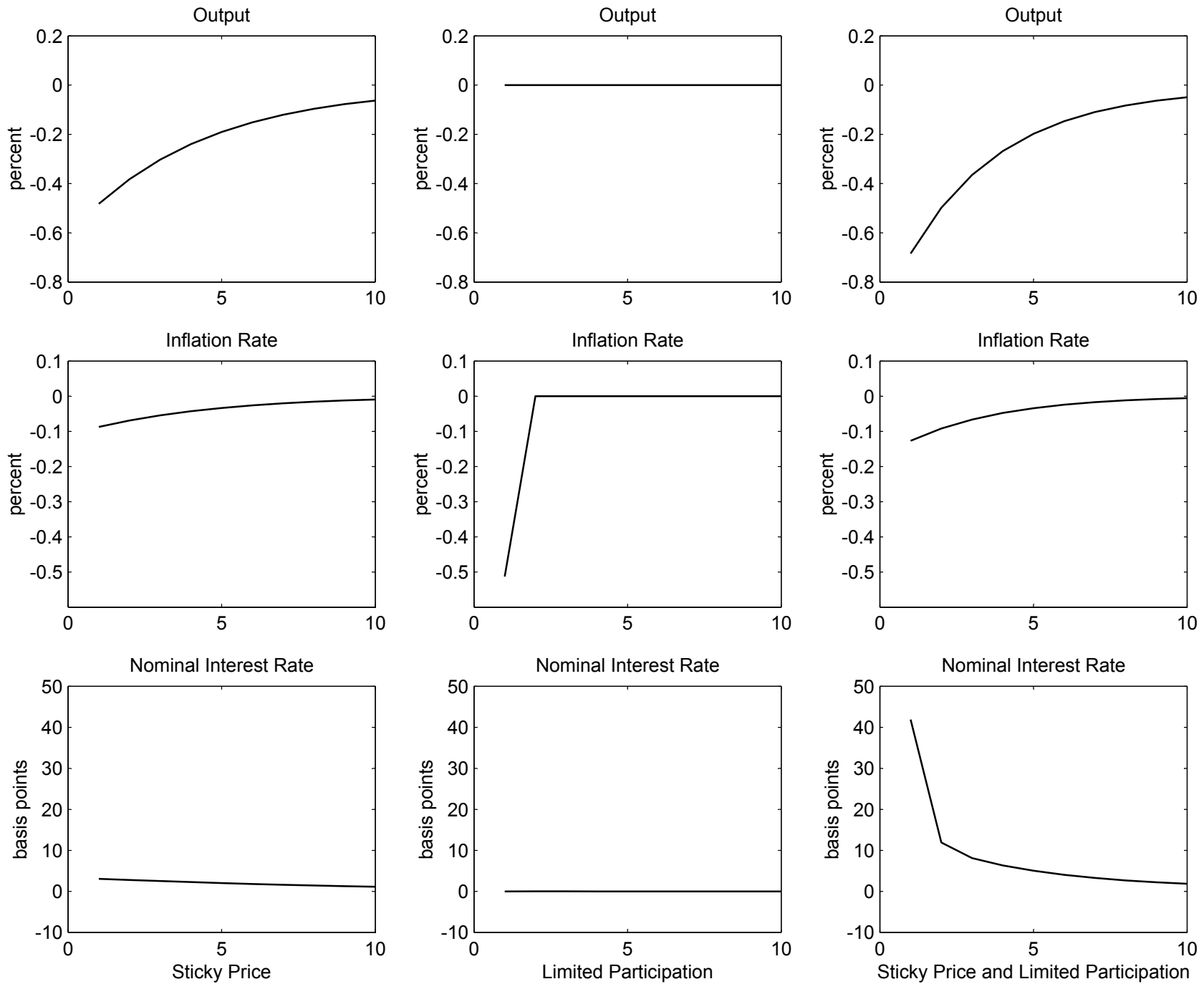


Figure 2: Vector Autocorrelation Functions, Sticky Price Model (dashed line) and Data (solid line)

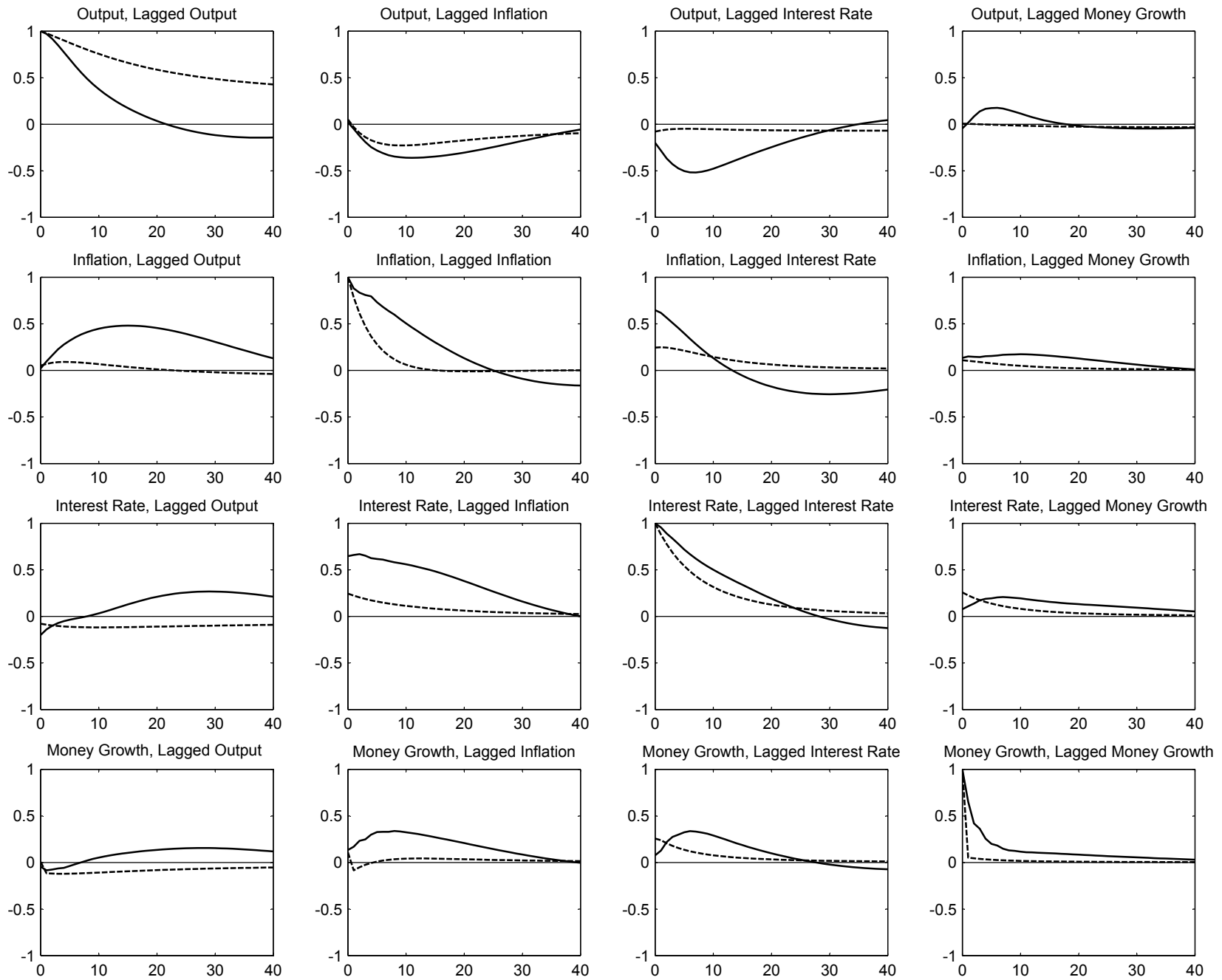


Figure 3: Vector Autocorrelation Functions, Limited Participation Model (dashed line) and Data (solid line)

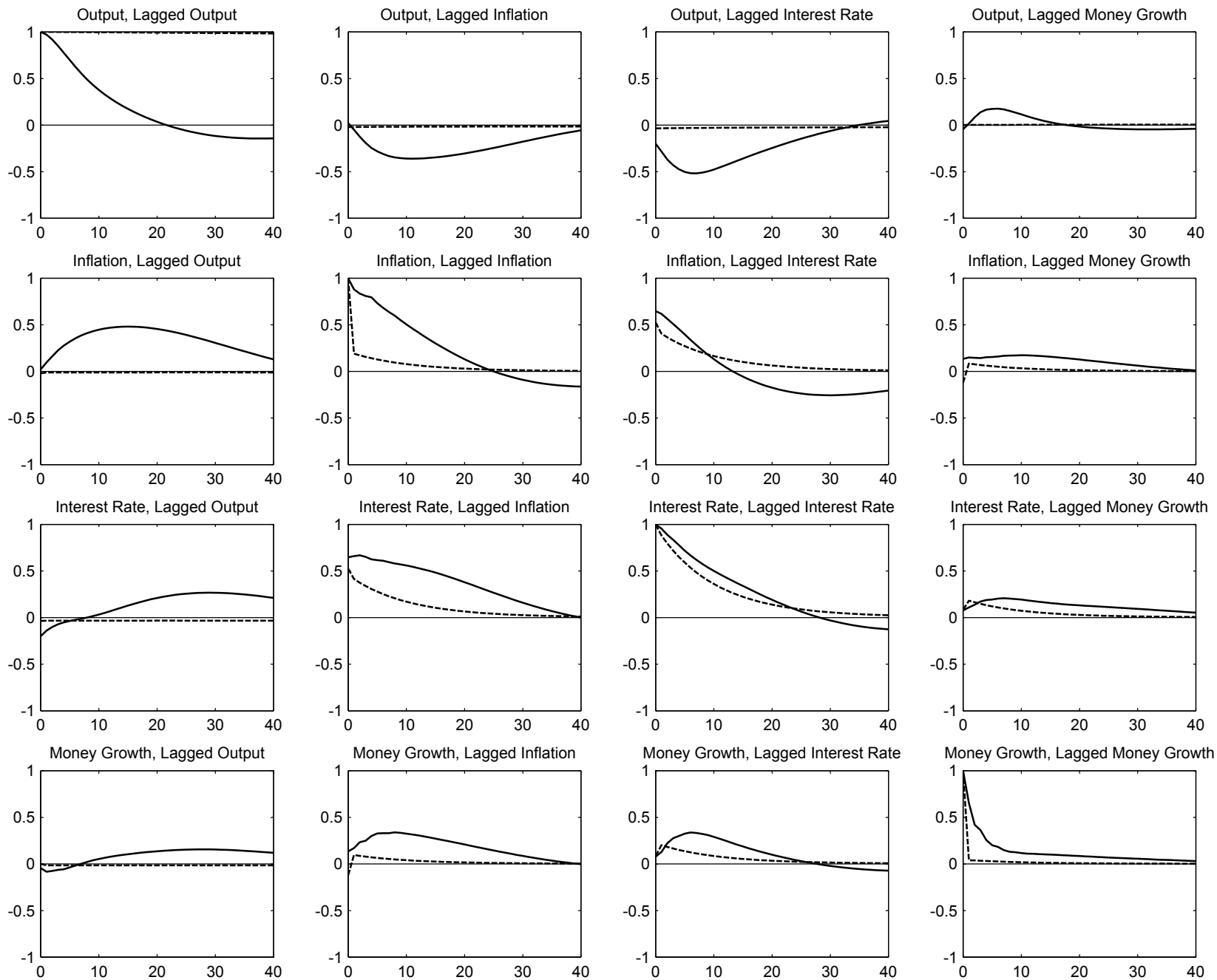


Figure 4: Vector Autocorrelation Functions, Sticky Price and Limited Participation Model (dashed line) and Data (solid line)

