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

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This version: November 2006

Abstract

This paper examines the impact of sticky price and limited participation frictions, both separately and combined, in a dynamic stochastic general equilibrium model. Using U.S. data on output, inflation, interest rates, money growth, consumption, and investment, likelihood ratio tests and Bayesian pseudo-odds measures 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 plausible impulse responses, and monetary policy shocks are responsible for only a modest amount of output, inflation, and nominal interest rate movements.

JEL Classification: C51; E31; E32; E52.

Keywords: Monetary policy; Business cycles; Sticky prices; Limited participation.

*I would like to thank John Duca, Jinill Kim, Robert King, and Christopher Otrok for many helpful discussions and comments. This research also has benefited from the comments of seminar participants at the University of Alabama, Colgate University, College of William & Mary, Southern Methodist University, Texas Tech University, and the 2004 Western Economic Association Annual Meetings. An earlier version of this paper circulated under the title, 'An Estimated Model of Monetary Policy with Real Rigidities.'

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1 Introduction

In recent years, the development of a plausible structural model of the monetary transmission mechanism has been an important objective in monetary economics. Most macroeconomists believe that such a model should be able to generate, at a minimum, a fall in output, a persistent decline in inflation, and a rise in the nominal interest rate after a contractionary monetary policy shock. While models with numerous frictions often are evaluated on their ability to replicate those responses, formal statistical tests also are needed to determine whether including those frictions improves a model's fit with the data. To address that matter, this paper uses maximum likelihood to estimate our model's parameters and then employs likelihood ratio tests and a Bayesian-motivated, pseudo-odds measure to compare our model's fit with and without certain frictions.

Interest in modeling the effects of monetary policy has generated numerous competing dynamic stochastic general equilibrium (DSGE) models, each stressing different structural features. Two popular structural features used in monetary models are price stickiness and limited participation of the representative household in financial markets.[1] 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 [2004] builds on the research of King and Watson [1996] by specifying a DSGE model with both sticky prices and limited participation and finds that the model can generate plausible qualitative responses for output, inflation, and the nominal interest rate. Those results suggest that statistical tests are needed to compare the fit of a model with sticky price and limited participation frictions to a model without either friction.

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. The parameters are estimated using quarterly U.S. data on output, inflation, money growth, nominal interest rate, consumption, and investment under the assumption that those data series provide the best information on the actual values for the degree of price stickiness, and the size of the time adjustment costs.[2] Analysis of our models using likelihood ratio tests and a Bayesian-motivated, pseudo-odds measure indicates that a sticky price and limited participation model fits the data better than either the sticky price model or the limited participation model. When evaluated at its estimated parameter values, our

[1] Limited participation is one source of financial market frictions. Other well-known sources include Carlstrom and Fuerst's [1997] agency costs and Bernanke, Gertler, and Gilchrist's [1999] financial accelerator.

[2] Time adjustment costs are a type of limited participation constraint.

sticky price and limited participation model is able to produce simultaneously the output, inflation, and liquidity effects after a monetary disturbance. The estimated model also is able to generate other business cycle features observed in many empirical studies. For example, monetary policy shocks account for a modest portion of the variability in output, inflation, and the nominal interest rate. The ability of a sticky price and limited participation model to fit the data and replicate key features suggests, at the very least, that the model is a reasonable benchmark for the development of future monetary models.

This study compliments a growing literature that estimates DSGE models and compares their performance to behavior observed in the data. Christiano, Eichenbaum, and Evans (CEE) [2005] develop a DSGE model with numerous nominal and real rigidities and then estimate its parameters by minimizing the distance between their DSGE model's and a vector-autoregression (VAR) model's impulse response functions. Furthermore, CEE [2006] show that their model can replicate many features observed in the data.[3] Using Bayesian methods, Smets and Wouters [2003] estimate a DSGE model similar to CEE [2005] with Euro data and find that their model fits the data better than a VAR model. Taking a more narrow approach, Ireland [2001] uses maximum likelihood to estimate a DSGE model, and then shows that the data supports stickiness in the price level but not in the inflation rate. Our paper is closer in methodology to Ireland [2001] than to Smets and Wouters [2003] and CEE [2005]. That is, we explicitly test for both price stickiness and limited participation in a DSGE model and compare the resulting business cycle features with those observed in the data. Note that it is not the objective of this paper to build an extensive model of the economy that fits the data better than a VAR model.

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 qualitative and quantitative properties of the model. Section 6 serves as the conclusion.

2 Existing Models of the Business Cycle

Many studies evaluate DSGE models by comparing their qualitative responses after a monetary policy shock to those obtained from the estimation of identified VAR models. Using Bayesian techniques, Schorfheide [2000], however, argues that that approach is credible only if the VAR model obtains a higher posterior probability than the DSGE model. The result suggests that models should not be rejected solely on the basis of their ability to match certain behavior emanating from the VAR literature. It is still reasonable, however, to examine whether a DSGE model can replicate results

[3]For example, CEE [2005] is able to generate a fall in output, a persistent decline in inflation, and a rise in the nominal interest rate after a contractionary monetary policy shock.

emerging from a large subset of the VAR literature. For example, after analyzing the results from that literature, CEE [1999] conclude that a contractionary monetary policy shock causes a reduction in output, a persistent decline in inflation, and a rise in the nominal interest rate.[4] This section briefly describes the ability of sticky price models and limited participation models to produce those outcomes. We then summarize findings that suggest that a model with both sticky prices and limited participation can generate results consistent with some key qualitative effects of a monetary policy shock observed in many empirical studies.

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 may be strong enough to dominate any rise in the real interest rate. As a result, the nominal interest rate in a sticky price model may fall instead of rising 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. This constraint then prevents 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 generates the liquidity effect, it fails to produce 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 [2004] 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 limited participation into a sticky price model enables the model to produce the liquidity effect by further reducing savings after a negative monetary disturbance.

[4] Using a new agnostic method, Uhlig [2005] argues that a monetary policy shock has no significant effect on output even though the price level gradually changes.

That reduction then leads to more upward pressure on both nominal and real interest rates. Keen [2004] 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, and the size of the time adjustment costs. Since the literature has not converged on a uniform set of values for those features, this paper uses maximum likelihood to estimate directly the parameters of a sticky price and limited participation model. The maximum likelihood estimation of the parameters also enables us to formally test whether a sticky price and limited participation model fits the data better than both a sticky price model and a limited participation model.

3 The Model

The model developed here extends the sticky price and limited participation model developed in Keen [2004] in two ways. One, this model, motivated by Bernanke and Blinder [1992] and Taylor [1993], identifies the nominal interest rate instead of the money growth rate as the target of monetary policy. Two, our model specifies five non-policy exogenous shocks to capture the effects of production technology, money demand, aggregate demand, investment technology, and government spending.

The model comprises a representative household, monopolistically competitive firms, a capital supplier, a government, and banks. The representative household purchases consumption goods from the firms. A fraction of those consumption purchases and lump-sum taxes must be paid in advance out of existing money balances. Remaining money balances plus a transfer from the monetary authority 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 representative household, and government spending is financed via lump-sum taxes on the representative household.

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 ($c_t(z)$, $z \in [0, 1]$):

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

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:

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

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:

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

The representative household begins each period with its money holdings, M_{t-1}, from last period. At the start of the period, the household receives a lump-sum injection from the monetary authority, $X_t = M_t - M_{t-1}$, but also must prepay a fraction, v_t, of its lump-sum taxes, T_t. Of the remaining funds, S_t is allocated for consumption purchases, while $M_{t-1} - S_t + X_t - v_t T_t$ is saved 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.[5] That restriction leads to the following cash constraint:

$$v_t P_t c_t = S_t, \tag{3}$$

where $0 < v_t < 1$.[6] 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 [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:

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

[5] 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.

[6] It is shown later that v_t is the inverse of the velocity of money.

where $\gamma > 0$ is the magnitude of the time adjustment costs and μ 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:

$$n_t + l_t + h_t = 1, \tag{4}$$

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, and the capital supplier, D_t^c. At the same time, the household pays for the remainder of its taxes, $(1 - v_t)T_t$, and consumption purchases, $(1 - v_t)P_t c_t$. Thus, end-of-the-period money balances, M_t, held by the household are:

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

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:

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

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.[7]

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

[7] 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.

the representative household and rents capital, $k_t(z)$, from the capital supplier to produce $y_t(z)$ according to the following production function:

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

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 zth firm yields the following input factor demands:

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

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

where q_t is the real user cost of capital and ψ_t is the real marginal cost.

Each period, a fraction of the firms, η, 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.[8] The advantage of such a 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:

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

where λ_t measures the marginal utility value of an additional dollar of profits to the household:

$$\lambda_t = U_l(c_t, l_t)/W_t.^{9}$$

[8]Keen [2004] specifics 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.

[9]If the value of profits to the representative household is expressed in terms of the marginal utility of consumption, λ_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, λ_t is expressed as:

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

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}, λ_{t+j}, and y_{t+j}, the demand schedule and the cost minimizing quantities of factor inputs are substituted into (8).[10] Solving that profit maximization problem yields the optimal price for an adjusting firm, $P_t(z)$, which can be written as:

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

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 each 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:

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

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

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

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

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

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 Government

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 this 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.[11] Third, Bernanke and Mihov [1998] and Strongin [1995] argue that money growth rates often are 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 incorporates an interest rate smoothing term into the rule used by Ireland [2001]. The monetary authority adjusts the nominal interest rate, R_t, in response to changes in the lagged nominal interest rate, R_{t-1}, output, y_t, inflation, $\pi_t = P_t/P_{t-1}$, and money growth, $\mu_t = M_t/M_{t-1}$, such that:

$$\ln(R_t/R) = \omega\ln(R_{t-1}/R)+(1-\omega)[\phi_y\ln(y_t/y)+\phi_\pi\ln(\pi_t/\pi)+\phi_\mu\ln(\mu_t/\mu)]+\varepsilon_{Rt}, \quad (11)$$

where ω is the degree of nominal interest rate smoothing and $\varepsilon_{Rt}\sim N(0,\sigma_R^2)$.

Nominal government spending, P_tg_t, is financed by lump-sum taxes, T_t, on the household such that:

$$P_tg_t = T_t. \quad (12)$$

Since a fraction of government spending, v_t, must be prepaid, an equivalent fraction of taxes are collected at the beginning of each period to finance this prepayment. The payments for the remaining fraction of government spending and taxes, $(1-v_t)$, are completed at the end of the period. Real government purchases are an exogenous stochastic fraction of output:

$$g_t = (1-1/G_t)y_t$$

[11] 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.

such that parameter G_t follows an autoregressive process:

$$\ln(G_t) = \rho_G \ln(G_{t-1}) + (1 - \rho_G)\ln(G) + \varepsilon_{Gt},$$

where $G > 0$, $0 < \rho_G < 1$, and $\varepsilon_{Gt} \sim N(0, \sigma_G^2)$.

3.5 Banks

Banks facilitate lending between the household and the capital supplier. Each period, banks receive household deposits, $M_{t-1} - S_t + X_t - v_t T_t$, and 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:

$$v_t P_t i_t = [M_{t-1} - S_t + X_t - v_t T_t]. \tag{13}$$

At the end of the period, the capital supplier repays its loan interest, $R_t v_t P_t i_t$, and the representative household receives its savings plus interest, $R_t(M_{t-1} - S_t + X_t - v_t T_t)$.

Combining the loan market clearing condition, (13), with the household's cash constraint, (3), and the government's budget constraint, (12), yields the quantity equation of money:

$$P_t y_t = M_t(1/v_t). \tag{14}$$

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

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, π, 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, T_t, M_t, D_t^c, and D_t^f are divided by π^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].[12] The solution of the model is transformed easily into the following state space form:

$$\mathbf{s}_t = \mathbf{M}\mathbf{s}_{t-1} + \boldsymbol{\varepsilon}_t, \tag{15}$$

$$\mathbf{Y}_t = \mathbf{\Pi}\mathbf{s}_t, \tag{16}$$

[12] The solution methodology of King and Watson [1998, 2002] is a generalization of the methods of Blanchard and Kahn [1980].

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 six independent innovations ε_{at}, ε_{vt}, ε_{Zt}, ε_{Jt}, ε_{Gt}, and ε_{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 $E[\boldsymbol{\varepsilon}_t\boldsymbol{\varepsilon}_t'] = \mathbf{\Omega}$ that is diagonal.

Data on output, inflation, money growth, the nominal interest rate, consumption, 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 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 consumption and investment also are included because they provide key information on the magnitude of the time adjustment costs and capital adjustment costs, respectively. Obtaining accurate parameter estimates for the probability of price adjustment and the magnitude of the time adjustment costs are 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, 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, (16).[13]

The state space representation of the model solution, (15) and (16), 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 (16) based on $\ddot{\mathbf{Y}}_{t-1} \equiv (\mathbf{Y}_{t-1}, ..., \mathbf{Y}_1)$. 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 $\mathbf{s}_1$:

$$L(\Theta) = \sum_{t=2}^{T} \log f_{\mathbf{Y}_t|\ddot{\mathbf{Y}}_{t-1}}(\mathbf{Y}_t|\ddot{\mathbf{Y}}_{t-1}, \Theta), \tag{17}$$

where Θ is a vector of parameters.[14] Since (17) is a function of $\mathbf{\Pi}$, $\mathbf{M}$, and $\mathbf{\Omega}$, the model's parameters are estimated by numerically maximizing (17) with respect to Θ.

The data used to estimate the model covers the period from 1959Q2-2003Q4. Output, consumption, and investment are obtained by dividing the nominal data for gross domestic product, personal consumption expenditures, and gross private

[13] Models with more variables than innovations require the presence of error terms in (16) to prevent the covariance matrix of the data from being singular.

[14] See Hamilton [1994, Ch. 13] for details on this technique.

domestic investment by their respective chain-weight price deflators.[15] Output, consumption, and investment data are expressed in per capita terms by dividing each series by the civilian, noninstitutional population, age 16 and over. Inflation is the percent change in the fixed-weight 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, consumption, and investment data. The model, however, assumes that those variables move around their steady states. The fact that output, consumption, and investment grow at different rates 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, output, consumption, and investment data are linearly detrended by their average quarterly growth rates of 0.00452, 0.00514, 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, θ_2, and the depreciation rate, δ. The value of θ_2 then is parameterized so that the nonstochastic steady state value of labor, $\overline{n}$, is 0.2. The depreciation rate, δ, 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 φ, φ', and φ''. 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, φ and φ' are set to i/k and 1, respectively. The only investment adjustment cost parameter estimated is the inverse of the elasticity of the investment-to-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 0.579, which is consistent with the average ratio of detrended real output to detrended real M2 balances. It is also difficult to distinguish the price elasticity of demand, ϵ, from the production technology parameter, Z, so ϵ 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]

[15] Deflating by a chain-weight price index is necessary because the Bureau of Economic Analysis has not produced fixed-weight price deflators for consumption and investment since 1996. The use of a chain-weight measure to deflate nominal series is also employed in Del Negro et. al. [2006] and Primiceri, Schaumburg, and Tambalotti [2006].

survey of empirical studies. Lastly, the ratio of the steady state government spending to output, $1 - 1/G$, is set to 0.265, since the sum of consumption and investment averages 73.5% of GDP over the sample period.

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, formal statistical tests can be used to determine whether the introduction of sticky prices and limited participation yields a statistically significant improvement in the ability of our combined model to fit the data. Two, the results generated by each model can be compared informally with results from the other models and empirical studies. Each model also is estimated over both the full sample (1959Q2-2003Q4) and a post-1979 sample (1979Q4-2003Q4). The post-1979 period is examined because many economists believe that a fundamental change occurred in Federal Reserve policy in October 1979. Tables 1-3 display the parameters' maximum likelihood estimates and their 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.

One way to assess the sticky price and limited participation frictions is to determine whether the estimated fraction of price setting firms, η, is significantly lower than one and the estimated degree of time adjustment costs, γ, is significantly greater than zero in their respective models. To begin, the sticky price model estimates a value for η of 0.2019 for the full sample and 0.2717 for the post-1979 sample, while the estimated value η of the sticky price and limited participation model is 0.2050 for the full sample and 0.2187 for the post-1979 sample. In every case, the estimates are statistically significant. Furthermore, our estimate that anywhere from $20\% - 27\%$ of all firms adjust their price in any given period is consistent with survey evidence, which finds that firms on average change their price about once a year.[16] The estimated value of γ in the limited participation model and the sticky price and limited participation model is 0.0075 and 0.0707, respectively, in the full sample and 0.0131 and 0.0588, respectively, in the post-1979 sample. The estimated values of γ are statistically significant in the post-1979 sample, but the hypothesis of $\gamma = 0$ cannot be rejected in the full sample.

We also conduct likelihood ratio tests to determine whether a model with both sticky prices and limited participation can better explain the empirical behavior of our observed variables than a model without either sticky prices or limited participation.[17] The likelihood ratio statistic is formed by doubling the difference between the

[16] See Rotemberg and Woodford [1997] for a discussion of this survey evidence.

[17] The likelihood ratio test is utilized because, unlike the Wald test, it does not reference standard errors.

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 $3,998.9$ in the full sample and $2,204.5$ in the post-1979 sample. When sticky prices are excluded (the constraint $\eta = 1$ is imposed), the limited participation model's maximum value of the log-likelihood function is $3,935.3$ in the full sample and $2,178.0$ in the post-1979 sample. Since the p-value for the null hypothesis of $\eta = 1$ is less than 0.001 in both sample periods, the introduction of sticky prices statistically improves the ability of the model to fit the data. In the case where limited participation is excluded (the constraint $\gamma = 0$ is imposed), the maximum value of the log-likelihood function for the sticky price model is $3,985.9$ in the full sample and $2,184.1$ in the post-1979 sample. As a result, the p-value for the null hypothesis $\gamma = 0$ is less than 0.001 for both sample periods, which indicates that the model's fit to the data is improved statistically by including limited participation.[18]

An alternative test to compare models is the Bayesian information criterion (BIC). Unlike the likelihood ratio test, the BIC allows a comparison of models that are non-nested. Therefore, the fit of our three models also can be compared with a VAR model.[19] The BIC is calculated by penalizing the log-likelihood value of a model by the number of estimated parameters such that:

$$BIC(i) = L(i) - \frac{N_P(i)}{2} \ln(T),$$

where $L(i)$ is the log-likelihood value for model i, $N_P(i)$ is the number of estimated parameters in model i, and T is the sample size of the data. Using the BIC, we can calculate a Bayesian-style, pseudo-odds measure that generates a data determined probability of model i:

$$\rho(i) = \frac{\exp(BIC(i))}{\sum_{j=1}^{z} \exp(BIC(j))},$$

where z is the number of models examined.

Table 4 reports the log-likelihood, the BIC, and pseudo-odds measure for the sticky price model, the limited participation model, the sticky price and limited participation model and low-order VAR models for both sample periods.[20] Specifically, all three DSGE models are tested against four separate VAR models where the number of lags, N, varies from 1 to 4. Our results from the pseudo-odds measure indicate that in both sample periods the sticky price and limited participation model fits the

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

[19] Brock, Durlauf, and West [2003] and Kiley [2006] are examples of other non-Bayesian studies that have used the BIC for model comparison.

[20] The VAR model used is $X_t = A(L)X_{t-1} + e_t$, where $X_t = [c_t, i_t, y_t, \pi_t, \Delta M_t, R_t]^T$.

data best when the VAR model has 3 or 4 lags. In addition, we can conclude from the test that the data supports including both sticky price and limited participation constraints in a DSGE model. When the VAR model has 1 or 2 lags, the pseudo-odds measure finds that the VAR model fits the data better than any of the DSGE models. This finding is not surprising given the fact that our sticky price and limited participation model does not include a large number of exogenous shocks and many of the features that economists find are critical to matching the data. Smets and Wouters [2003], for example, note that an estimated DSGE model "is sufficiently rich to capture the time series properties of the data, as long as a sufficient number of structural shocks is considered."[21] Kiley [2006] argues that a sticky price specification with a backward-looking component to inflation (i.e., Fuhrer and Moore [1995]) matches the data much better than the standard sticky price specification used in our model. Del Negro et. al. [2006] also assert that habit persistence in consumption "substantially improves the fit of the DSGE model."

5.2 Impulse Responses

DSGE models are evaluated frequently by comparing their dynamic responses after a monetary disturbance to those responses observed in the data. Many macroeconomists believe that a plausible model of the monetary transmission mechanism should produce a decline in real output, a persistent fall in the inflation rate, and an increase in the nominal interest rate after a contractionary monetary policy shock. Figure 1 displays the impact of a temporary 1% contractionary monetary policy shock for our three estimated DSGE models for both sample periods.

Column one 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 is observed in many empirical studies. The nominal interest rate rises by only 5 basis points in the full sample and 33 basis points in the post-1979 sample. The size of those increases, however, is still lower than many macroeconomists would expect. Failure of the nominal interest rate to generate a sizable increase occurs because the real interest rate does not rise enough to compensate for falling inflation expectations. The estimated limited participation model's impulse responses of output, inflation, and the nominal interest rate are displayed in the second column of Figure 1. For both samples, the impulse responses to a contractionary monetary disturbance are virtually identical. (Note: The impulse response for the '1959Q2-2003Q4' sample overlays the impulse response for the model '1979Q4-2003Q4' sample.) Output and the nominal interest rate remain virtually unchanged in the limited participation model, while inflation falls for one period but 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

[21] Smets and Wouters [2003] find that their model with ten exogenous shocks fits the data better than a low-order VAR model.

the small estimates of the time adjustment costs ($\gamma = 0.0075$ in the full sample and $\gamma = 0.0131$ in the post-1979 sample). In fact, those costs are so small that our estimated limited participation model is equivalent essentially to a flexible price model without limited participation.

Column three of Figure 1 demonstrates that a contractionary monetary policy shock in our estimated sticky price and limited participation model produces a drop in output, a persistent decline in the inflation rate, and a sizeable rise in the nominal interest rate. 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 ($\gamma = 0.0707$ in the full sample and $\gamma = 0.0588$ in the post-1979 sample), although at least four times larger than in the estimated limited participation model, help push up the real interest rate. That increase in the real interest rate dominates any decline in inflation expectations, so that the nominal interest rate rises. A drawback of our estimated sticky price and limited participation model, and other sticky price specifications without a backward-looking component to inflation, 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 a decline in output, a persistent drop in inflation, and a sizeable increase in the nominal interest rate following a monetary policy shock. Without both sticky prices and limited participation, our model finds it difficult to generate simultaneously those responses. Therefore, our results show quantitatively that a combined sticky price and limited participation model can generate dynamic responses for output, inflation, and the nominal interest rate after a monetary disturbance that are consistent with a large subset of the VAR literature.

5.3 Variance Decompositions

Another way to evaluate 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 5-7 show the forecast error variance decomposition for output, the inflation rate, and the nominal interest rate over the full sample in our estimated sticky price model, limited participation model, and sticky price and limited participation model, respectively. Tables 8-10 then repeat that analysis for the post-1979 sample. 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, investment technology, and government spending. 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 5-10 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. At a forecast horizon of two or more years, the production technology shock is responsible for more than 50% of output's variation in all of our models estimated over the full sample period. When estimated using the post-1979 data, the impact of production technology shocks on output movements diminishes slightly while investment technology shocks explain around 1/3 of output's variability at a forecast horizon of five years. The full sample results are consistent with Primiceri, Schaumburg, and Tambalotti's (PST) [2006] finding that intratemporal shocks, like our production technology shock, drive output variations when real rigidities are absent from a DSGE model.[22] Our post-1979 sample results, however, suggest that PST's [2006] conclusion that a mix of nominal and real frictions are necessary for intertemporal shocks, like our investment technology shock, to have an important role in explaining output variation maybe at least partially sensitive to the estimation period.[23] When prices are sticky, money demand shocks are an important source of the variation in output at a forecast horizon of one year or less. Since prices cannot adjust completely in those models, output must change after a money demand shock according to the quantity equation, (14).[24] Monetary policy shocks in our estimated models with sticky prices explain anywhere from $26\% - 37\%$ of output's movements at a forecast horizon of one quarter, but that size decreases to around $15\% - 25\%$ 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 VAR literature. Specifically, Leeper, Sims, and Zha [1996] and CEE [1999] indicate there is broad agreement in the VAR literature that monetary policy shocks account for a fairly small portion of output's variability in the actual economy.[25] Even Uhlig [2005], who criticizes some conclusions from the VAR literature, generates the same result.

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. When models with price stickiness are estimated over the full sample, production technology shocks are responsible for 50% or more of inflation's movements over all forecast horizons. In the post-1979 sample, production technology shocks have less of an influence on inflation, while money demand and aggregate demand shocks have a greater impact. Monetary policy shocks are responsible for only $9\% - 16\%$ of in-

[22] Capital adjustment costs is the only real rigidity present in our model.

[23] PST [2006] estimate their model over the period 1954Q3-2004Q4.

[24] Since all the exogenous variables are independent of each other, monetary policy is unable to accommodate shifts in money demand.

[25] 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 that result does not deny that the endogenous component of monetary policy can play a sizeable role in the variability of output.

flation's variability in all models with sticky prices, except the post-1979 sticky price model where its contribution is $15\% - 28\%$ of the variation in inflation. Such a fairly small role for the monetary policy shock is consistent with CEE's [1999] assertion that monetary disturbances account for a very modest portion of inflation's movements. In the limited participation model, however, more than 50% of inflation's variability 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 nearly 60% or more of its variability in all of our estimated models at all forecast horizons. That result is consistent with PST's [2006] claim that intertemporal shocks drive nominal interest rate movements in DSGE models. Monetary policy shocks, on the other hand, account for a very small amount of the nominal interest rate's variability in the sticky price model and in the limited participation model. In the sticky price and limited participation model, the nontrivial amount of interest rate smoothing in the estimated monetary policy rule enables monetary policy shocks to have modest short-run effects on nominal interest rate movements. Specifically, monetary policy shocks explain about 30% of the nominal interest rate's movements one quarter ahead, but that amount reduces to about 16% when the time horizon increases to one year ahead. The contribution of monetary policy shocks to nominal interest rate movements declines further as the time horizon increases. Therefore, the majority of the variation in the nominal interest rate results from systematic responses of monetary policy to economic conditions. Our finding that monetary policy shocks account for a small percentage of the variation in the nominal interest rate is consistent with empirical studies such as Uhlig [2005].

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 VAR.[26]

The vector autocorrelation functions for our three estimated models and the data are displayed in Figures 2-4 for the full sample and Figures 5-7 for the post-1979 sample. The autocorrelations for the sticky price model and the sticky price and limited participation model estimated over the full sample match the data quite well given the fact that the models have just 22 and 23 estimated parameters, respectively. In the post-1979 sample, the sticky price model overpredicts output persistence, but oth-

[26] Fuhrer and Moore [1995] suggest this procedure for calculating vector autocorrelation functions in the data.

erwise does a decent job fitting the data. The sticky price and limited participation model not only overpredicts output in the post-1979 sample, but also it generates the wrong sign for the correlations between output and other key macroeconomic variables. Finally, the limited participation model fails miserably in both sample periods at replicating any of the autocorrelations involving output, and it also underpredicts dramatically the degree of inflation persistence.

Two business cycle features that DSGE models often are unable to replicate is the degree of inflation persistence and the relationship between output and the lagged nominal interest rate. In the full sample, the sticky price model and the sticky price and limited participation model, like most models with price stickiness, underpredict the degree of inflation persistence.[27] Ireland [2001], however, finds that a DSGE model with price stickiness estimated using post-1979 data is able to match the degree of inflation persistence observed in the data.[28] An examination of the results from our post-1979 sample for our sticky price model and sticky price and limited participation model confirms that finding. As for the relationship between output and lagged nominal interest rates, King and Watson [1996] argue that a common deficiency of most DSGE models is their inability to generate a strong negative relationship observed over much of the post-WWII data. Both of our models with price stickiness estimated over the full sample generate that negative relationship, but that relationship is much weaker than what is observed in the data. In the post-1979 data, the observed relationship between output and the lagged nominal interest rate is positive. The sticky price model estimated with post-1979 data produces a slight positive relationship between output and the nominal interest rate, but the combined sticky price and limited participation model does not.

6 Conclusion

One of the primary long-term goals in monetary economics is to develop a structural model usable for monetary policy analysis. Many studies focus on building DSGE models with many frictions that can replicate the impulse responses for key variables like output, inflation, and the nominal interest rate. Formal testing, however, is necessary also to determine whether including certain frictions enables the model to fit the data better. Our paper addresses that issue by using formal econometric methods to estimate the model's parameters and to test for the significance of the sticky price and limited participation frictions.

Our objective in this paper is to qualitatively and quantitatively evaluate the empirical plausibility of three DSGE models: a sticky price model, a limited partici-

[27] See Fuhrer and Moore [1995] for a discussion of inflation persistence in models with price stickiness.

[28] 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. Estimates in Tables 1-3 imply that those shocks are extremely persistent in our models.

pation model, and a sticky price and limited participation model. Keen [2004] 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 imply that the fit of the sticky price and limited participation frictions to the data should be tested formally. To undertake that challenge, we estimate directly the parameters for our three DSGE models using maximum likelihood. Likelihood ratio tests and a Bayesian-motivated, pseudo-odds measure indicate that the combined sticky price and limited participation model matches the data better than the sticky price model or the limited participation model. Furthermore, a contractionary monetary policy shock in the sticky price and limited participation model produces impulse responses for output, inflation, and the nominal interest rate that is consistent with its qualitative behavior observed in the data. The estimated sticky price and limited participation model also generates the finding in many empirical VAR models that only a limited amount of the variation in output, inflation, and the nominal interest rate is due to monetary policy shocks.

The combination of sticky prices and limited participation in a DSGE model is a promising development in our overall understanding of the monetary transmission process. This paper shows that a model with only those couple of features is consistent 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

	1959Q2-2003Q4		1979Q4-2003Q4	
Parameter	Estimate	Standard Error	Estimate	Standard Error
α	0.1624	0.0050	0.1778	0.0102
θ_1	1.0006	0.0001	1.0023	0.0016
β	0.9945	0.0010	0.9919	0.0010
π	1.0087	0.0011	1.0025	0.0033
η	0.2019	0.0286	0.2717	0.0407
ϕ_y	0.0680	0.0401	0.0057	0.0104
ϕ_π	0.2501	0.2094	0.5014	0.1115
ϕ_μ	1.9040	0.5478	0.7299	0.0931
ω	0.0025	0.3414	3×10^{-6}	0.4014
γ	–	–	–	–
χ	-0.2602	0.0678	-0.1460	0.0427
Z	$13,062$	842.59	$13,996$	$1,871.8$
ρ_Z	0.9306	0.0247	0.8541	0.0368
ρ_a	0.8996	0.0225	0.9332	0.0232
ρ_J	0.8198	0.0369	0.9951	0.0068
ρ_v	0.9978	0.0059	0.9999	0.0071
ρ_G	0.9607	0.0129	0.9959	0.0051
σ_R	0.0169	0.0053	0.0075	0.0028
σ_Z	0.0166	0.0020	0.0120	0.0017
σ_a	5×10^{-6}	9×10^{-7}	1×10^{-5}	9×10^{-6}
σ_J	0.0148	0.0031	0.0213	0.0049
σ_v	0.0108	0.0006	0.0108	0.0008
σ_G	0.0038	0.0002	0.0035	0.0002

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

	1959Q2-2003Q4		1979Q4-2003Q4	
Parameter	Estimate	Standard Error	Estimate	Standard Error
α	0.1428	0.0100	0.1593	0.0106
θ_1	1.0001	3×10^{-5}	0.9999	2×10^{-7}
β	0.9939	0.0011	0.9919	0.0011
π	1.0090	0.0021	1.0061	0.0043
η	–	–	–	–
ϕ_y	4×10^{-7}	0.0258	3×10^{-9}	0.0223
ϕ_π	1.7108	0.2026	1.4936	0.1228
ϕ_μ	0.3504	0.1114	0.3067	0.0698
ω	0.1177	0.3551	4×10^{-5}	0.1502
γ	0.0075	0.0095	0.0131	0.0062
χ	-0.9103	0.3381	-0.2955	0.0526
Z	$15,944$	$1,954.9$	$16,357$	$2,557.6$
ρ_Z	0.9833	0.0096	0.9835	0.0180
ρ_a	0.9028	0.0158	0.8886	0.0191
ρ_J	0.9664	0.0197	0.9983	0.0080
ρ_v	0.9956	0.0106	0.9985	0.0057
ρ_G	0.9638	0.0187	0.9977	0.0052
σ_R	0.0077	0.0025	0.0052	0.0008
σ_Z	0.0082	0.0005	0.0071	0.0006
σ_a	1×10^{-6}	1×10^{-7}	1×10^{-8}	2×10^{-9}
σ_J	0.0655	0.0197	0.0401	0.0126
σ_v	0.0108	0.0006	0.0109	0.0008
σ_G	0.0036	0.0002	0.0034	0.0002

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

	1959Q2-2003Q4		1979Q4-2003Q4	
Parameter	Estimate	Standard Error	Estimate	Standard Error
α	0.1658	0.0051	0.1717	0.0098
θ_1	1.0005	0.0002	1.0001	1×10^{-6}
β	0.9934	0.0011	0.9923	0.0011
π	1.0097	0.0019	1.0056	0.0018
η	0.2050	0.0363	0.2187	0.0267
ϕ_y	0.0476	0.0244	0.0252	0.0163
ϕ_π	0.5845	0.1095	0.6851	0.1585
ϕ_μ	1.1357	0.2021	0.8517	0.1135
ω	0.5556	0.2322	0.2270	0.2253
γ	0.0707	0.0529	0.0588	0.0274
χ	-0.2808	0.1289	-0.1802	0.0427
Z	$12,432$	805.37	$15,120$	$1,961.6$
ρ_Z	0.9223	0.0267	0.8361	0.0493
ρ_a	0.9090	0.0431	0.8916	0.0307
ρ_J	0.9010	0.0252	0.9963	0.0054
ρ_v	0.9992	0.0091	0.9998	0.0083
ρ_G	0.9770	0.0122	0.9966	0.0050
σ_R	0.0055	0.0026	0.0062	0.0017
σ_Z	0.0168	0.0033	0.0150	0.0027
σ_a	5×10^{-6}	1×10^{-6}	1×10^{-7}	2×10^{-8}
σ_J	0.0167	0.0072	0.0258	0.0054
σ_v	0.0108	0.0006	0.0109	0.0008
σ_G	0.0038	0.0002	0.0034	0.0003

Table 4: Model Comparison

Panel A: 1959Q2-2003Q4

	Log-likelihood	BIC	Pseudo-odds measure N=4	N=3	N=2	N=1
Sticky Price	3,985.9	3,928.8	0.00	0.00	0.00	0.00
Limited Participation	3,935.3	3,878.2	0.00	0.00	0.00	0.00
Sticky Price and Limited Part.	3,998.9	3,939.2	1.00	0.94	0.00	0.00
VAR, N equals 4	4,296.7	3,855.1	0.00	–	–	–
VAR, N equals 3	4,285.5	3,936.5	–	0.06	–	–
VAR, N equals 2	4,267.7	4,011.5	–	–	1.00	–
VAR, N equals 1	4,225.7	4,062.5	–	–	–	1.00

Panel B: 1979Q4-2003Q4

	Log-likelihood	BIC	Pseudo-odds measure N=4	N=3	N=2	N=1
Sticky Price	2,184.1	2,133.8	0.00	0.00	0.00	0.00
Limited Participation	2,178.0	2,127.7	0.00	0.00	0.00	0.00
Sticky Price and Limited Part.	2,204.5	2,151.9	1.00	1.00	0.00	0.00
VAR, N equals 4	2,432.1	2,044.6	0.00	–	–	–
VAR, N equals 3	2,412.4	2,105.7	–	0.00	–	–
VAR, N equals 2	2,387.7	2,162.3	–	–	1.00	–
VAR, N equals 1	2.347.4	2,203.6	–	–	–	1.00

Table 5: Forecast Error Variance Decompositions
Sticky Price Model
1959Q2-2003Q4

Panel A: Output Decompositions

	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	37.2	33.4	29.4	25.6	15.9	11.8	9.2
Production technology	6.7	14.8	23.7	32.2	54.5	64.0	70.0
Aggregate demand	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Money demand	55.2	49.8	44.0	38.4	24.0	18.0	14.0
Investment technology	0.7	1.3	2.0	2.5	3.1	2.9	2.6
Government spending	0.2	0.6	1.0	1.4	2.5	3.2	4.0

Panel B: Inflation Rate Decompositions

	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	15.9	16.0	16.0	16.0	15.9	15.8	15.7
Production technology	56.9	56.2	55.6	55.0	53.2	52.5	52.1
Aggregate demand	4.0	4.6	5.1	5.6	7.1	7.9	8.4
Money demand	21.6	21.5	21.4	21.3	20.8	20.6	20.4
Investment technology	0.0	0.2	0.4	0.6	1.4	1.8	1.9
Government spending	1.6	1.6	1.6	1.6	1.5	1.5	1.5

Panel C: Nominal Interest Rate Decompositions

	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Production technology	0.1	0.3	0.4	0.6	1.5	2.4	3.8
Aggregate demand	36.5	38.6	40.5	42.2	46.8	48.8	49.8
Money demand	1.6	1.6	1.7	1.7	1.9	2.0	2.1
Investment technology	60.6	58.3	56.1	54.2	48.5	45.4	43.0
Government spending	0.3	0.4	0.4	0.5	0.5	0.6	0.6

Table 6: Forecast Error Variance Decompositions
Limited Participation Model
1959Q2-2003Q4

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	67.0	66.4	65.7	65.0	62.2	59.5	55.0
Aggregate demand	0.3	0.3	0.2	0.2	0.1	0.1	0.1
Money demand	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Investment technology	22.1	23.1	24.2	25.3	29.3	32.9	38.7
Government spending	10.6	10.2	9.9	9.6	8.5	7.5	6.1

Panel B: Inflation Rate Decompositions

	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	69.8	67.2	65.2	63.6	60.0	58.5	57.4
Production technology	8.0	7.7	7.5	7.3	6.9	6.8	6.7
Aggregate demand	4.4	7.8	10.3	12.2	16.6	18.4	19.4
Money demand	16.9	16.3	15.8	15.4	14.5	14.2	13.9
Investment technology	0.3	0.5	0.7	0.9	1.4	1.7	2.0
Government spending	0.6	0.6	0.6	0.6	0.6	0.6	0.6

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	4.3	2.6	2.1	1.8	1.6	1.7	1.9
Aggregate demand	80.7	85.3	86.7	87.2	87.2	86.6	85.5
Money demand	4.6	2.6	1.9	1.5	1.1	0.9	0.9
Investment technology	10.2	9.3	9.2	9.3	10.0	10.7	11.5
Government spending	0.3	0.2	0.2	0.2	0.2	0.2	0.21

Table 7: Forecast Error Variance Decompositions
Sticky Price and Limited Participation Model
1959Q2-2003Q4

Panel A: Output Decompositions

	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	30.8	27.0	22.6	18.9	10.9	8.2	6.5
Production technology	11.3	23.3	34.1	42.8	60.9	66.7	69.2
Aggregate demand	0.4	0.4	0.4	0.3	0.2	0.2	0.2
Money demand	49.2	39.9	32.6	26.9	15.5	11.6	9.3
Investment technology	6.6	7.1	7.5	7.8	7.9	7.7	7.4
Government spending	1.8	2.3	2.8	3.2	4.6	5.7	7.4

Panel B: Inflation Rate Decompositions

	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	12.4	12.1	11.7	11.4	10.5	10.1	9.8
Production technology	56.9	55.9	54.9	54.0	51.4	50.0	49.0
Aggregate demand	14.7	16.6	18.3	19.9	24.1	26.2	27.6
Money demand	14.4	13.8	13.3	12.8	11.7	11.3	11.0
Investment technology	0.0	0.1	0.2	0.3	0.7	0.9	0.9
Government spending	1.5	1.6	1.6	1.6	1.6	1.6	1.7

Panel C: Nominal Interest Rate Decompositions

	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	30.0	22.6	18.9	16.7	12.6	11.0	9.9
Production technology	0.4	0.4	0.3	0.5	3.2	5.9	8.8
Aggregate demand	25.2	37.7	44.5	48.9	56.2	58.1	58.5
Money demand	2.9	5.4	6.1	6.2	5.4	4.8	4.4
Investment technology	37.7	31.4	28.1	26.1	21.5	19.2	17.3
Government spending	3.8	2.6	2.0	1.7	1.2	1.1	1.0

Table 8: Forecast Error Variance Decompositions
Sticky Price Model
1979Q4-2003Q4

Panel A: Output Decompositions

	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	37.6	29.3	23.0	18.6	11.2	8.8	6.8
Production technology	17.1	30.6	40.2	46.1	50.9	47.1	38.4
Aggregate demand	0.1	0.2	0.2	0.3	0.4	0.5	0.5
Money demand	41.6	32.6	25.6	20.7	12.5	9.9	7.6
Investment technology	2.5	5.0	7.4	9.6	16.8	22.5	31.2
Government spending	1.2	2.4	3.7	4.7	8.3	11.2	15.6

Panel B: Inflation Rate Decompositions

	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	27.4	26.8	25.5	23.9	19.1	16.9	15.3
Production technology	25.6	21.2	18.3	16.9	15.0	13.8	12.5
Aggregate demand	14.1	18.1	21.6	24.2	29.6	32.0	34.5
Money demand	30.0	29.3	27.9	26.2	20.9	18.5	16.7
Investment technology	1.0	2.8	5.0	7.4	14.3	17.8	20.1
Government spending	1.9	1.7	1.6	1.5	1.2	1.1	1.0

Panel C: Nominal Interest Rate Decompositions

	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	5.7	5.0	4.4	4.0	3.0	2.6	2.3
Production technology	22.3	18.4	15.5	13.4	9.3	8.1	7.6
Aggregate demand	24.4	27.5	30.0	32.0	36.8	39.1	41.3
Money demand	6.1	5.3	4.7	4.3	3.2	2.8	2.5
Investment technology	40.1	42.4	44.0	45.1	46.5	46.4	45.4
Government spending	1.5	1.4	1.3	1.3	1.1	1.0	0.9

Table 9: Forecast Error Variance Decompositions
Limited Participation Model
1979Q4-2003Q4

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	63.5	62.6	61.8	61.1	58.3	55.6	50.7
Aggregate demand	1.7	1.6	1.5	1.4	1.1	0.9	0.6
Money demand	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Investment technology	23.2	24.2	25.0	25.8	28.9	31.6	36.7
Government spending	11.5	11.6	11.7	11.7	11.8	11.9	12.0

Panel B: Inflation Rate Decompositions

	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	47.3	44.4	42.3	40.7	37.4	36.0	35.0
Production technology	11.9	11.2	10.6	10.3	9.4	9.1	8.9
Aggregate demand	8.6	13.7	17.2	19.8	25.1	26.9	27.8
Money demand	31.1	29.2	27.8	26.8	24.5	23.6	23.0
Investment technology	0.3	0.8	1.3	1.7	2.8	3.6	4.6
Government spending	0.9	0.9	0.8	0.8	0.7	0.7	0.7

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	5.6	3.4	2.6	2.2	1.7	1.6	1.8
Aggregate demand	65.1	75.3	78.6	79.9	80.7	79.7	77.7
Money demand	15.2	8.9	6.6	5.5	3.9	3.4	3.1
Investment technology	13.7	12.2	12.0	12.2	13.6	15.1	17.3
Government spending	0.4	0.3	0.2	0.2	0.2	0.2	0.2

Table 10: Forecast Error Variance Decompositions
Sticky Price and Limited Participation Model
1979Q4-2003Q4

Panel A: Output Decompositions

	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	26.5	21.7	17.6	14.6	9.0	7.0	5.2
Production technology	13.1	24.6	33.5	39.3	44.9	41.2	32.3
Aggregate demand	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Money demand	53.4	43.0	34.8	28.9	17.8	13.9	10.4
Investment technology	5.1	7.6	10.0	12.2	20.0	26.7	36.9
Government spending	1.9	3.0	4.0	5.0	8.3	11.1	15.1

Panel B: Inflation Rate Decompositions

	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	12.4	12.2	12.0	11.6	10.5	9.9	9.6
Production technology	43.2	39.4	36.3	34.0	29.9	28.5	27.6
Aggregate demand	19.1	23.4	27.3	30.4	37.5	40.0	41.4
Money demand	23.0	22.6	22.0	21.3	19.2	18.3	17.7
Investment technology	0.2	0.2	0.2	0.2	0.4	0.5	0.6
Government spending	2.1	2.2	2.3	2.4	2.6	2.7	3.2

Panel C: Nominal Interest Rate Decompositions

	Quarters Ahead						
	1	2	3	4	8	12	20
Monetary policy	29.2	21.6	18.2	16.2	12.5	11.3	10.6
Production technology	5.7	5.6	4.5	3.9	4.1	4.9	5.4
Aggregate demand	22.4	35.4	42.6	47.0	54.4	56.4	57.5
Money demand	1.3	5.3	6.4	6.5	5.7	5.2	4.9
Investment technology	36.3	28.8	25.8	24.2	21.6	20.6	19.8
Government spending	5.1	3.3	2.6	2.3	1.7	1.6	1.8

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

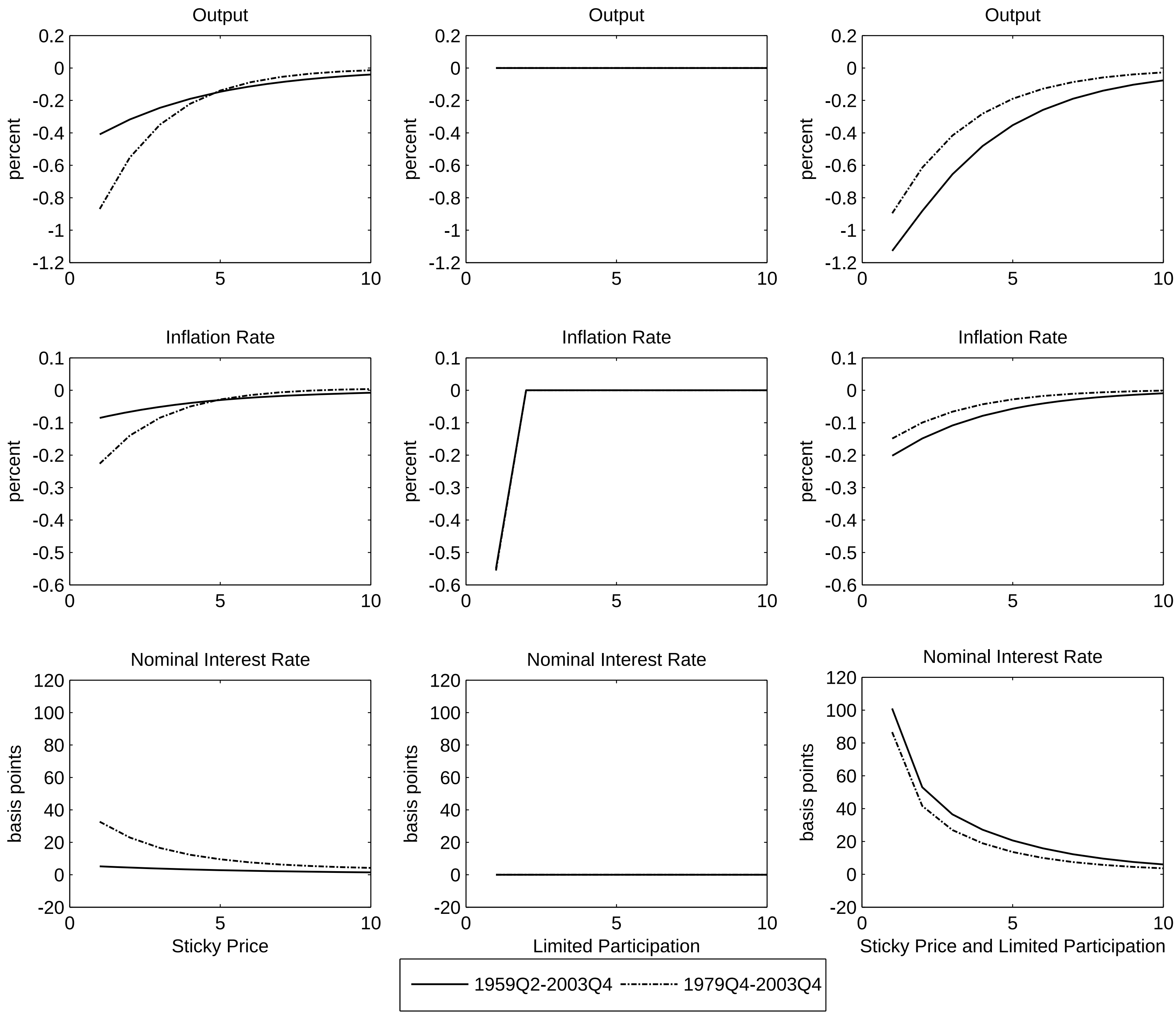

Figure 2: Vector Autocorrelation Functions, 1959Q2-2003Q4, Sticky Price Model (dashed line) and Data (solid line)

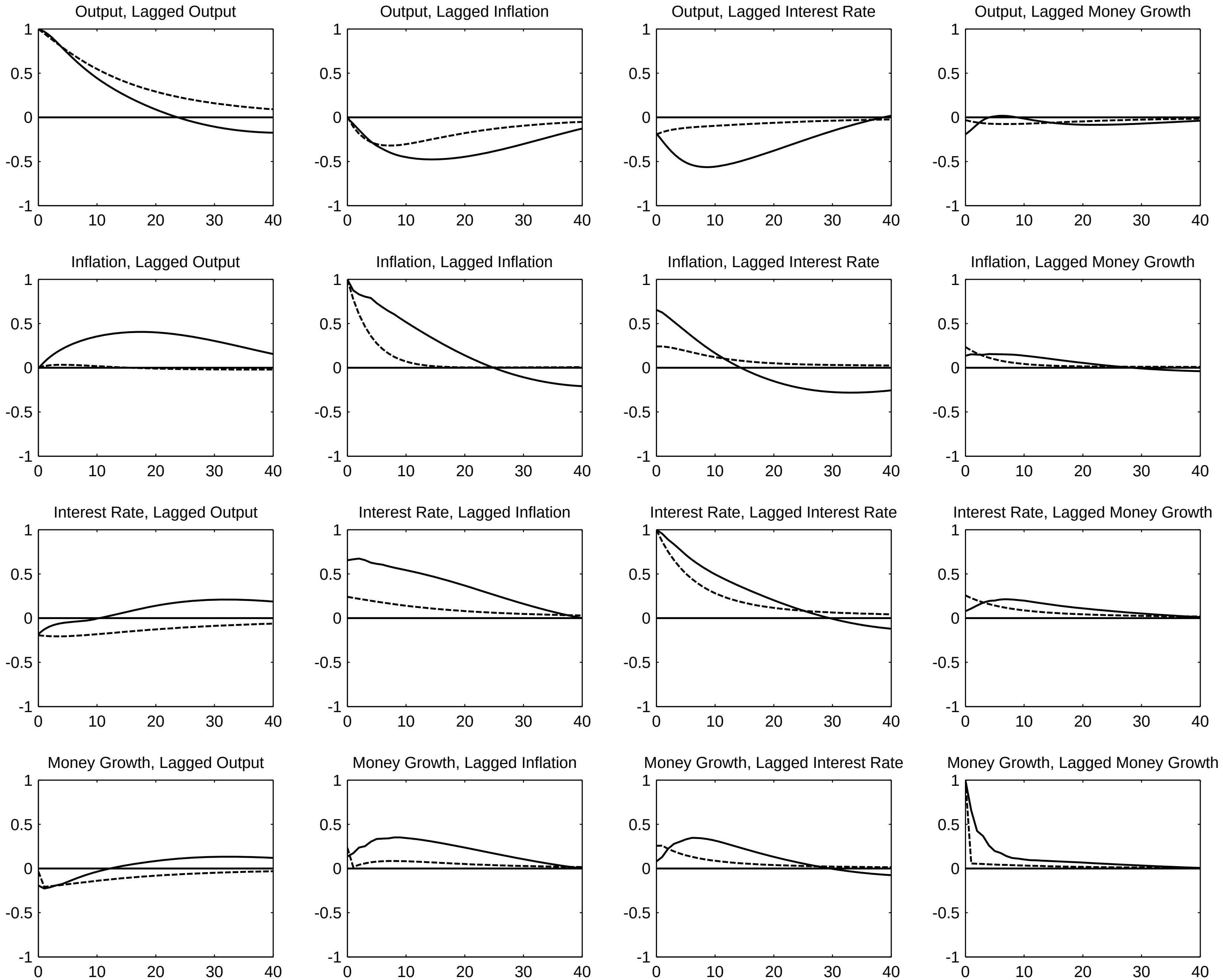

Figure 3: Vector Autocorrelation Functions, 1959Q2-2003Q4, Limited Participation Model (dashed line) and Data (solid line)

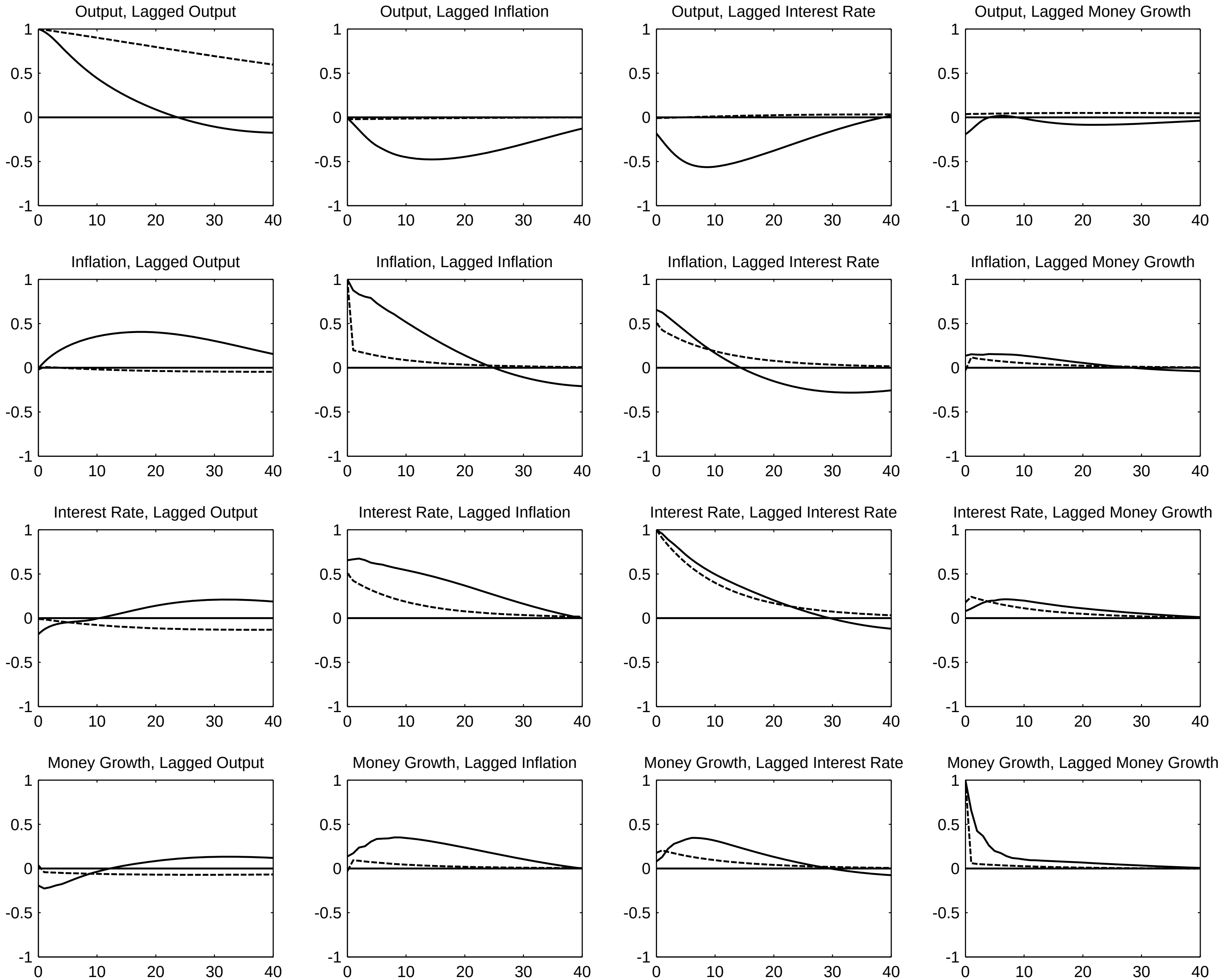

Figure 4: Vector Autocorrelation Functions, 1959Q2-2003Q4, Sticky Price and Limited Participation Model (dashed line) and Data (solid line)

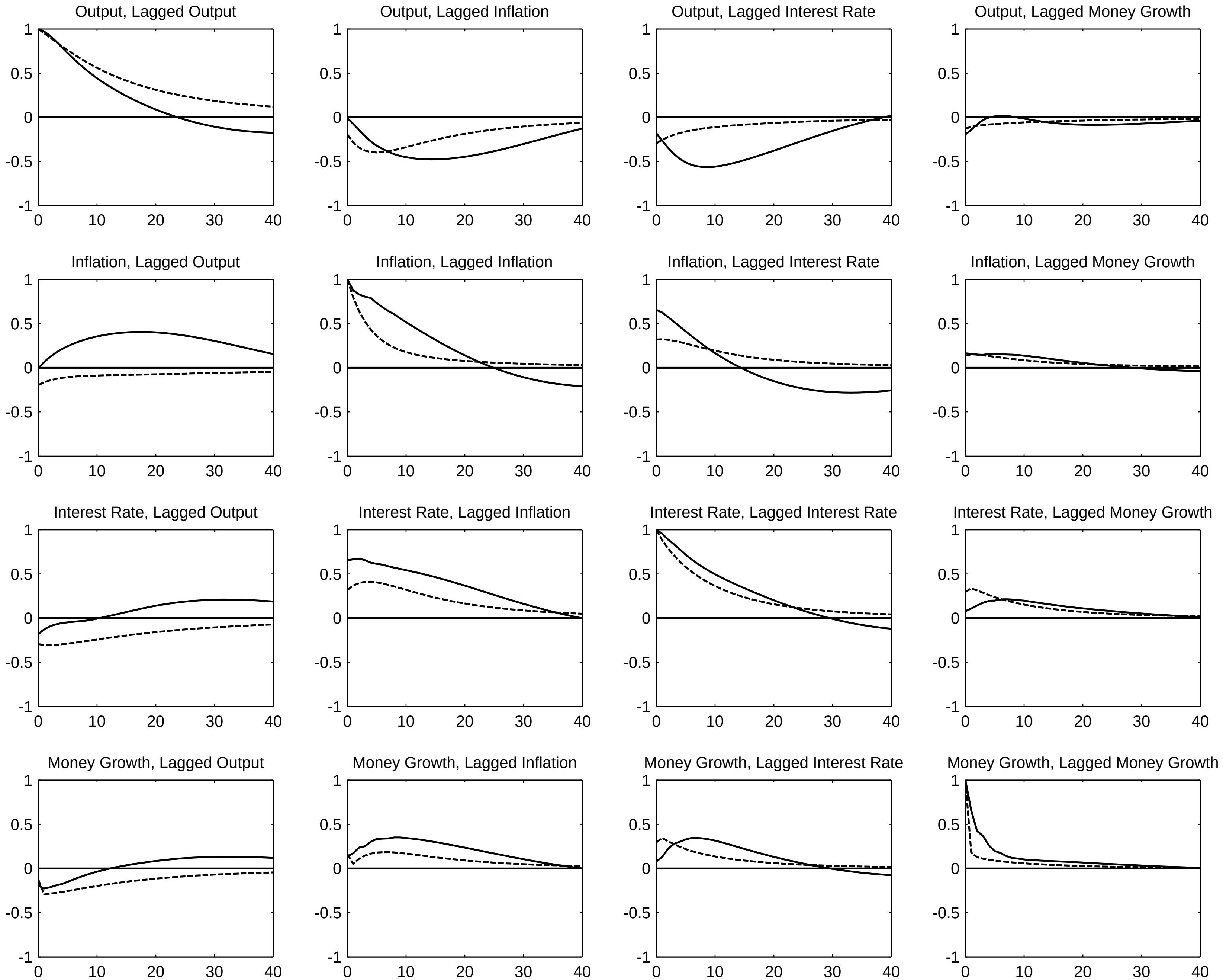

Figure 5: Vector Autocorrelation Functions, 1979Q4-2003Q4, Sticky Price Model (dashed line) and Data (solid line)

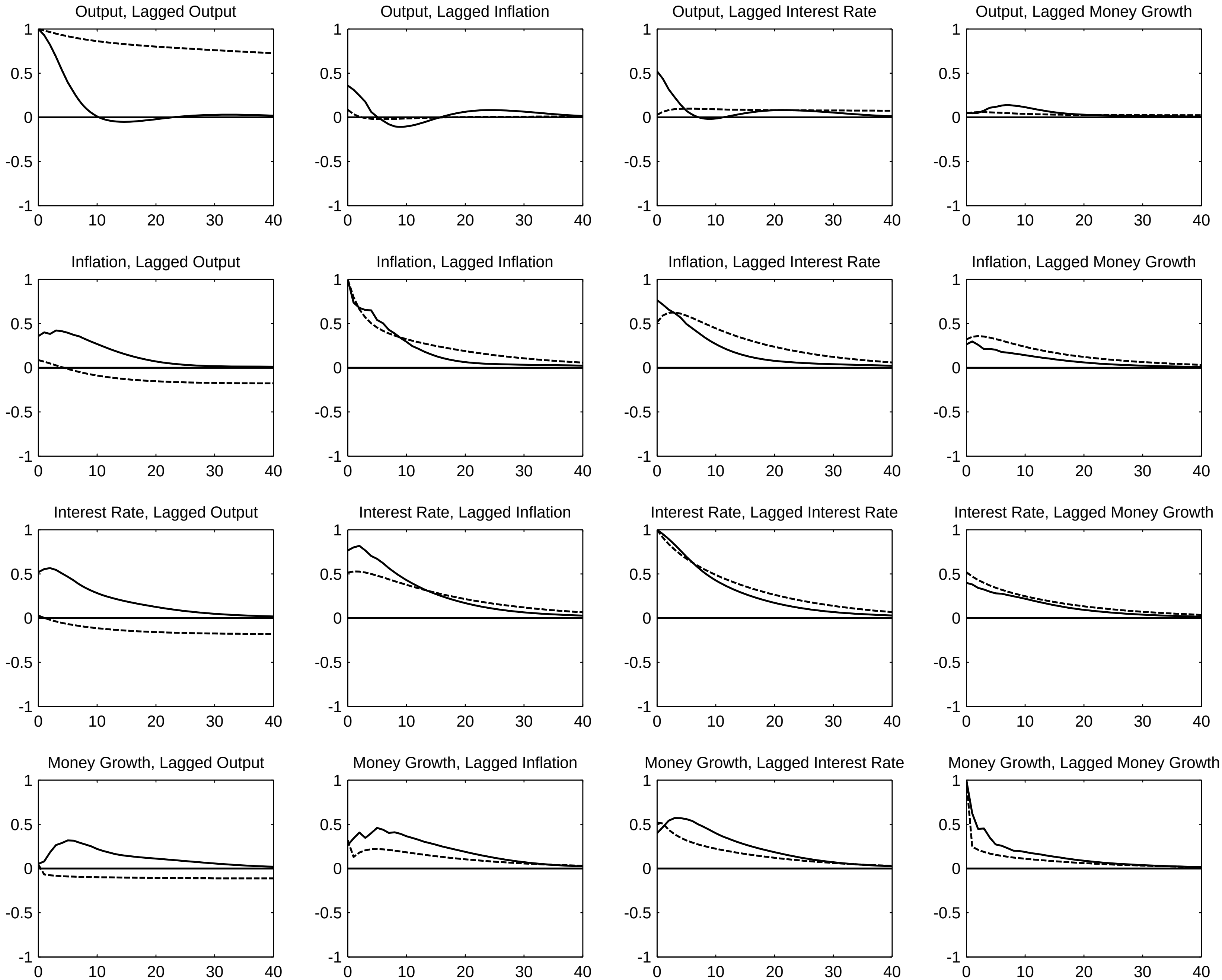

Figure 6: Vector Autocorrelation Functions, 1979Q4-2003Q4, Limited Participation Model (dashed line) and Data (solid line)

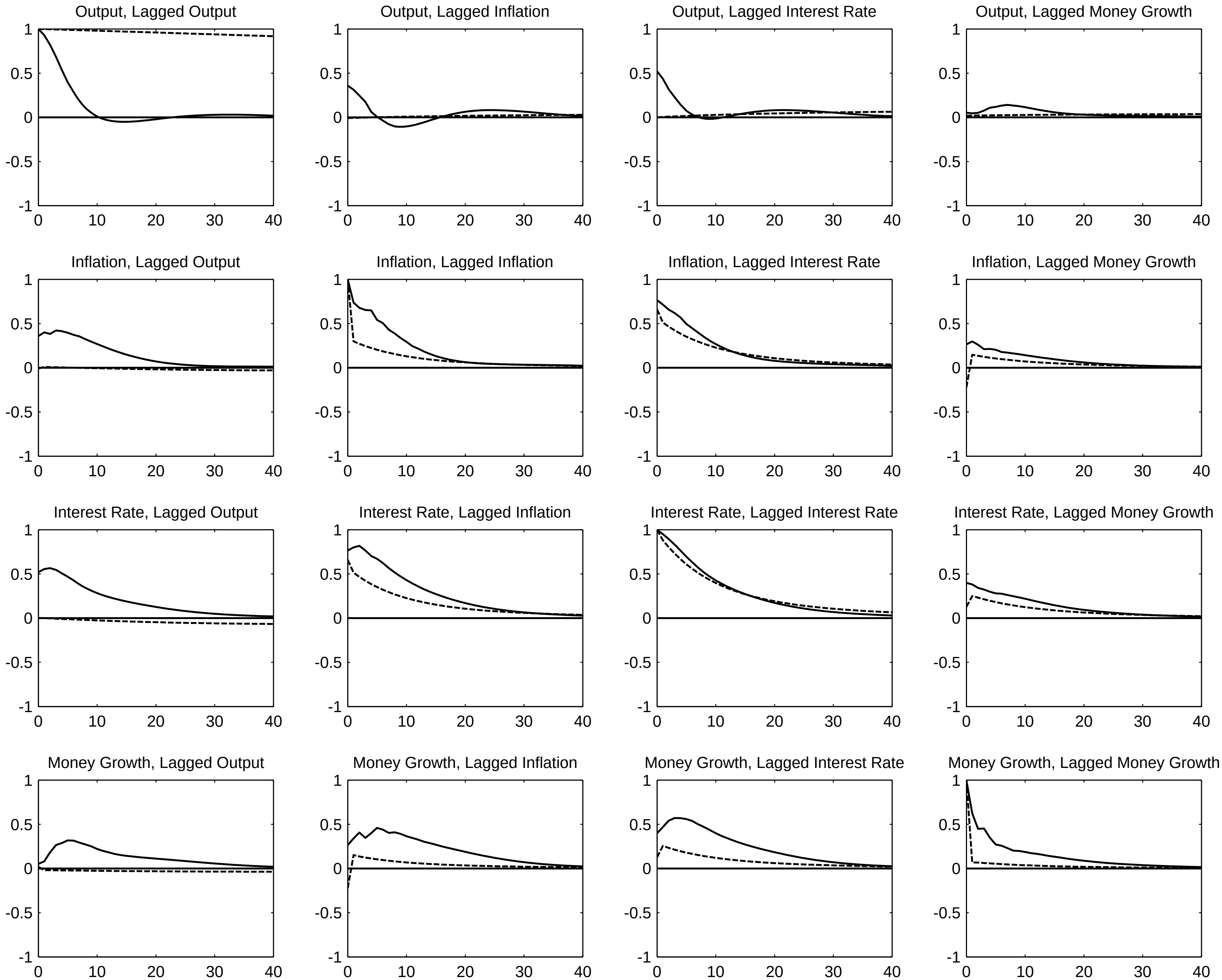

Figure 7: Vector Autocorrelation Functions, 1979Q4-2003Q4, Sticky Price and Limited Participation Model (dashed line) and Data (solid line)