THE ROLE OF THE TERM SPREAD IN ESTIMATED MONETARY POLICY RULES: A STRUCTURAL APPROACH *

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ABSTRACT

This paper estimates a standard version of the New Keynesian Monetary (NKM) model augmented with term structure in order to analyze (i) whether the Fed responds only to the information content of the spread about inflation and real activity or responds independently to the spread; and (ii) the relative importance of policy inertia, persistent policy shocks and the term spread in the estimated U.S. monetary policy rule. The estimation procedure implemented is a classical structural method based on the indirect inference principle. The empirical results show that (i) the Fed does not seem to respond independently to the spread, but it contains relevant information on current and future inflation and the output gap; and (ii) policy inertia and persistent policy shocks are still significant determinants in the estimated U.S. monetary policy rule when the term spread is included in the estimated policy rule.

1 INTRODUCTION

There is a fast-growing literature (Hördahl, Tristani and Vestin, 2006; Dewachter and Lyrio, 2006; Rudebusch and Wu, 2004; and Bekaert, Cho and Moreno, 2005) that seeks to link the New Keynesian Monetary (NKM) model dynamics with the term structure of interest rates.[1] Most papers in this literature assume a sort of dichotomy where the three-equation NKM model is solved first, independently from term structure; that is, they consider no feedback from term structure to the macroeconomy. An exception is the paper by Rudebusch and Wu (2004), which builds upon a typical affine no-arbitrage term structure representation with two latent factors (level and slope) by linking, (admittedly) in an ad-hoc fashion, these two factors to macroeconomic variables (inflation and output gap) which are determined by an NKM model. In a similar vein, using little macroeconomic structure, Ang, Dong and Piazzesi (2005) consider a single latent factor interpreted as a transformation of Fed policy actions on the short-term rate. In their model, persistent policy shocks are allowed but policy inertia is not. As discussed below, term spreads, policy inertia and persistent policy shocks are, in principle, three alternative candidates for explaining the highly persistent dynamics of the short rate.

The aim of this paper is twofold. First, we analyze whether the Fed responds only to the information content of the spread about inflation and real activity or responds independently to the spread. Second, we analyze the relative importance of policy inertia, term structure and persistent policy shocks in the characterization of the estimated U.S. monetary policy rule. We build upon the above literature by estimating a New-Keynesian Monetary (NKM) model augmented with term structure where the Fed funds rate and the 1-year Treasury constant maturity rate are considered.

The idea of including the term spread in the monetary rule is not new. McCallum (1994) suggests a policy rule characterized by interest rate smoothing and the assumption that the Fed tends to tighten monetary policy when the term spread is large. As pointed out by Laurent (1988), the term spread is an indicator of monetary policy looseness, so a high value of the term spread calls for corrective action (for instance, an increase in the Fed rate).[2]

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[1] There is also a related literature (for instance, see Ang and Piazzesi, 2003; and Diebold, Rudebusch and Aruoba, 2003) linking macro variables to the yield curve using little or no macroeconomic structure.

[2] More recently, following reduced-form estimation approaches, Carey (2001) includes

The inclusion of the term spread in the monetary rule is further motivated by two strands of literature. First, the empirical evidence found by many researchers (among others, Fama, 1990, Mishkin, 1990, Estrella and Hardouvelis, 1991, and Estrella and Mishkin, 1997) that the term spread contains useful information concerning market expectations of both future real economic activity and inflation. Second, many empirical studies (see for instance, Clarida, Galí and Gertler, 2000) have found that the lagged interest rate is a key component in estimated policy rules. Two alternative interpretations have been proposed in the relevant literature. On the one hand, there are several arguments suggesting that the significant role of the lagged interest rate may reflect the existence of an optimal policy inertia. These arguments range from the traditional concern of central banks for the stability of financial markets (see Goodfriend, 1991 and Sack, 1997) to the more psychological argument posed by Lowe and Ellis (1997) that there might be a political incentive for smoothing whenever policymakers are likely to be embarrassed by reversals in the direction of interest-rate changes if they believe that the public may interpret them as repudiations of previous actions. By contrast, a series of interest-rate changes in the same direction looks like a well-designed programme, and that may give rise to the sluggish behavior of the intervention interest rate. On the other hand, Rudebusch (2002) argues that the significance of the lagged interest rate in estimated policy rules is due to the existence of relevant omitted variables. The existence of omitted variables results in persistent monetary policy shocks in estimated policy rules. In this paper, we investigate whether short-term spreads are good candidates for solving the omitted-variable problem.

Considering term structure in an otherwise standard NKM model introduces two types of feature. On the one hand, it introduces persistent effects through the IS equation, which are different for instance from the ones introduced by habit formation à la Furher (2000). On the other hand, it allows us to consider the term spread as an additional determinant in the structural estimation of the monetary policy rule and then to tackle the first goal of the paper as explained below.

Hördahl et al. (2006) and Bekaert et al. (2005) introduce term structure by assuming an affine term structure model derived from first principles. In contrast to these papers, our paper introduces term structure by simply

a 10-year bond yield and Gerlach-Kristen (2004) includes the spread between a safe bond (the 10-year Treasury constant maturity rate) and a risky bond (the Moody's Baa corporate bond index) in standard Taylor rules for analyzing the relative importance of the term structure of interest rates.

considering a representative agent optimization problem allowing the agent to have access to bonds with different maturities, which implies that the non-arbitrage asset pricing equation must hold for any bond.

Closely related to Rudebusch and Wu (2004) and Ang et al. (2005), our paper focuses on analyzing whether term structure helps to characterize the policy rule whereas the main focus in Hördahl et al. (2006), Dewachter and Lyrio, (2006) and Bekaert et al. (2005) is on studying how term structure is determined by macroeconomic factors. Moreover, these papers differ from our paper in the structural econometric approach followed. Hördahl et al. (2006), Dewachter and Lyrio, (2006) and Rudebusch and Wu (2004) use a maximum likelihood approach, Bekaert et al. (2005) use the generalized method of moments and Ang et al. (2005) implement a Bayesian estimation approach to estimate their macro-finance models of the term structure. We follow María-Dolores and Vázquez (2006) by considering (i) a structural econometric approach based on the *indirect inference* principle; and (ii) three alternative specifications for the monetary policy rule called the standard, forward-looking and backward-looking rules. In a standard three-equation NKM model, María-Dolores and Vázquez (2006) show that the estimates of some behavioral/structural parameters are largely sensitive to the specification of the policy rule assumed. This result is quite unpleasant and it may point out to specification problems since, by definition of structural parameters, one would expect to get estimates for these parameters that were robust to alternative specifications of monetary policy. Moreover, the analysis of alternative policy rules helps us to answer the question of whether the term spread plays an independent role in the estimated policy rule.

The empirical results in this paper show that the term spread is significant under a backward-looking Taylor rule but not under a standard or a forward-looking rule. This empirical evidence suggests that the Fed may respond to the information content of the spread about current inflation and real activity, but the Fed does not seem to respond independently to the spread. Some authors (for instance, Leeper, Sims and Zha, 1996) believe that it is appropriate not to include contemporaneous variables in the Fed's reaction function as featured by a backward-looking Taylor rule. Arguably, this allows for a closer match between the information set available to the researcher and the data used by the Fed at the time of implementing monetary policy.

Moreover, the empirical results show that (i) a standard Taylor rule fits U.S. data better than a forward-looking rule or a backward-looking Taylor rule; and (ii) policy inertia and persistent policy shocks are significant features under all three specifications even when the term spread is included in the policy rule. The latter result is similar to that found by English et al. (2003) and Gerlach-Kristen (2004) considering a standard Taylor rule and a reduced-form estimation approach. In contrast to Gerlach-Kristen (2004), the coefficient associated with the term spread in the Taylor rule is not significant in most cases studied and is much smaller than the one obtained by Gerlach-Kristen. The evidence of monetary policy inertia also contrasts with that found by Rudebusch and Wu (2004). Nevertheless, it must be noted that our empirical results are similar to those found by Rudebusch and Wu (2004) in the sense that the relative importance of policy inertia decreases once persistent policy shocks are considered.

The rest of the paper is organized as follows. Section 2 introduces the log-linearized approximation of a standard version of the NKM augmented with term structure. Moreover, this section motivates the use of a structural econometric strategy to estimate monetary policy rules. Section 3 describes the structural estimation method used in this paper. Section 4 presents and discusses the estimation results. Section 5 provides diagnostic tests, unconditional moments, impulse response and comovement analyses to identify features of the data (not) accounted for by the NKM model augmented with term structure. Section 6 concludes.

2 A NEW KEYNESIAN MONETARY MODEL WITH TERM STRUCTURE

The model analyzed in this paper is a now-standard version of the NKM model augmented with term structure, which is given by the following set of equations:

$$y_t = E_t y_{t+j} - \tau(i_t^{\{j\}} - E_t \pi_{t+j}) + g_t^{\{j\}}, \text{ for } j = 1, ..., n \tag{1}$$

$$\pi_t = \beta E_t \pi_{t+1} + \kappa y_t + z_t, \tag{2}$$

$$i_t = \rho i_{t-1} + (1-\rho)[\psi_1 \pi_t + \psi_2 y_t + \psi_3 (i_{t-1}^{\{j\}} - i_{t-1}^{\{k\}})] + v_t. \tag{3}$$

where y, π and $i^{\{j\}}$ denote the log-deviations from the steady states of output, inflation and nominal interest rate associated with a j-period bond, respectively. E_t denotes the conditional expectation based on the agents' information set at time t. $g^{\{j\}}$, z and v denote aggregate demand, aggregate supply and monetary policy shocks, respectively. As discussed by Ireland (2004), there is a long standing tradition (dating back at least to Sargent,

1989) of introducing additional disturbances in dynamic stochastic general equilibrium models until the number of shocks equals the number of data series used in estimation. The reason is that models of this type are quite stylized and introduce fewer shocks than observable variables, which implies that models are stochastically singular. That is, the model implies that certain combinations of endogenous variables are deterministic. If these combinations do not hold in the data, any approach that attempts to estimate the complete model will fail. In order to cope with this stochastic singularity problem, we consider that the shocks are different due to measurement errors and the approximation error that results from the log-linear approximation carried out.[3] Each of these shocks is further assumed to follow a first-order autoregressive process

$$g_t^{\{j\}} = \rho_g^{\{j\}} g_{t-1}^{\{j\}} + \epsilon_{gt}^{\{j\}}, \text{ for } j = 1, ..., n \tag{4}$$

$$z_t = \rho_z z_{t-1} + \epsilon_{zt}, \tag{5}$$

$$v_t = \rho_v v_{t-1} + \epsilon_{vt}, \tag{6}$$

where $\epsilon_{gt}^{\{j\}}$, ϵ_{zt} and ϵ_{vt} denote i.i.d. random shocks. We further allow for correlation between $\epsilon_{gt}^{\{j\}}$ shocks.

Equations (1) are the log-linearized consumption first-order conditions obtained from the representative agent optimization plan. The parameter $\tau > 0$ represents the intertemporal elasticity of substitution obtained when assuming a standard constant relative risk aversion utility function.[4] Combining two IS equations, say j and l, one gets a highly persistent IS where expected realizations of output at different forecast horizons are linked to the ex-ante real interest rates associated with the alternative maturity bonds in the economy:

$$E_t y_{t+j} = E_t y_{t+l} - \tau[(i_t^{\{l\}} - E_t \pi_{t+l}) - (i_t^{\{j\}} - E_t \pi_{t+j})] + g_t^{\{l\}} - g_t^{\{j\}},$$

for $j = 1, ..., n$, and $j \neq l$. Without loss of generality we can assume that $l > j$. This equation can be further manipulated to obtain the following *intertemporal IS-equation:*

$$i_t^{\{l\}} - i_t^{\{j\}} = \frac{1}{\tau} E_t(y_{t+l} - y_{t+j}) + E_t(\pi_{t+l} - \pi_{t+j}) + \frac{1}{\tau}(g_t^{\{l\}} - g_t^{\{j\}}). \tag{7}$$

[3] See also Hamilton (1994, p.426) for a lucid discussion on the need to add error terms to behavioral equations and its consequences on econometric identification.

[4] Appendix 1 shows a detailed derivation of the j-IS curves, one IS curve for each j-period bond of the economy.

The *intertemporal IS-equation* structurally links the term spread for bonds with maturity l and j with the expected growth rate of output between periods $t+j$ and $t+l$ (weighted by the risk aversion parameter, $1/\tau$) and the expected change in the rate of inflation between periods $t+j$ and $t+l$.

Equation (2) is the new Phillips curve that is obtained in a sticky price à la Calvo (1983) model where monopolistically competitive firms produce (a continuum of) differentiated goods and each firm faces a downward sloping demand curve for its produced good. The parameter $\beta \in (0,1)$ is the agent discount factor and κ measures the slope of the New Phillips curve.[5]

Equation (3) is a standard Taylor-type monetary rule where the nominal interest rate exhibits inertial behavior, captured by parameter ρ, for which there are several motivating arguments in the relevant literature, such as those mentioned in the introduction. Moreover, the monetary policy rule (3) assumes that the nominal interest rate responds, on the one hand, to current deviations of output and inflation from their respective steady state values and, on the other hand, to lagged term spreads, $i_{t-1}^{\{j\}} - i_{t-1}^{\{k\}}$ for $j > k$.[6] Alternatively, we also consider a forward-looking Taylor rule[7]

$$i_t = \rho i_{t-1} + (1-\rho)[\psi_1 E_t \pi_{t+1} + \psi_2 E_t y_{t+1} + \psi_3 (i_{t-1}^{\{j\}} - i_{t-1}^{\{k\}})] + v_t, \qquad (8)$$

and a backward-looking Taylor rule

$$i_t = \rho i_{t-1} + (1-\rho)[\psi_1 \pi_{t-1} + \psi_2 y_{t-1} + \psi_3 (i_{t-1}^{\{j\}} - i_{t-1}^{\{k\}})] + v_t. \qquad (9)$$

By considering alternative policy rule specifications, the term spread in the estimated policy rule and a structural estimation procedure, we expect to shed light on two relevant questions: (i) does the Fed respond only to the information content of the spread about current and future inflation and real activity, or does it respond independently to the spread?; and (ii) are the deep structural parameter estimates stable across alternative policy rule specifications? The first question is important because it allows us to assess whether the Fed responds to the term spread in order to reduce perceived misalignments in interest rates or responds to the term spread according to its influence on the outlook for output and inflation. The

[5]See, for instance, Galí (2002) for a detailed analytical derivation of the New Phillips curve.

[6]In the empirical analysis below, we also consider the case where current spread enters into the policy rule.

[7]A forward-looking Taylor rule is derived in a technical appendix (not intended for publication) from the optimization programme faced by a central bank that minimizes the inflation deviation from a specific inflation target.

second question is also important because the analysis might help to shed light on misspecification issues associated with the standard NKM model. As pointed out above, María-Dolores and Vázquez (2006) show that the estimates of some behavioral parameters in a standard three-equation NKM model are largely sensitive to the specification of the policy rule assumed, and this result may indicate misspecification problems. By considering an NKM model augmented with term structure, we seek to investigate whether the term structure of interest rates helps to identify all behavioral parameters.

Equation (7) shows that term spreads are endogenously linked to economic aggregates and that term spreads, expected output and inflation paths are linked to IS-shocks. Therefore, estimating single-equation policy rules by ordinary least squares is not appropriate because regressors are endogenous. Moreover, when IS-shocks and policy shocks are highly persistent (as widely reported in the literature) it is difficult to find appropriate instrumental variables to control for regressor endogeneity. These results further motivate the use of a structural estimation approach. As clearly stated by Lubik and Schorfheide (2005), structural (system-based) estimation methods correct for endogeneity by taking into account the non-zero conditional expectation of structural and policy shocks.

The use of a structural econometric strategy to estimate monetary policy rules can be further motivated as follows. As pointed out by Clarida, Galí and Gertler (1999), the forward-looking Taylor rule can be solved to obtain a reduced form for the interest rate in terms of predetermined variables. This reduced form looks like standard and backward-looking Taylor rules, but the difference is that the coefficients associated with the reduced form of the forward-looking rule are cumbersome functions linking structural and policy parameters. More precise, the reduced-form coefficients associated with the forward-looking rule must satisfy a set of cross-equation restrictions imposed by the rational expectations assumption. Therefore, alternative policy rules are not likely to be statistically identical and a system-based econometric strategy is then required to discriminate between alternative monetary policy rules.

Since the structural econometric approach implemented is computationally quite demanding, we consider an economy with only two bonds: a 4-period bond as the long-term bond and a 1-period bond as the short-term bond.[8] Equations (1)-(6) can then be written as

$$y_t = E_t y_{t+4} - \tau(i_t^{\{4\}} - E_t\pi_{t+4}) + g_t^{\{4\}},$$

$$y_t = E_t y_{t+1} - \tau(i_t - E_t\pi_{t+1}) + g_t,$$

$$\pi_t = \beta E_t\pi_{t+1} + \kappa y_t + z_t,$$

$$i_t = \rho i_{t-1} + (1-\rho)[\psi_1\pi_t + \psi_2 y_t + \psi_3(i_{t-1}^{\{4\}} - i_{t-1})] + v_t,$$

$$g_t = \rho_g g_{t-1} + \epsilon_{gt},$$

$$z_t = \rho_z z_{t-1} + \epsilon_{zt},$$

$$g_t^{\{4\}} = \rho_g^{\{4\}} g_{t-1}^{\{4\}} + \epsilon_{gt}^{\{4\}},$$

$$v_t = \rho_v v_{t-1} + \epsilon_{vt},$$

where for the sake of simplicity we further assume that the 1-period bond and the policy interest rate are the same.[9]

These eight equations (together with eight extra identities involving forecast errors) can be written in matrix form as follows

$$\Gamma_0 X_t = \Gamma_1 X_{t-1} + \Psi\epsilon_t + \Pi\eta_t, \quad (10)$$

where[10]

$$X_t = (y_t, \pi_t, i_t, i_t^{\{4\}}, E_t y_{t+1}, E_t y_{t+2}, E_t y_{t+3}, E_t y_{t+4},$$
$$E_t\pi_{t+1}, E_t\pi_{t+2}, E_t\pi_{t+3}, E_t\pi_{t+4}, g_t, z_t, g_t^{\{4\}}, v_t)',$$

$$\epsilon_t = (\epsilon_{gt}, \epsilon_{zt}, \epsilon_{gt}^{\{4\}}, \epsilon_{vt})',$$

$$\eta_t = (y_t - E_{t-1}[y_t], E_t[y_{t+1}] - E_{t-1}[y_{t+1}], E_t[y_{t+2}] - E_{t-1}[y_{t+2}],$$
$$E_t[y_{t+3}] - E_{t-1}[y_{t+3}], \pi_t - E_{t-1}[\pi_t], E_t[\pi_{t+1}] - E_{t-1}[\pi_{t+1}],$$
$$E_t[\pi_{t+2}] - E_{t-1}[\pi_{t+2}], E_t[\pi_{t+3}] - E_{t-1}[\pi_{t+3}])'.$$

[8] We also tried to consider the 10-year Treasury rate instead of the 1-year rate to ease comparison with Gerlach-Kristen (2004) results. However, the GAUSS programs we use to solve the NKM model augmented with term structure break down since the sizes of matrices Γ_0, Γ_1, Π and Ψ defined below are too large. For instance, Γ_0 and Γ_1 are 88×88 matrices.

[9] This assumption is not very harmful when using quarterly data since the 3-month T-bill rate dynamics are similar to the Fed rate dynamics, which represents the short-term rate used by the Fed to monitor monetary policy. More precisely, the sample correlation between these two interest rates was 0.994 during the Greenspan era. In order to save notation, we have also removed the superscripts associated with the 1-period interest rate, shock and shock parameter, respectively.

[10] Appendix 2 displays the matrices Γ_0, Γ_1, Ψ and Π.

Equation (10) represents a linear rational expectations (LRE) system. It is well known that LRE systems deliver multiple stable equilibrium solutions for certain parameter values. Lubik and Schorfheide (2003) characterize the complete set of LRE models with indeterminacies and provide a numerical method for computing them that builds on Sims' (2002) approach.[11] In this paper, we deal only with sunspot-free equilibria.[12]

3 ESTIMATION PROCEDURE

In order to estimate the structural and policy parameters of the NKM model with term structure, we follow the *indirect inference* principle proposed by Gouriéroux, Monfort and Renault (1993), Smith (1993), and Gallant and Tauchen (1996). Following Smith (1993), an unrestricted VAR representation is considered as the auxiliary model. More precisely, we first estimate a four-variable VAR with four lags in order to summarize the joint dynamics exhibited by U.S. quarterly data on output gap, inflation, Fed funds rate and 1-year Treasury constant maturity rate. Second, we apply the simulated moments estimator (SME) suggested by Lee and Ingram (1991) and Duffie and Singleton (1993) to estimate the underlying structural and policy parameters of the NKM model.[13]

This estimation strategy is especially appropriate in this context for three main reasons.[14] First, we have to emphasize that the NKM model

[11] The GAUSS code for computing equilibria of LRE models can be found on Frank Schorfheide's website.

[12] Lubik and Schorfheide (2003) deal with multiple equilibria by assuming that agents observe an exogenous sunspot shock ζ_t, in addition to the fundamental shocks, ϵ_t. Since an LRE system such as (10) is linear, the forecast errors, η_t, can be expressed as a linear function of ϵ_t and ζ_t : $\eta_t = A_1\epsilon_t + A_2\zeta_t$, where A_1 is 2×3 and A_2 is 2×1 in this model. There are three possible scenarios: (i) no stable equilibrium; (ii) a unique stable equilibrium in which A_1 is completely determined by the structural parameters of the model and $A_2 = 0$; and (iii) multiple stable equilibria in which A_1 is not uniquely determined by the structural parameters of the model and A_2 can be non-zero. In this last case, one can deal only with a stable sunspot-free equilibrium by imposing $A_2 = 0$ and then the corresponding equilibrium can be understood as a sunspot equilibrium with no sunspots.

[13] In this vein, Amato and Laubach (2003) and Boivin and Giannoni (2003) use a minimum distance estimator based on impulse-response functions instead of VAR coefficients. See Gutiérrez and Vázquez (2004) and Ruge-Murcia (2003) for other recent applications of this estimation strategy based on VAR coefficients.

[14] At this point, the reader may have the following three questions in mind. Why do we not estimate the NKM model directly by maximum-likelihood? Why do we use

augmented with term structure is a highly stylized model of a complex world. Therefore, maximum-likelihood (ML) estimation of the model will impose strong restrictions which are not satisfied by the data and inference will be misleading. In the words of Cochrane (2001, p. 293) "[*ML*] *does the "right" efficient thing if the model is true. It does not necessarily do the "reasonable" thing for "approximate" models.*" We believe that one of the main virtues of the indirect inference approach is that the econometrician has in principle the possibility of choosing an auxiliary model that imposes looser restrictions than those imposed by ML. Second, we consider the coefficients from an unrestricted VAR instead of matching the structural impulse responses[15] because a reduced form VAR does not require the arbitrary identification of structural shocks. Moreover, applications of the minimum distance estimator based on impulse response functions use a diagonal weighting matrix that includes the inverse of each impulse response's variance on the main diagonal. This weighting matrix delivers consistent estimates of the structural parameters, but it is not asymptotically efficient since it does not take into account the whole covariance matrix structure associated with the set of moments.[16] By considering the VAR coefficients as the set of moments in order to implement the minimum distance estimator, an estimator of the efficient weighting matrix is found to be straightforward.[17] Finally, the unrestricted VAR auxiliary model nests the NKM model augmented with term structure considered. As shown by Gallant and Tauchen (1996), if the auxiliary model nests the structural model then the estimator is as efficient as ML. Moreover, the estimation approach based on the indirect inference principle may help to identify which structural parameter estimates are forced outside the economically reasonable support (for instance, the prior distribution support used by Bayesian estimator applications) to achieve a better fit of the model.

The SME makes use of a set of statistics computed from the data set used and from a number of different simulated data sets generated by the model being estimated. More specifically, the statistics used to carry out the SME are the coefficients of the four-variable VAR with four lags, which is considered as the auxiliary model in this paper. The

VAR coefficients instead of impulse response functions to construct the minimum distance estimator? What do we learn from the estimation of the NKM model based on the indirect inference principle? This paragraph answers these three questions.

[15] This approach is followed by Rotemberg and Woodford (1997), Amato and Laubach (2003) and Boivin and Giannoni (2005).

[16] Boivin and Giannoni (2005) indicate this drawback, but provide no alternative.

[17] See Duffie and Singleton (1993, p.939) for a discussion on the choice of a weighting matrix to obtain asymptotic efficient estimates.

lag length considered is fairly reasonable when using quarterly data. To implement the method, we construct a $p \times 1$ vector with the coefficients of the VAR representation obtained from actual data, denoted by $H_T(\theta_0)$, where p in this application is 78,[18] T denotes the length of the time series data, and θ is a $k \times 1$ vector whose components are the model parameters. The true parameter values are denoted by θ_0. In the NKM model with term structure, the structural and policy parameters are $\theta = (\tau, \beta, \rho, \kappa, \psi_1, \psi_2, \psi_3, \rho_g, \rho_g^{\{4\}}, \rho_z, \rho_v, \rho_{gg}, \sigma_g, \sigma_g^{\{4\}}, \sigma_z, \sigma_\varepsilon, \pi^*)$ and then $k = 17$. ρ_{gg} denotes the coefficient characterizing the noisy linear relationship between ϵ_{gt} and $\epsilon_{gt}^{\{4\}}$ shocks.[19]

As pointed out by Lee and Ingram (1991), the randomness in the estimator is derived from two sources: the randomness in the actual data and the simulation. The importance of the randomness in the simulation to the covariance matrix of the estimator can be decreased by simulating the model a large number of times. For each simulation a $p \times 1$ vector of VAR coefficients, denoted by $H_{N,i}(\theta)$, is obtained from the simulated time series of output gap, inflation and interest rate generated from the NKM model, where $N = nT$ is the length of the simulated data. Averaging the m realizations of the simulated coefficients, i.e. $H_N(\theta) = \frac{1}{m}\sum_{i=1}^{m} H_{Ni}(\theta)$, we obtain a measure of the expected value of these coefficients, $E(H_{Ni}(\theta))$. To generate simulated values of output gap, inflation and interest rate we need the starting values of these variables. For the SME to be consistent, the initial values must be drawn from a stationary distribution. In practice, to avoid the influence of the starting values we follow Lee and Ingram's (1991) suggestion of generating a realization from the stochastic processes of the four variables of length $2N$, discarding the first N-simulated observations, and using only the remaining N observations to carry out the estimation. After N observations have been simulated, the influence of the initial conditions must have disappeared.

The choice of values for n and m deserves some attention. Gouriéroux, Renault and Touzi (2000) suggests that is important for the sample size of synthetic data to be identical to T (that is, $n = 1$) in order to get identical size of finite sample bias in estimators of the auxiliary parameters computed from actual and synthetic data. By contrast, most indirect inference applications (for instance, Smith, 1993; Ruge-Murcia, 2003; Gutiérrez and Vázquez, 2004) consider N larger than T (that is, $n = 5, 10, 20$) because

[18] We have 68 coefficients from a four-lag, four-variable system and 10 extra coefficients from the non-redundant elements of the variance-covariance matrix of the VAR residuals.

[19] We also allowed for correlation between ϵ_{gt} shocks and ϵ_{zt}, but the corresponding parameter turns out to be non-significant.

a large N is important to estimate persistent dynamic process. We make $n = m = 10$ in this application, but we check the robustness of the empirical results by also considering $n = 1$ and $m = 100$.

The SME of θ_0 is obtained from the minimization of a distance function of VAR coefficients from actual and simulated data. Formally,

$$\min_{\theta} \; J_T = [H_T(\theta_0) - H_N(\theta)]'W[H_T(\theta_0) - H_N(\theta)],$$

where the weighting matrix W^{-1} is the covariance matrix of $H_T(\theta_0)$.

Denoting the solution of the minimization problem by $\hat{\theta}$, Lee and Ingram (1991) and Duffie and Singleton (1993) prove the following results:

$$\sqrt{T}(\hat{\theta} - \theta_0) \to N\left[0, \left(1 + \frac{1}{m}\right)(B'WB)^{-1}\right],$$

$$\left(1 + \frac{1}{m}\right) TJ_T \to \chi^2(p - k),$$

where B is a full rank matrix given by $B = E(\frac{\partial H_{Ni}(\theta)}{\partial \theta})$.[20]

4 EMPIRICAL EVIDENCE

4.1 The data

We consider quarterly U.S. data for the output gap, the inflation rate obtained for the implicit GDP deflator, the Fed funds rate and the 1-year Treasury constant maturity rate during the Greenspan era.[21] We focus on the Greenspan period for several reasons. First, it allows a more straightforward

[20] The objective function J_T is minimized using the optimization package OPTMUM programmed in GAUSS language. The Broyden-Fletcher-Glodfard-Shanno algorithm is applied. To compute the covariance matrix we need to obtain B. Computation of B requires two steps: first, obtaining the numerical first derivatives of the coefficients of the VAR representation with respect to the estimates of the structural parameters θ for each of the m simulations; second, averaging the m-numerical first derivatives to get B. The GAUSS programs for estimating the NKM model augmented with term structure are available from the authors upon request.

[21] U.S. output gap is measured as the percentage deviation of GDP from the real potential GDP time series constructed by the U.S. Congressional Budget Office. Appendix 3 describes the data sources.

comparison with the estimated monetary policy rules of English et al. (2003), Gerlach-Kristen (2004), and Rudebusch and Wu (2004). Second, the Taylor rule seems to fit better in this period than in the pre-Greenspan era. Third, considering the pre-Greenspan era opens the door to many other issues studied in the literature, including the presence of macroeconomic switching regimes and the existence of switches in monetary policy (Sims and Zha, 2004, Cogley and Sargent, 2005, and Canova, 2004). These issues are beyond the scope of this paper. Figure 1 shows the four time series.

4.2 Estimation results

Tables 1-3 show the estimation results under the standard, forward-looking and backward-looking Taylor rules, respectively. The second column shows the estimates for the model without restrictions. The third column shows the estimates imposing the restriction that the term spread does not enter into the policy rule ($\psi_3 = 0$). The fourth column displays the estimates obtained when we do not allow for persistent monetary policy shocks ($\rho_v = 0$). The fifth column shows the estimates when the current term spread enters into the policy rule instead of the lagged term spread. The values of the goodness-of-fit statistic, $\left(1 + \frac{1}{n}\right) TJ_T$,which is distributed as a $\chi^2(p-k)$,[22] confirm the hypothesis stated above that the NKM model augmented with term structure under any specification considered is still too stylized to be supported by actual data.

At this point the reader may wonder why we should consider a model that does not fit the data well. Moreover, he/she may wonder why it is of interest to look at parameter estimates when the model is misspecified. We believe it is a worthwhile econometric exercise to estimate misspecified models because we can gain confidence on what parameters can be robustly estimated by estimating the model under alternative specifications (for instance, under alternative specifications of the policy rule).[23]

The best fit is obtained under a standard Taylor rule that includes the lagged term spread without imposing any restriction (Table 1, second

[22]For the NKM model without imposing any restriction the goodness-of-fit statistic is distributed as a $\chi^2(61)$ since the number of VAR coefficients is $p = 78$ and the number of parameters being estimated is $k = 17$.

[23]This econometric exercise is valuable for precisely the same reason that policy analysis is believed to be worthwhile when performed in a misspecified framework. That is, one gains confidence on the policy prescriptions implied by a misspecified model only if they are fairly robust to alternative specifications.

column). We observe that the coefficients associated with the term spread (ψ_3), policy inertia (ρ) and the persistency of policy shocks (ρ_v) are all significant at any standard significance level.[24]

Following the suggestion of Gourieroux et al. (2000), we study the robustness of the empirical results by re-estimating the model for $n = 1$ and $m = 100$. These estimation results are shown in Table 4. Comparing the columns of Table 4 with their counterparts in Tables 1-3, we observe that the empirical results are robust to the choice of n and m. The only exception is the lack of significance of the term spread coefficient in the standard Taylor rule under $n = 1$ and $m = 100$.

Interestingly, it can be observed from Tables 1-4 that the estimates of structural parameters in the NKM model augmented with term structure are robust to alternative specifications of the policy rule, in contrast with the highly sensitive estimates of τ and κ found by María-Dolores and Vázquez (2006) when considering a standard NKM model without term structure. This result suggests that the NKM model augmented with term structure helps to identify τ and κ . However, the large standard deviations may also indicate that, conditional on the model specification, there is not enough information in the data to estimate these parameters with precision.[25] Moreover, Tables 1-4 also show that all parameters measuring shock persistence are much smaller than the ones found by María-Dolores and Vázquez (2006).

The policy parameter that monitors the response of interest rates to inflation, ψ_1, is less than one and is statistically different from zero and from one. The *Taylor principle* does not hold and indeterminacy emerges. We next investigate how robust the indeterminacy result is by estimating the model under the restriction that the Taylor principle holds (that is

[24] Moreover, Wald tests based on the values of the goodness-of-fit statistic provide extra support for the hypothesis that the term spread and persistent policy shocks are features characterizing the estimated monetary policy rule.

[25] To detect identification problems, we follow Canova and Sala (2006) in analyzing whether the estimated Hessian associated with the minimization of the distance function in the estimation procedure shows rank deficiencies. The Hessian is obtained as a by-product of the optimization routine. Since the eigenvalues of the Hessian may depend on the units of measurement, Anderson (2003, pp.479-480) suggests analyzing whether the ratio of the smallest k' eigenvalues to the sum of all k values of the Hessian is low to detect identification problems. We carry out this analysis on the Hessian obtained under the standard rule, imposing no restrictions. The Anderson ratio shows rank deficiencies because twelve of the seventeen roots are relatively small: the sum of the smallest twelve eigenvalues is 1.24% of the sum of all eigenvalues.

$\psi_1 > 1$). We first imposed that $\psi_1 > 1$, but the estimation algorithm was not able to reach convergence whereas the value of ψ_1 got closer and closer to one. For this reason, we estimate the model setting $\psi_1 = 1.00001$, which is a sufficient condition for determinacy. The sixth column in Table 1 shows the estimation results for this case. Since we impose the restriction $\psi_1 = 1.00001$, we can carry out a J-Wald-test for this determinacy restriction. The J-Wald-test statistic for the determinacy restriction is 46.1. This test is distributed as a $\chi^2(1)$. Thus, the determinacy restriction is rejected at any standard significance level, which suggests empirical evidence on the existence of indeterminacy during the Greenspan era.[26]

The fact that the term spread is significant under a backward-looking Taylor rule but not under a standard or a forward-looking rule suggests that the Fed may respond to the information content of the spread about current inflation and real activity, but does not seem to respond independently to the spread.

In spite of the better fit obtained under the standard rule, it might be thought that the backward-looking estimated rule provides a better characterization of the actual policy rule followed by the Fed because it may be appropriate not to include contemporaneous variables in the Fed's reaction function. The reason is that a backward-looking rule allows for a closer match between the information set available to the researcher and the data used by the Fed at the time of implementing monetary policy. Under this view, the finding of a large, significant coefficient associated with the lagged term spread in the estimated backward-looking rule can be understood as evidence that the Fed may in fact consider the spread as a key determinant of the actual policy rule because it contains information about current economic aggregates (output gap and inflation) which may not be directly observable at the time of implementing monetary policy.

Based on a structural estimation approach, our empirical results then confirm qualitatively the reduced-form estimation results obtained by English et al. (2003) and Gerlach-Kristen (2004) that policy inertia and persistent policy shocks play a role in the U.S. estimated policy rule. The evidence of monetary policy inertia challenges the empirical results found by Rudebusch and Wu (2004). Nevertheless, it must be noted that our empirical results are consistent with those found by Rudebusch and Wu (2004) in one sense:

[26] The identification problem is very severe when the determinacy restriction $\psi_1 = 1.00001$ is imposed: the sum of the fourteen smallest roots is 0.0007% of the sum of all eigenvalues.

the importance of policy inertia decreases once persistent policy shocks are considered (that is, when ρ_v is not restricted to be zero). Moreover, the point estimate of ρ_v (≈ 0.35) is much smaller than the estimate reported by Rudebusch and Wu (2004) ($\rho_u = 0.975$ in their notation). The empirical results also suggest that the importance of persistent policy shocks (probably due to an omitted explanatory variable problem), measured by ρ_v, is reduced by considering the term spread in the policy rule (but still remains significant).

Our results do not fully support the finding of Gerlach-Kristen (2004) that the term spread is also a determinant of the estimated policy rule. The different results may be due to the different long-term interest rate used. Gerlach-Kristen (2004) considers the 10-year maturity rate, which may contain additional information (not included in the 1-year rate) for characterizing Fed rate movements. However, the large sample correlation (0.86) and the similar auto-correlation functions between the 1-year and the 10-year rate (although the 10-year maturity rate shows slightly more persistence than the 1-year rate) suggest that the above explanation is not good enough and that the different results on the term spread significance may be due to the alternative econometric strategies implemented in the two papers. As emphasized in Section 2, we believe that a system-based econometric approach deals better with endogeneity problems than a single-equation econometric strategy.

5 Model performance

Based on the J-Wald test, we concluded above that the overall performance of the NKM model augmented with term structure was not good. This result does not mean that the model fails in all interesting dimensions. In this section, we consider diagnostic tests, unconditional moments, impulse response analysis and comovement analysis to identify features of the data (not) accounted for by the NKM model augmented with term structure.[27]

5.1 Diagnostic tests

Since the VAR residuals are orthogonal to the VAR dependent variables, the goodness-of-fit statistic can be decomposed into two terms: $J_T(\theta) =$

[27]The empirical results reported in this section are based on $n = m = 10$. Similar results are found with $n = 1$ and $m = 100$.

$J_T^1(\theta) + J_T^2(\theta)$, where $J_T^1(\theta)$ measures the distance associated with the systematic part of the VAR and $J_T^2(\theta)$ measures the distance associated with the coefficients of the variance-covariance matrix of the VAR residuals. The estimation results obtained with the NKM model augmented with term structure under the standard Taylor rule results in $J_T^1(\theta) = 1.8425$ and $J_T^2(\theta) = 0.7534$. Therefore, the model has more trouble in accounting for the non-systematic part than for the systematic part of the VAR.[28]

The components of the vector $[H_T(\theta_0) - H_N(\theta)]$ contain information on how well the NKM model augmented with term structure accounts for the estimates of the VAR (auxiliary) model. Larger components point to the estimates of the auxiliary model that the NKM model augmented with term structure has trouble accounting for. As suggested by Gallant, Hsieh and Tauchen (1997) the following quasi-t-ratios statistics can identify sources of model failure:

$$\sqrt{1+\frac{1}{n}}\sqrt{T}\left[\left(diag(W_T^{-1})\right)_i^{1/2}\right]^{-1}[H_T(\theta_0) - H_N(\theta)]_i \quad \text{for} \quad i = 1, ..., p, \quad (11)$$

where W_T is a consistent estimate of W, $\left(diag(W_T^{-1})\right)_i$ denotes the i-th element of the diagonal of matrix W_T^{-1} and $[H_T(\theta_0) - H_N(\theta)]_i$ is the i-th element of $[H_T(\theta_0) - H_N(\theta)]$. In particular, a large i-th diagnostic statistic indicates that the NKM model does a poor job of fitting the i-th coefficient of the VAR model.

The second and third columns in Table 5 show the VAR estimates and the corresponding standard errors, respectively. The remaining columns in Table 5 show the corresponding quasi-t-ratio diagnostic statistic (11) for the alternative policy rules studied. The fourth column in Table 5 reveals that the NKM model augmented with term structure under the standard Taylor rule has trouble in accounting for output gap, inflation, Fed rate and 1-year rate persistence since for each equation some dependent variable lags are significant and the associated diagnostic statistic is large. These results are robust to alternative specifications of the monetary policy rule.

5.2 Unconditional moments

Table 6 shows the unconditional second moment statistics of actual data and synthetic data. Panel A considers unfiltered data whereas Panel B considers

[28]Notice that $J_T^1(\theta)$ is computed based on 68 coefficients whereas $J_T^2(\theta)$ is based on 10. Our conclusion is then based on the fact that the ratio 68/10 is almost three times larger than $J_T^1(\theta)/J_T^2(\theta) = 2.45$.

Hodrick-Prescott filtered data. The unconditional moments of simulated data are the averages of the moments obtained from five hundred simulated time series of each variable. Panel A shows that the model does a good job in replicating the standard deviations of inflation, the Fed rate and the 1-year rate, but it fails to reproduce the volatility of the output gap. The model also replicates the low contemporaneous correlation between output and inflation and the high contemporaneous correlation between the two interest rates considered. However, the model performs poorly when trying to reproduce the other correlations studied. Comparing Panels A and B we observe that the model has much more trouble when trying to reproduce the unconditional moments of Hodrick-Prescott filtered data. Finally, Table 6 (fourth column) shows that the NKM model imposing the determinacy condition does a poor job in replicating the unconditional moments. These results suggest additional evidence for the indeterminacy hypothesis during the Greenspan era.

5.3 Impulse response analysis

Figure 2 shows four plots with the impulse responses of output gap, inflation, short-term rate and long-term rate to a monetary policy shock. In these plots, the solid line represents the impulse response implied by the model whereas the dashed lines are 95% confidence bands. The size of the shock is determined by its estimated standard deviation. Figure 2 reveals that a contractionary monetary policy shock reduces output in the short-run, but output recovers rapidly (five quarters). A contractionary monetary policy shock has significant positive (negative) effects on interest rates (inflation) but only in the short-run.

5.4 Comovement analysis

There is a long standing debate on the relationship between economic activity and prices (inflation). For a long time economists widely accepted that output and inflation displayed a positive correlation at least in the short-run. For a large group of economists, the positive short-run correlation between output and inflation (the so-called Phillips curve phenomenon) is still considered a necessary building block of business cycle theory (for instance, Mankiw, 2001). Yet this view is rather controversial in the literature. For instance, Kydland and Prescott (1990) argue that "*any theory in which procyclical prices figure crucially in accounting for postwar business* *cycle fluctuations is doomed to failure.*" Moreover, Cooley and Ohanian (1991) find evidence that the U.S. correlation between output and prices is negative during the postwar period.

Den Haan (2000) argues that an important source of disagreement in this literature is the focus on only the unconditional correlation coefficient. Den Haan proposes using correlations of VAR forecast errors at different horizons to analyze the comovement between pairs of variables. As discussed by Den Haan (2000), this methodology has two main advantages. First, variables need not be stationary for their comovement to be analyzed, so prior filtering is not required. Second, it avoids the type of *ad-hoc* assumptions necessary to compute impulse response functions. Since the comovement between a pair of variables is an equilibrium outcome (that is, an outcome resulting from the interaction between supply and demand shocks that is observed in the data with no need for any identifying assumption) comovement dynamics are good 'stylized' facts for analyzing a model's performance.

In this subsection, we apply the methodology suggested by Den Haan to study the comovement between (i) the level of economic activity measured by the output gap and inflation; and (ii) the Fed funds rate and the 1-year rate. The goal is to analyze the ability of the NKM model augmented with term structure to replicate the type of comovement between pairs of variables observed in U.S. data. Recently, María-Dolores and Vázquez (2004) have shown the presence of a weak comovement between economic activity and inflation in U.S. data using a wide range of alternative measures of economic activity and inflation.

Figures 3 and 4 show the comovement between output gap and inflation and between the Fed funds rate and the 1-year rate, respectively.[29] In each figure, the solid line represents the estimated correlations at different forecast horizons using U.S.data, the lines with long-dashes are 95% confidence bands computed using bootstrap methods and the line with short-dashes shows the correlation coefficients implied by the model. Figure 3 shows (i) the presence of a weak comovement between output and inflation in the U.S.; and (ii) the NKM model with term structure is able to mimic the weak negative comovement between output and inflation in the short-run (up to two quarters forecast horizons) and a non-significant comovement at longer forecast horizons.

Figure 4 shows a weak positive comovement between the two interest rates at short-run forecast horizons whereas a strong positive comovement

[29] See Den Haan (2000) for details on this methology for analyzing comovement.

is present at medium- and long-run forecast horizons. Moreover, Figure 4 shows that the NKM model with term structure generates a negative comovement between interest rates in the short-run in contrast to the weak comovement exhibited by actual interest rate data. However, the model is able to reproduce the strong comovement between the two interest rates at medium- and long-run forecast horizons observed in U.S. data.

6 CONCLUSIONS

This paper follows a structural approach to analyze the relative importance of term structure, policy inertia, and persistent monetary policy shocks in the characterization of the estimated U.S. monetary policy rule. The framework considered is an NKM model augmented with term structure where the monetary policy rule is one of the building blocks. A structural econometric approach based on the *indirect inference* principle is implemented. In order to tackle the question of whether the Fed responds only to the information content of the spread about inflation and real activity or responds independently to the spread, three alternative specifications for the monetary policy rule are considered, called the standard rule, forward-looking rule and backward-looking rule.

The empirical results show that the Fed does not seem to respond independently to the spread, but it contains relevant information of current and future inflation and output gap. Moreover, policy inertia and persistent policy shocks are still significant factors under all three specifications even when the term spread is included in the policy rule. The latter result is similar to that found by English et al. (2003) and Gerlach-Kristen (2004) considering a standard Taylor rule and a reduced-form estimation approach. In contrast to Gerlach-Kristen (2004), the coefficient associated with the term spread in the policy rule is not significant in most cases and is always much smaller than that obtained by Gerlach-Kristen. The empirical evidence also suggests that the Fed may respond to the information content of the spread about current inflation and real activity, but it does not seem to respond independently to the spread.

Furthermore, the estimates of structural parameters in the NKM model augmented with term structure are robust to alternative specifications of the policy rule, in sharp contrast with the results found by María-Dolores and Vázquez (2006) under the standard NKM model. This result then indicates that the augmented model helps to improve parameter identification. Finally, we show that the NKM model augmented with term structure is able to mimic the weak comovement between output and inflation as well as the strong comovement at medium- and long-term forecast horizons between the Fed funds rate and the 1-year rate observed in actual data. However, diagnostic tests also show that the model fails to reproduce the highly persistent dynamics characterizing U.S. output gap, inflation and interest rate time series.

Our empirical results should be interpreted with caution since the structural NKM model, like any other dynamic stochastic general equilibrium model, is likely to be misspecified in several dimensions. As is well known (see, for instance, Lubik and Schorfheide, 2005), overall model specification is important since it may lead to biased estimates, prevent identification of the true structural parameters and affect model selection. In despite of these warnings, the estimation of an NKM augmented with term structure looks like the most reasonable starting point for empirically analyzing the interaction between macroeconomic variables and term structure.

APPENDIX 1

This appendix derives the set of IS equations (1). Consider that the representative consumer solves the problem of maximizing

$$E_0 \sum_{t=0}^{\infty} \beta^t U(C_t)$$

subject to the condition that

$$C_t + \sum_{j=1}^{n} B_t^{\{j\}} \leq Y_t + \sum_{j=1}^{n} B_{t-j}^{\{j\}} R_{t-j}^{\{j\}},$$

where C, Y, $B^{\{j\}}$, $R^{\{j\}}$ denote consumption, income, stock of the j-period bonds and gross real return of the j-period bond, respectively. Under fairly general conditions this problem has a solution with a finite value of the objective function. The first-order necessary conditions are given by

$$U'(C_t) = \lambda_t,$$

$$\beta^j E_t(\lambda_{t+j} R_t^{\{j\}}) = \lambda_t, \text{ for } j = 1, ..., n$$

where $\{\lambda_t\}$ is a sequence of Lagrange multipliers. Substituting the first equation into each of the j-conditions gives

$$E_t \left[\beta^j \frac{U'(C_{t+j})}{U'(C_t)} R_t^{\{j\}} \right] = 1, \text{ for } j = 1, ..., n$$

Assuming (i) a standard constant relative risk aversion utility function and (ii) no physical capital, it is straightforward to log-linearize these Euler equations in order to obtain (1).

APPENDIX 2

This appendix shows the matrices involved in equation (10).

$$
\Gamma_0 = \begin{pmatrix}
1 & 0 & 0 & \tau & 0 & 0 & 0 & -1 & 0 & 0 & 0 & -\tau & 0 & 0 & -1 & 0 \\
1 & 0 & \tau & 0 & -1 & 0 & 0 & 0 & -\tau & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\
-\kappa & 1 & 0 & 0 & 0 & 0 & 0 & 0 & -\beta & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\
-(1-\rho)\psi_2 & -(1-\rho)\psi_1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0
\end{pmatrix},
$$

$$
\Gamma_1 = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \rho-(1-\rho)\psi_3 & (1-\rho)\psi_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \rho_g & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \rho_z & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \rho_g^{\{4\}} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \rho_v \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0
\end{pmatrix},
$$

$$\Pi = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix},$$

$$\Psi = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}.$$

APPENDIX 3

This appendix describes the time series considered.

Economic activity indexes:

- GDP: quarterly, seasonally adjusted data. Period: 1987:3-2004:3. Source: U.S. Department of Commerce, Bureau of Economic Analysis.
- Real potential GDP: quarterly data. Period: 1987:3-2004:3. Source: U.S. Congress, Congressional Budget Office.

Price level index:

- U.S. implicit price deflator of GDP: quarterly, seasonally adjusted data. Period: 1987:3-2004:3. Source: U.S. Department of Commerce, Bureau of Economic Analysis.

Interest rates:

- Federal funds rate: quarterly data. Period: 1987:3-2004:3. Source: Board of Governors of the Federal Reserve System.
- 1-Year Treasury Constant Maturity Rate: quarterly data. Period: 1994:1-2004:3. Source: Board of Governors of the Federal Reserve System.

MATHEMATICAL APPENDIX

(not intended for publication)

Optimal Taylor rule under the New Keynesian Monetary model

Assuming a quadratic per-period loss function in inflation performance, $L(\widetilde{\pi}_t) = \frac{1}{2}[\widetilde{\pi}_t^2]$, and a fixed discount rate δ, the policymaker's objective in period t is to minimize the expected present discounted value of the per-period losses:

$$E_t \sum_{s=0}^{\infty} \frac{1}{2} \beta^s L(\widetilde{\pi}_{t+s}), \tag{12}$$

subject to the following two equations describing the variation over time of the economy which are contemplated inside the standard New Keynesian Monetary model:

$$y_t = E_t[y_{t+1}] - \tau(i_t - E_t[\pi_{t+1}]) + g_t, \tag{13}$$

$$\pi_t = \beta E_t[\pi_{t+1}] + ky_t + z_t, \tag{14}$$

where $\widetilde{\pi}_t$ is the deviation of inflation from a specific target (that is, $\widetilde{\pi} = \pi - \pi^*$), y_t is the output gap, E_t is the conditional expectations operator,$\beta \in [0, 1)$, and g_t and z_t are zero-mean normally distributed shocks.

Totally differentiating (12) with respect to i_t, subject to $(13)-(14)$, yields the following Euler equation:

$$\pi_t = \pi^*. \tag{15}$$

This Euler equation can be solved recursively,

$$\begin{gathered}
\beta E_t[\pi_{t+1}] + ky_t + z_t = \pi^*, \\
\beta E_t[\pi_{t+1}] + k[E_t[y_{t+1}] - \tau(i_t - E_t[\pi_{t+1}]) + g_t] + z_t = \pi^*, \\
(\beta + k\tau)E_t[\pi_{t+1}] + kE_t[y_{t+1}] - \tau k i_t + kg_t + z_t = \pi^*. \qquad (16)
\end{gathered}$$

Taking expectations for one lead in output and inflation we obtain,

$$\begin{gathered}
y_{t+1} = E_{t+1}[y_{t+2}] - \tau(i_{t+1} - E_{t+1}[\pi_{t+2}]) + g_{t+1}, \\
E_t y_{t+1} = E_t[y_{t+2}] - \tau(E_t i_{t+1} - E_t[\pi_{t+2}]), \qquad (17) \\
\pi_{t+1} = \beta E_{t+1}[\pi_{t+2}] + ky_{t+1} + z_{t+1}, \\
E_t \pi_{t+1} = \beta E_t[\pi_{t+2}] + kE_t y_{t+1},
\end{gathered}$$

where, for the sake of simplicity, we assume that g_t and z_t are i.i.d. process with mean zero. Using the expression for $E_t y_{t+1}$, we have that

$$\begin{gathered}
E_t \pi_{t+1} = \beta E_t[\pi_{t+2}] + k[E_t[y_{t+2}] - \tau(E_t i_{t+1} - E_t[\pi_{t+2}])], \\
E_t \pi_{t+1} = (\beta + k\tau)E_t[\pi_{t+2}] + kE_t[y_{t+2}] - \tau k E_t i_{t+1}. \qquad (18)
\end{gathered}$$

Substituting (17) and (18) in (16), we obtain

$$\begin{gathered}
(\beta + k\tau)[(\beta + k\tau)E_t[\pi_{t+2}] + kE_t[y_{t+2}] - \tau k E_t i_{t+1}] \\
+k[E_t[y_{t+2}] - \tau(E_t i_{t+1} - E_t[\pi_{t+2}])] - \tau k i_t + kg_t + z_t = \pi^*,
\end{gathered}$$

$$[(\beta + k\tau)^2 + k\tau]E_t[\pi_{t+2}] + k(\beta + k\tau + 1)E_t[y_{t+2}] - k\tau(\beta + k\tau + 1)E_t i_{t+1}$$

$$-\tau k i_t + k g_t + z_t = \pi^* \tag{19}$$

Following the approach of Campbell and Shiller (1987, 1991) on the expectations theory of the term structure of interest rates, we can consider the following expression for interest rates at different maturities,

$$i_t^T = \frac{1}{T}\sum_{j=1}^{T} E_t i_{t+j-1} + \frac{1}{T}\sum_{j=1}^{T-1} E_t RP_{t+j-1} \tag{20}$$

where RP_t is the time-varying term premium. Then, we obtain for $T = 2$ that

$$i_t^2 = \frac{1}{2}(i_t + E_t i_{t+1}) + RP_t,$$

$$E_t i_{t+1} = 2i_t^2 - i_t - 2RP_t,$$

$$i_{t+1} - i_t = 2(i_t^2 - i_t) - 2RP_t + \epsilon_{t+1}, \tag{21}$$

where $\epsilon_{t+1} = i_{t+1} - E_t i_{t+1}$. Next, we can add and substract $\tau k i_{t+1}$ in (19) and then include (21) in order to derive a Taylor rule that includes the term-spread as an explanatory variable,

$$[(\beta + k\tau)^2 + k\tau]E_t[\pi_{t+2}] + k(\beta + k\tau + 1)E_t[y_{t+2}]$$

$$-k\tau(\beta + k\tau + 1)E_t i_{t+1} - \tau k i_t + \tau k i_{t+1} - \tau k i_{t+1} + k g_t + z_t = \pi^*,$$

$$[(\beta + k\tau)^2 + k\tau]E_t[\pi_{t+2}] + k(\beta + k\tau + 1)E_t[y_{t+2}]$$

$$-k\tau(\beta + k\tau + 1)E_t i_{t+1} + k\tau[i_{t+1} - i_t] - \tau k i_{t+1} + k g_t + z_t = \pi^*,$$

$$[(\beta + k\tau)^2 + k\tau]E_t[\pi_{t+2}] + k(\beta + k\tau + 1)E_t[y_{t+2}]$$

$$-k\tau(\beta + k\tau + 1)E_t i_{t+1} + k\tau[2(i_t^2 - i_t) - 2RP_t + \epsilon_{t+1}] - \tau k i_{t+1} + k g_t + z_t = \pi^*,$$

$$[(\beta + k\tau)^2 + k\tau]E_t[\pi_{t+2}] + k(\beta + k\tau + 1)E_t[y_{t+2}] + 2k\tau(i_t^2 - i_t)$$

$$-k\tau(\beta + k\tau + 1)E_t i_{t+1} - 2k\tau RP_t + k\tau\epsilon_{t+1} - \tau k i_{t+1} + k g_t + z_t = \pi^*.$$

Next, we add and subtract $k\tau(\beta + k\tau + 1)i_{t+1}$ and re-arrange:

$$[(\beta + k\tau)^2 + k\tau]E_t[\pi_{t+2}] + k(\beta + k\tau + 1)E_t[y_{t+2}] + 2k\tau(i_t^2 - i_t)$$

$$+k\tau(\beta + k\tau + 1)\epsilon_{t+1} - 2k\tau RP_t + k\tau\epsilon_{t+1} - \tau k(\beta + k\tau + 2)i_{t+1} + k g_t + z_t = \pi^*,$$

where $A = \beta + k\tau + 1$ and $B = \tau k$. This gives a forward-looking Taylor Rule with a lagged term-spread

$$i_t = \frac{[(A-1)^2 + B]}{[B(A+1)]} E_{t-1}[\pi_{t+1}] + \frac{A}{\tau(A+1)} E_{t-1}[y_{t+1}] + \frac{2}{(A+1)} (i^2_{t-1} - i_{t-1}) - \frac{1}{B(A+1)} \pi^* + \xi_t, \quad (22)$$

where

$$\xi_t = -\frac{2}{(A+1)} RP_{t-1} + \epsilon_t + \frac{1}{\tau(A+1)} g_{t-1} + \frac{1}{B(A+1)} z_{t-1}.$$

Notice that the optimal policy rule (22) looks like the one considered in the paper: the only difference is that the expectation operator is conditional on the information set at time $t-1$ instead of time t. In spite of this difference, the NKM model augmented with term structure under the expectation theory implies that $\hat{\psi}_3$ must be $2/(A+1)$ where $A = \beta + \kappa\tau + 1$. Therefore, if we consider the estimates obtained assuming the forward-looking Taylor rule, we obtain that $\hat{\beta} = 0.992$, $\widehat{\kappa} = 0.990$ and $\hat{\tau} = 0.993$. These coefficients imply a value $\psi_3 = 0.503$, which is much larger that the estimated value found $\hat{\psi}_3 = 0.0317$. This result suggests an informal test that the expectation theory of term structure and/or the optimal monetary policy assumption should be rejected.

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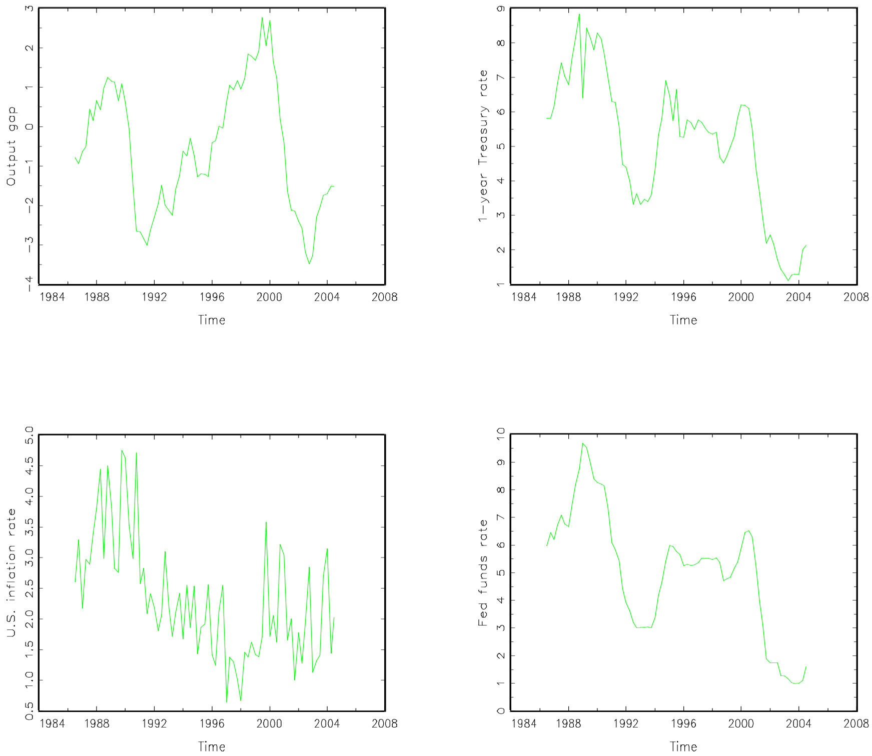

Figure 1: Time series plots

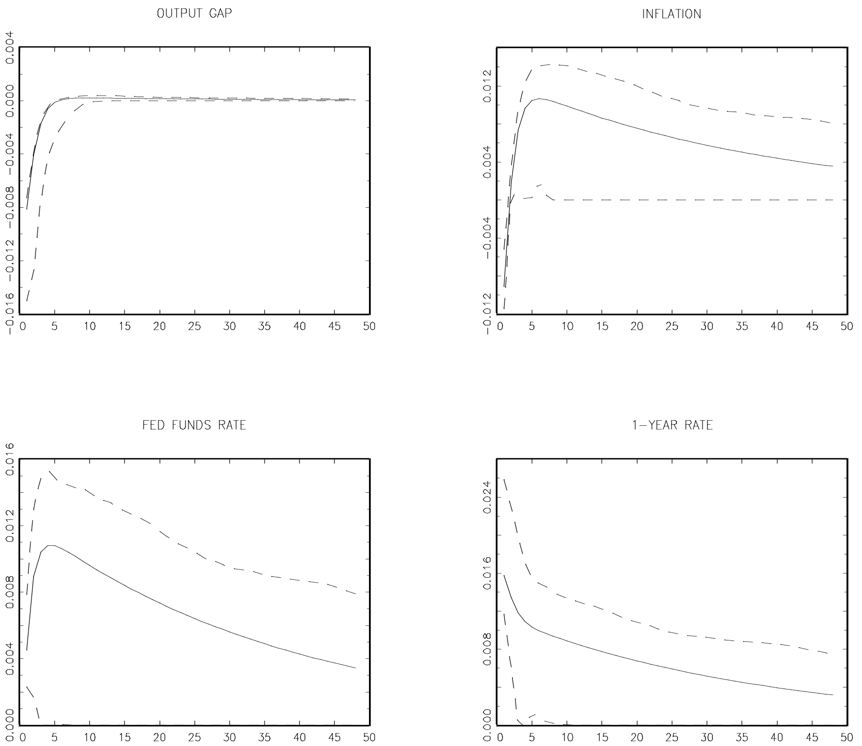

Figure 2: Response to a contractionary monetary policy shock

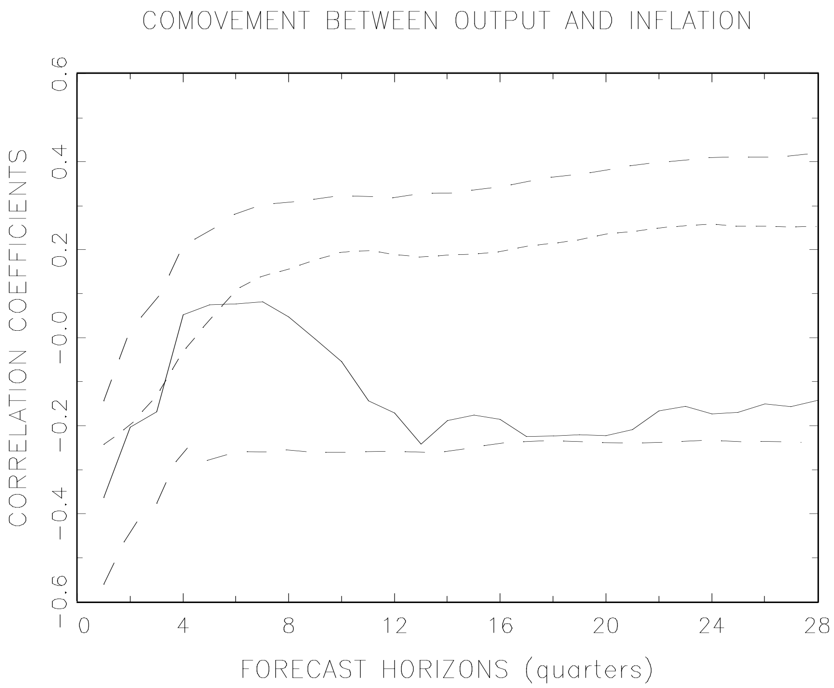

Figure 3: Comovement between output and inflation

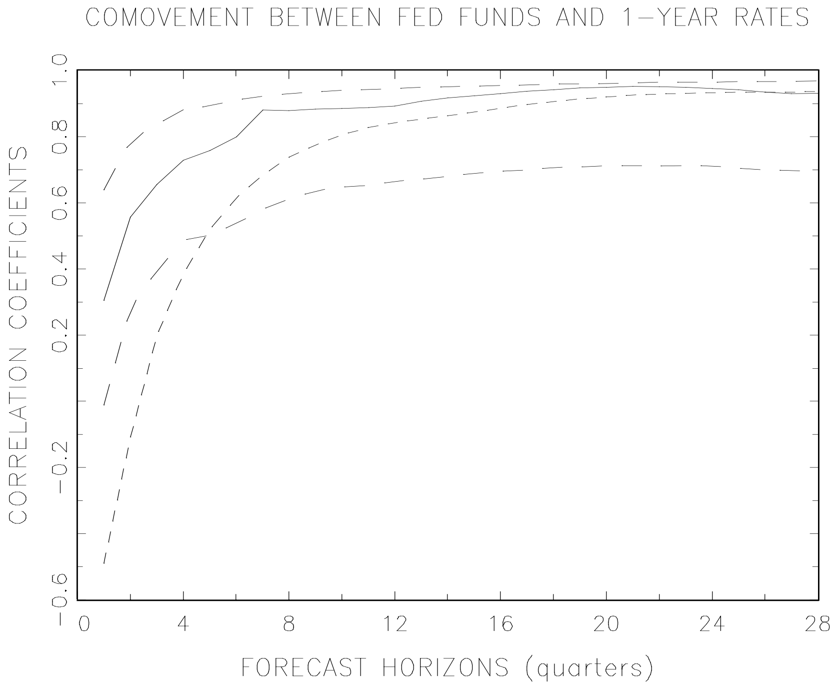

Figure 4: Comovement between the Fed funds and the 1-year rate

Table 1. Estimation results of the NKM model with term structure and standard Taylor rule (3)

		$\psi_3 = 0$	$\rho_v = 0$	Current spread	$\psi_1 > 1$
J_T	2.5959	2.9107	3.1075	2.6801	3.2571
τ	0.9937	0.9946	0.9932	0.9944	0.9819
	(0.3414)	(0.2896)	(0.1705)	(0.2978)	(0.2739)
β	0.9983	0.9970	0.9925	0.9979	0.9945
	(0.0009)	(0.0012)	(0.0007)	(0.0011)	(0.0013)
ρ	0.5611	0.3553	0.7537	0.4022	0.1196
	(0.0910)	(0.1205)	(0.0495)	(0.0963)	(0.0312)
κ	0.9918	0.9932	0.9909	0.9926	0.9699
	(0.3956)	(0.4138)	(0.2032)	(0.4643)	(0.5135)
ψ_1	0.9757	0.9180	0.7460	0.9828	1.00001
	(0.0108)	(0.0313)	(0.0783)	(0.0164)	
ψ_2	0.1917	0.1471	0.5033	0.1038	0.0071
	(0.0657)	(0.0499)	(0.1035)	(0.0510)	(0.0030)
ψ_3	0.4858		0.3300	0.4363	0.1003
	(0.2056)		(0.3256)	(0.2008)	(0.0252)
ρ_g	0.6724	0.5443	0.9676	0.6787	0.9913
	(0.0702)	(0.1044)	(0.0561)	(0.0800)	(0.0025)
$\rho_g^{\{4\}}$	0.8556	0.8656	0.9714	0.8456	0.0001
	(0.0624)	(0.0498)	(0.0962)	(0.0680)	(0.0057)
ρ_z	0.9125	0.9370	0.9172	0.9246	0.9517
	(0.0213)	(0.0219)	(0.0194)	(0.0224)	(0.0155)
ρ_v	0.3586	0.5620		0.5562	0.5878
	(0.0995)	(0.0582)		(0.0633)	(0.0512)
ρ_{gg}	0.9932	0.9924	0.9928	0.9930	0.9305
	(0.2898)	(0.3628)	(0.8645)	(0.3811)	(0.4029)
σ_g	0.0716	0.0585	0.0036	0.0734	0.0002
	(0.0184)	(0.0183)	(0.0035)	(0.0190)	(0.0001)
$\sigma_g^{\{4\}}$	0.0586	0.0712	0.0324	0.0425	0.0129
	(0.0113)	(0.0136)	(0.0044)	(0.0199)	(0.0030)
σ_z	0.2279	0.2333	0.1892	0.2449	0.0359
	(0.0789)	(0.0934)	(0.0379)	(0.1068)	(0.0171)
σ_ϵ	0.0103	0.0158	0.0014	0.0121	0.0002
	(0.0117)	(0.0104)	(0.0028)	(0.0079)	(0.0001)
π^*	0.4817	0.7451	2.2438	0.5743	1.5810
	(0.2681)	(0.2925)	(0.1987)	(0.3033)	(0.4253)

Note: Standard errors in parentheses.

Table 2. Estimation results of NKM model with term structure and forward-looking Taylor rule (8)

		$\psi_3 = 0$	$\rho_v = 0$	Current spread
J_T	2.9846	2.9866	3.1553	3.0843
τ	0.9931	0.9931	0.9932	0.9943
	(0.1959)	(0.1898)	(0.1291)	(0.2613)
β	0.9923	0.9923	0.9927	0.9976
	(0.0007)	(0.0007)	(0.0008)	(0.0010)
ρ	0.4076	0.3867	0.5473	0.8049
	(0.0793)	(0.0620)	(0.0562)	(0.1798)
κ	0.9906	0.9906	0.9908	0.9931
	(0.2786)	(0.2839)	(0.2248)	(0.2651)
ψ_1	0.9300	0.9243	0.9363	0.9524
	(0.0306)	(0.0272)	(0.0337)	(0.0520)
ψ_2	0.0371	0.0382	0.1035	1.5944
	(0.0181)	(0.0176)	(0.0449)	(2.1022)
ψ_3	0.0317		0.1750	0.0000
	(0.0918)		(0.0987)	(0.2082)
ρ_g	0.5996	0.6052	0.5961	0.9246
	(0.0956)	(0.0915)	(0.7117)	(0.0425)
$\rho_g^{\{4\}}$	0.7227	0.7228	0.9567	0.9763
	(0.0660)	(0.0711)	(0.0616)	(0.0177)
ρ_z	0.9598	0.9601	0.9299	0.8827
	(0.0111)	(0.0109)	(0.0184)	(0.0229)
ρ_v	0.4462	0.4740		0.5079
	(0.0949)	(0.0648)		(0.0715)
ρ_{gg}	0.9928	0.9928	0.9928	0.9938
	(0.5102)	(0.5238)	(1.8117)	(0.4115)
σ_g	0.0213	0.0211	0.0027	0.0044
	(0.0112)	(0.0108)	(0.0038)	(0.0022)
$\sigma_g^{\{4\}}$	0.0183	0.0182	0.0235	0.0250
	(0.0029)	(0.0030)	(0.0031)	(0.0084)
σ_z	0.19870	0.20136	0.17404	0.08327
	(0.0657)	(0.0676)	(0.0404)	(0.0184)
σ_ϵ	0.0071	0.0075	0.0012	0.0000
	(0.0030)	(0.0030)	(0.0028)	(0.0019)
π^*	2.34950	2.35370	2.15510	0.68060
	(0.2613)	(0.2642)	(0.2321)	(0.2802)

Note: Standard errors in parentheses.

Table 3. Estimation results of NKM model with term structure and backward-looking Taylor rule (9)

		$\psi_3 = 0$	$\rho_v = 0$	Current spread
J_T	2.8294	2.8893	3.1476	2.8893
τ	0.9996	0.9964	0.9999	0.9964
	(0.3166)	(0.2802)	(0.1552)	(0.2912)
β	0.9982	0.9973	0.9929	0.9973
	(0.0007)	(0.0010)	(0.0008)	(0.0010)
ρ	0.7512	0.8350	0.8387	0.8350
	(0.0826)	(0.0987)	(0.0802)	(0.1002)
κ	0.9438	0.9985	1.0000	0.9985
	(0.2317)	(0.2456)	(0.1916)	(0.2737)
ψ_1	0.6556	0.1296	0.68310	0.1296
	(0.1006)	(0.2889)	(0.3987)	(0.3100)
ψ_2	1.1129	1.7714	0.8854	1.7714
	(0.4092)	(1.1398)	(0.5628)	(1.1540)
ψ_3	0.9998		1.4007	0.0000
	(0.3311)		(0.7329)	(0.3659)
ρ_g	0.9762	0.9693	0.9684	0.9693
	(0.0112)	(0.0143)	(0.0309)	(0.0146)
$\rho_g^{\{4\}}$	0.9899	0.9910	0.9844	0.9910
	(0.0048)	(0.0046)	(0.0171)	(0.0046)
ρ_z	0.8817	0.9110	0.9100	0.9110
	(0.0385)	(0.0262)	(0.0255)	(0.0262)
ρ_v	0.3543	0.4462		0.4462
	(0.1326)	(0.1339)		(0.1358)
ρ_{gg}	0.9999	0.9971	0.9999	0.9971
	(0.1507)	(0.1419)	(0.38639)	(0.1454)
σ_g	0.0325	0.0253	0.0044	0.0253
	(0.0152)	(0.0111)	(0.0026)	(0.0116)
$\sigma_g^{\{4\}}$	0.0608	0.0514	0.0305	0.0514
	(0.0107)	(0.0085)	(0.0040)	(0.0099)
σ_z	0.2824	0.2923	0.1742	0.2923
	(0.0593)	(0.0680)	(0.0334)	(0.0714)
σ_ϵ	0.0120	0.0000	0.0008	0.0000
	(0.0063)	(0.0097)	(0.0009)	(0.0100)
π^*	0.2692	0.4284	2.1062	0.4284
	(0.1338)	(0.1876)	(0.2191)	(0.1898)

Note: Standard errors in parentheses.

Table 4. Estimation results of the NKM model with n=1 and m=100

	Standard	Forward-look	Backward-look	Current spread	$\psi_1 > 1$
J_T	3.1239	3.3414	3.8185	3.4405	3.4221
τ	1.0000	1.0000	1.0000	0.9971	0.9921
	(0.1719)	(0.2715)	(0.2432)	(0.1504)	(0.3942)
β	0.9954	0.9940	0.9988	0.9953	0.9924
	(0.0008)	(0.0011)	(0.0002)	(0.0008)	(0.0008)
ρ	0.3953	0.4992	0.7925	0.6312	0.5940
	(0.0799)	(0.0700)	(0.0434)	(0.0544)	(0.0417)
κ	1.0000	1.0000	1.0000	0.9973	0.6668
	(0.3138)	(0.3911)	(0.2142)	(0.2186)	(0.3132)
ψ_1	0.9006	0.9892	0.7028	0.8484	1.2849
	(0.0314)	(0.0105)	(0.0660)	(0.0837)	(0.0842)
ψ_2	0.0842	0.0000	1.2186	0.3496	0.1062
	(0.0164)	(0.0062)	(0.2113)	(0.1416)	(0.0265)
ψ_3	0.0390	0.1145	1.0637	0.0000	0.7069
	(0.0845)	(0.0872)	(0.3248)	(0.4698)	(0.1342)
ρ_g	0.7411	0.7159	0.9408	0.8946	1.0000
	(0.0746)	(0.0478)	(0.0173)	(0.0616)	(0.0028)
$\rho_g^{\{4\}}$	0.9682	0.7777	0.9170	0.9507	0.3728
	(0.0192)	(0.0554)	(0.0266)	(0.0500)	(0.0824)
ρ_z	0.9804	0.9822	0.9005	0.9385	0.9846
	(0.0050)	(0.0066)	(0.0195)	(0.0156)	(0.0091)
ρ_v	0.6743	0.6946	0.4339	0.2583	0.3629
	(0.0538)	(0.0515)	(0.1027)	(0.0784)	(0.0567)
ρ_{gg}	1.0000	1.0000	1.0000	0.9961	0.0000
	(0.1889)	(0.1840)	(0.1323)	(0.3712)	(0.5265)
σ_g	0.0137	0.0265	0.0607	0.0089	0.0014
	(0.0035)	(0.0089)	(0.0252)	(0.0026)	(0.0008)
$\sigma_g^{\{4\}}$	0.0307	0.0114	0.0586	0.0267	0.0215
	(0.0040)	(0.0034)	(0.0081)	(0.0050)	(0.0055)
σ_z	0.2438	0.1757	0.2499	0.2152	0.0838
	(0.0900)	(0.0934)	(0.0441)	(0.0542)	(0.0357)
σ_ϵ	0.0061	0.0099	0.0366	0.0051	0.0054
	(0.0025)	(0.0042)	(0.0125)	(0.0022)	(0.0031)
π^*	1.1100	1.5911	0.1817	1.3445	2.1817
	(0.1979)	(0.3067)	(0.0336)	(0.2072)	(0.1922)

Table 5. VAR estimates and diagnostic tests

Variable	Estimate	Standard error	Diag. stat. for (3)	Diag. stat. for (8)	Diag. stat. for (9)
	Output	**gap**	**equation**		
constant	0.081450	0.24292	0.44589	0.73065	0.44300
outputgap(1)	1.13403***	0.15121	1.59487	0.78879	0.85754
outputgap(2)	0.01556	0.21266	0.20661	0.41210	0.74737
outputgap(3)	−0.43313**	0.20519	−2.30888	−2.13297	−2.34313
outputgap(4)	0.09938	0.14841	0.60361	0.61018	0.51371
inflation(1)	0.04411	0.09145	−0.16722	−0.57633	0.33596
inflation(2)	−0.10954	0.08574	−0.41272	−1.07259	−1.14360
inflation(3)	−0.09446	0.09737	−0.98243	−1.26966	−1.06333
inflation(4)	−0.08307	0.09889	−1.25748	−0.91230	−1.08227
Fed rate(1)	0.291505	0.25601	1.59695	1.72040	1.07937
Fed rate(2)	−0.08858	0.34167	−0.63354	−0.46469	−0.18493
Fed rate(3)	0.11778	0.32782	0.58232	0.57433	0.46486
Fed rate(4)	−0.09673	0.17466	−0.67417	−0.79736	−0.77564
1-year rate(1)	−0.06454	0.12000	−1.43968	−1.50222	−1.08369
1-year rate(2)	0.02248	0.14641	0.64146	0.52151	0.58992
1-year rate(3)	−0.29845**	0.14641	−2.21393	−2.46649	−2.33959
1-year rate(4)	0.195724	0.15644	1.41180	1.57185	1.56781
	Inflation	**equation**			
constant	0.64491*	0.36181	2.19838	2.70936	2.28764
outputgap(1)	0.20367	0.22521	0.57191	0.67331	0.64803
outputgap(2)	−0.12120	0.31675	−0.44351	−0.30204	−0.26653
outputgap(3)	0.14103	0.30561	0.74774	0.18475	0.50323
outputgap(4)	−0.18291	0.22105	−0.85322	−0.20463	−0.54400
inflation(1)	0.19503	0.13621	−3.05449	−2.29684	−3.66787
inflation(2)	0.09031	0.12770	0.64107	1.08717	0.60195
inflation(3)	0.17990	0.14502	1.38965	1.31617	0.21443
inflation(4)	0.41321***	0.14729	3.36270	3.52824	3.82600
Fed rate(1)	−0.39995	0.38131	−1.98112	−1.78725	−1.66116
Fed rate(2)	0.34854	0.50889	1.00360	0.80288	0.76405
Fed rate(3)	0.53918	0.48826	1.28200	1.22098	1.39985
Fed rate(4)	−0.20357	0.26014	−0.79122	−0.70195	−0.72646
1-year rate(1)	0.22395	0.17873	0.89156	0.74251	0.81751
1-year rate(2)	0.10468	0.21807	0.52155	0.52850	0.72424
1-year rate(3)	−0.35473	0.21807	−1.86743	−1.92442	−1.95681
1-year rate(4)	−0.31689	0.23300	−1.44574	−1.58472	−1.37198

Table 5. (Continued)

Variable	Estimate	Standard error	Diag. stat. for (3)	Diag. stat. for (8)	Diag. stat. for (9)
	Fed funds	**rate**	**equation**		
constant	−0.09659	0.12861	−0.93639	−0.14060	−0.99298
outputgap(1)	0.31942***	0.08005	1.99824	1.30827	1.06253
outputgap(2)	−0.05555	0.11259	−0.16552	−0.18860	0.52460
outputgap(3)	−0.07561	0.10863	−0.58157	−0.42524	−0.48226
outputgap(4)	−0.03052	0.07857	0.08345	0.55791	−0.08729
inflation(1)	0.03523	0.04842	0.04184	−0.49885	0.78292
inflation(2)	0.14275**	0.04539	−0.32401	−0.37637	0.45391
inflation(3)	0.05327	0.05155	1.18351	1.98123	0.03232
inflation(4)	0.04727	0.05235	1.01738	0.74852	3.52028
Fed rate(1)	0.97088***	0.13554	−0.73394	−0.63721	−0.75215
Fed rate(2)	−0.64342***	0.18089	−2.25276	−1.74868	−2.48988
Fed rate(3)	0.37923**	0.17355	2.37983	2.45563	2.63725
Fed rate(4)	−0.22931**	0.09247	−2.19375	−2.31232	−2.88810
1-year rate(1)	0.29229***	0.06353	0.42519	1.80033	2.01406
1-year rate(2)	0.05208	0.07751	1.35846	−0.39948	−0.15196
1-year rate(3)	0.10992	0.07751	1.60699	1.90575	1.71270
1-year rate(4)	−0.03902	0.08282	0.08581	−1.00187	0.26401
	1-year	**rate**	**equation**		
constant	0.23396	0.29469	0.71146	−1.25502	0.38178
outputgap(1)	0.35880*	0.18343	1.15968	0.01260	1.07386
outputgap(2)	−0.10878	0.25798	−0.26728	0.74966	−0.39736
outputgap(3)	−0.04059	0.24892	−0.72260	0.78294	−0.17197
outputgap(4)	−0.12736	0.18004	−0.71983	−1.88874	−1.27196
inflation(1)	−0.02604	0.11094	−1.48077	−1.77168	−1.22227
inflation(2)	0.21906**	0.10401	−0.76173	1.75857	0.33738
inflation(3)	−0.01992	0.11812	0.19738	0.67749	−0.74554
inflation(4)	0.01583	0.11997	−0.00385	−0.87021	−0.28770
Fed rate(1)	0.49114	0.31057	1.66141	0.68605	1.83429
Fed rate(2)	−0.76472*	0.41449	−1.26136	−0.55308	−1.11289
Fed rate(3)	0.46950	0.39768	1.28338	1.51689	1.42875
Fed rate(4)	−0.12385	0.21188	−0.44589	−0.53957	−0.77117
1-year rate(1)	0.59354***	0.14557	−2.56420	0.91261	−1.93877
1-year rate(2)	0.20563	0.17761	1.07408	0.18512	0.19927
1-year rate(3)	0.22268	0.17762	0.78056	1.42834	0.86502
1-year rate(4)	−0.22513	0.18978	−1.55475	−2.11129	−1.75388

Table 5. (Continued)

Variable	Estimate	Standard error	Diag. stat. for (3)	Diag. stat. for (8)	Diag. stat. for (9)
	VAR residuals	variance	matrix		
s11	0.16765	0.23709	4.88828	5.33677	5.22570
s21	−0.08010	0.26223	−2.43836	−1.74392	−2.32153
s31	0.02270	0.09161	2.94185	3.68503	2.76910
s41	0.04903	0.20920	2.38349	1.26924	0.88244
s22	0.37190	0.52594	5.61964	5.16367	5.81972
s23	−0.00545	0.13230	−1.57128	−1.44254	−0.64903
s24	−0.01403	0.30323	0.95577	1.76615	0.97168
s33	0.04699	0.06645	0.33517	1.18831	0.55761
s34	0.03480	0.11315	0.08394	−0.61637	−1.02016
s44	0.24671	0.34891	0.85427	0.53449	−0.12236

Note: ***,**,* denote that the corresponding coefficients are statistically significant at the 1%, 5% and 10% levels, respectively.

Table 6. Unconditional moments

Panel A. Unfiltered time series

	Actual	Synthetic unrestricted	Synthetic determinacy
σ_y	1.646	0.399	0.084
σ_π	0.992	0.870	0.212
σ_i	2.280	1.926	0.490
$\sigma_{i\{4\}}$	2.054	1.759	0.486
$\rho_{y\pi}$	0.064	0.041	−0.561
ρ_{yi}	0.591	0.094	−0.609
$\rho_{yi\{4\}}$	0.571	0.165	−0.661
$\rho_{\pi i}$	0.508	0.962	0.985
$\rho_{\pi i\{4\}}$	0.484	0.792	0.929
$\rho_{ii\{4\}}$	0.963	0.914	0.978

Panel B. Hodrick-Prescott filtered time series

	Actual	Synthetic unrestricted	Synthetic determinacy
σ_y	0.963	0.239	0.044
σ_π	0.672	0.318	0.110
σ_i	1.065	0.537	0.233
$\sigma_{i\{4\}}$	0.963	0.558	0.229
$\rho_{y\pi}$	0.160	−0.196	−0.489
ρ_{yi}	0.447	−0.182	−0.613
$\rho_{yi\{4\}}$	0.447	−0.107	−0.732
$\rho_{\pi i}$	0.307	0.830	0.966
$\rho_{\pi i\{4\}}$	0.297	0.112	0.821
$\rho_{ii\{4\}}$	0.867	0.576	0.938

Note: σ_x denotes the standard deviation of variable x. ρ_{xw} denotes the unconditional correlation coefficient between variables x and w.