Unconventional monetary policy reaction functions: evidence from the US

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Unconventional Monetary Policy Rules*

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Abstract

We estimate unconventional monetary policy rules using linear and nonlinear econometric frameworks. We find that nonstandard policy measures are largely driven by the dynamics of inflation and the output gap. Moreover, when the output gap is low, there is a substantial amount of monetary accommodation vis-à-vis inflation, but this is significantly reduced when the output gap is high. Additionally, we uncover the presence of asymmetry and regime dependence in central bank actions since the global financial crisis, especially concerning the response of the term spread to the growth rate of reserves. Finally, rather than being directly included in the monetary policy reaction function, asset prices are used as conditioning information that influences the transition across policy regimes.

JEL: Unconventional monetary policy, policy rule, term spread, central bank reserves, inflation, output gap, asset prices,linear and nonlinear models.
Keywords: E21, E43, E51, E53.

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1. Introduction

The key goal of monetary policy is to preserve price stability over the medium-term. In the majority of developed countries, this objective is set by the monetary authority either via inflation targeting regimes or an explicit target for inflation.

In normal (conventional) times, the central bank conducts monetary policy by controlling short-term nominal interest rates. More specifically, it announces a target interest rate and, then, it uses open market operations to align interbank rates with the target.[1]

Yet, central bank rates are typically constrained from below at the zero lower bound. This means that the task of boosting an economy that faces deflationary prospects is complicated by the fact that further monetary stimulus cannot be deployed via cuts in nominal interest rates. Moreover, even if negative rates could be implemented, the monetary authority might have a strict preference for a non-negative bound in order to avoid the breakdown of inter-bank activity.

Given this and in light of the severity of the Great Recession, central banks have turned to nonstandard (unconventional) policies, especially via the so-called "Quantitative Easing" (QE). Under this monetary policy setup, the monetary authority puts in place a compression of the term spread - i.e. the difference between long-term and short-term nominal interest rates - via large-scale asset purchases. By doing so, it engineers an expansion of its own balance sheet with the aim of supporting economic activity and promoting a higher inflation rate when the short-term nominal interest rate is no longer available due to the zero bound constraint (Blinder, 2000; Bernanke and Reinhart, 2004).

These unconventional monetary policies have stabilised financial markets and reduced yields on targeted assets (Mallick et al., 2017). But retaining them for too long might also induce excessive risk-taking and negatively impinge on the functioning of financial markets, thus, causing potential disruptions on the central bank's mandate to preserve financial stability.

[1] For a review of the impact of conventional monetary policy actions on real output, inflation and cross-country inflation differentials, and asset prices, see Agnello and Shucknecht (2011), Arestis et al. (2014) and Agnello et al. (2017a).

Against this background, while one would agree that the global financial turmoil of 2008-2009 has led to a dramatic change in how monetary policy is conducted,[2] understanding the central bank's nonstandard reaction function remains an essential and largely unexplored issue. Indeed, despite the increasing number of studies on the transmission of unconventional policies to real economic activity, as well as on their wealth effects (Jawadi et al., 2017), there is still an important gap in the literature concerning the way central banks respond to economic and asset market developments in nonstandard or exceptional times. Therefore, the main goal of the current paper is to fill this gap.

We estimate unconventional monetary reaction functions using U.S. monthly data for the post-Lehman collapse period and focusing on compressions of the term spread. To do so, we start by relying on a linear framework based on the Dynamic Ordinary Least Squares (DOLS) estimator. Then, we account for potential nonlinearity in the nonstandard monetary policy rule and consider other econometric methodologies, namely: (i) a Threshold Autoregressive (TAR) model; (ii) a Markov-Switching Regression (MSR); and (iii) a Time-Varying Probability Markovian Process (TVPMS). These approaches can be useful in terms of capturing major QE policy actions and the asymmetry and regime dependence that they potentially generate in the nonstandard response of the central bank to economic and asset market developments. They are also relevant when these developments are closely tracked by the monetary authority but, rather than directly entering its reaction function, they act as conditioning variables affecting the transition among policy rule regimes.

[2] Additionally, some of the most visible facets of the world economy in the aftermath of the Lehman Brothers' collapse were the detrimental roots on the boom-bust cycle of the housing market cycle (Agnello et al., 2015), the sharp rise in financial stress (Mallick and Sousa, 2013), the strong linkages between monetary and financial stability (Granville and Mallick, 2009; Sousa, 2010; Castro, 2011; Castro and Sousa, 2012; Jawadi et al., 2017), the intensification of the bank-sovereign nexus and its implications for capital markets' exclusion (Agnello et al., 2017b, 2018), the somewhat de-synchronization of the business cycle (Rafiq and Mallick, 2008; Castro, 2010; Mallick and Mohsin, 2010, 2016), the implementation of fiscal consolidation programs (Chortareas, 2013; Agnello et al., 2013; Chortareas and Mavrodimitrakis, 2016; Dufrénot et al., 2017) and the significant rise in national and regional disparities (Agnello et al., 2014, 2016).

Our linear and nonlinear setups show that nonstandard monetary policy actions are largely driven by the dynamics of inflation and the output gap. In particular, the DOLS estimator suggests that an acceleration of large-scale asset purchases by the central bank creates the expectations of further purchases in the future, thereby, pushing inflation upwards and stimulating the recovery of the economy.

Considering the nonlinear econometric frameworks, our TAR model reveals that the response of the term spread to macroeconomic and asset market fluctuations is characterized by the presence of threshold effects. In particular, when the output gap is low, the monetary authority adopts a very accommodative policy vis-à-vis the dynamics of inflation. By contrast, when the output gap is high, the degree of monetary accommodation is significantly tightened.

The results from the MSR model also support the presence of regime-dependence in unconventional monetary policy actions. This mainly accrues to an asymmetric (switching-type of) response of the term spread to the growth rate of central bank reserves. This characterisation of the nonstandard monetary policy reaction function captures the main Federal Open Market Committee (FOMC) actions since the global financial crisis in a particularly good fashion.

Finally, the empirical evidence associated with the estimation of the TVPMS model shows that, despite not being directly included in the reaction function of the central bank - a result that the lack of statistical significance of asset prices confirms across all econometric methodologies employed in this paper -, stock and housing prices are used as conditioning information in the design of nonstandard monetary policy measures.

The rest of the paper is organized as follows. Section 2 presents the related literature. Section 3 discusses the econometric methodologies. Section 4 describes the data and provides the empirical results. Finally, Section 5 concludes.

2. Literature Review

From a theoretical perspective, standard New Keynesian macroeconomic models suggest that the economy would be in a "liquidity trap" under the zero short-term interest rate, in which a monetary expansion provides no further stimulus. Hence, portfolio rebalancing effects would not occur no matter how much money is injected to the economy (Keynes, 1936). Krugman (1998) brings back the issue of the liquidity trap to the case of Japan, assuming perfect substitutability between money and bonds. Liquidity trap is seen as a credibility problem, i.e. the public believes that the monetary expansion will not be sustained unless the central bank can credibly commit to a sufficiently high inflation target program for a sustained period. In the same spirit, Eggertsson and Woodford (2003) and Eggertsson (2006) find that the zero lower bound restricts stabilization outcomes although the effects are more modest than the deflation pessimists presume. The authors prove that the optimal policy for combating the deflationary slump is to manage expectations through signalling effects in which the expected future path of the interest rate and the inflation rate are crucial determinants of aggregate demand.

By contrast, Auerbach and Obstfeld (2005) and Doh (2010) argue that money is an imperfect substitute for a wide range of financial and real assets. Hence, a change in monetary policy induces a portfolio rebalancing effect by affecting nominal demands on various assets and influencing the wealth of economic agents. Additionally, Cúrdia and Woodford (2010) assume the presence of heterogeneity in spending opportunities that are available to different households at any point in time. This financial friction is essential to prevent the private sector from adjusting its asset purchases in response to central bank purchases, hence, equilibrium asset prices would change.

From an empirical point of view, the evidence reaches a wide consensus about the influence of unconventional policy on financial markets (namely, by lowering long-term interest rates and narrowing term spreads) and suggests that the impact of QE has been dominated by a portfolio rebalancing channel. For instance, Bernanke et al. (2004) use event-study methods to examine the market responses to BOJ's announcements and no-arbitrage VAR models to investigate portfolio rebalancing effects. They find no relationship between one-year-ahead expectations and policy statements, but unconventional policy effectively lowers long-term interest rates. Gagnon et al. (2011) employ US monthly data from January 1985 to June 2008, and find a strong and long-lasting negative effect of the Fed's asset purchases on long-term interest rates of a wide range of securities, even those outside the scope of the programs. Using data for the UK, Meier (2009), Joyce et al. (2011) and Joyce and Tong (2012) claim that the effects of lowering risky asset yields mainly emerge via the portfolio rebalancing channel. The effects from the QE announcement are moderate, as the Bank of England's asset purchases appear to have slightly pushed yields downwards during the first four months after the announcements, while overall liquidity has improved.

Despite this, there is no unified view QE's impact on real economic activity. For instance, while several studies find that unconventional monetary operations are considerably effective in boosting aggregate demand and reversing deflation (Chung et al., 2011), others claim that the effect is rather limited or not significant (Keister and McAndrews, 2009). Joyce et al. (2011) and Joyce and Tong (2012) find that the effect of the BOE's purchase program on the wider economy remains uncertain. Chung et al. (2011) take into account the Fed's large-scale asset purchases and show that, by increasing the stock prices and lowering the US dollar exchange rate, the program can stimulate the real economy. For Japan, Schenkelberg and Watzka (2013) use a Sign-Restrictions VAR approach and find that unconventional monetary policy shocks have a significantly positive (albeit temporary) impact on output, but do not affect inflation.[3]

The current paper contributes to the existing literature along three main dimensions. First, we investigate the reaction function of the monetary authority in the context of nonstandard measures. This represents the major novelty of this work, as previous studies have generally focused on a rather different question, i.e. the macroeconomic and the wealth effects of

[3] Micro and macro approaches have tried to address this question, namely: (i) DSGE techniques (Cúrdia and Woodford, 2011; Del Negro et al., 2017); (ii) VARs with time-varying parameters (Baumeister and Benati, 2013); (iii) Markov-Switching VARs (MS-VARs) (Kapetanios et al., 2012); (iv) Factor-Augmented VARs (FAVARs) (Stock and Watson, 2005); and (iv) Markov-Switching Factor-Augmented VARs (MS-FAVARs) (Girardin and Moussa, 2009).

unconventional monetary policy (Jawadi et al., 2017). Second, we use a broad range of econometric techniques to distinguish between linear and nonlinear monetary policy rules adopted in nonstandard times. This allows us to investigate the presence of asymmetry, regime dependence and time-varying transition across different policy regimes. Third, we account for the response of monetary policy to a broad range of indicators. More specifically, we assume that the policy instrument reacts to macroeconomic activity (as proxied by the inflation rate and the output gap), asset prices (i.e. the growth rate of the stock price index and the growth rate of the housing price index) and monetary conditions (as captured by the growth rate of central bank reserves). In this context, our work extends the studies of Agnello et al. (2012) and Castro and Sousa (2012), who estimate conventional policy rules that account for asset price developments.

3. Econometric Methodology

3.1. Linear framework

We start by estimating an unconventional monetary policy rule using the Dynamic Ordinary Least Squares (DOLS) regressor of Stock and Watson (1993), where the term spread (*TS*) is the policy instrument. Thus, we specify the following equation

$$TS_t = c + \beta_{INFL} INFL_t + \beta_{OG} OG_t + \beta_{RG} RG_t + \beta_{SPG} SPG_t + \beta_{HPG} HPG_t + \quad (1)$$

$$+ \sum_{i=-k}^{k} \beta_{INFL,i} \Delta INFL_{t+i} + \sum_{i=-k}^{k} \beta_{OG,i} \Delta OG_{t+i} + \sum_{i=-k}^{k} \beta_{RG,i} \Delta RG_{t+i} + \sum_{i=-k}^{k} \beta_{SPG.i} \Delta SPG_{t+i} + \sum_{i=-k}^{k} \beta_{HPG,i} \Delta HPG_{t+i} + \varepsilon_{\text{t}},$$

where $INFL_t$ is the inflation rate, OG_t is the output gap, RG_t is the growth rate of central bank reserves (*RG*), SPG_t is the growth rate of the stock price index, HPG_t is the growth rate of the housing price index, *Δ* denotes the first difference operator, c is a constant, *k* is the number of leads and lags of the explanatory variables, and ε_{t} is the error term. The parameters, β_{INFL}, β_{OG}, β_{RG}, β_{SPG} and β_{HPG} denote the response of the policy instrument to the inflation rate, the output gap, the growth rate of central bank reserves, the growth rate of the stock price index and the growth rate of the housing price index, respectively.[4]

3.2. Nonlinear frameworks

3.2.1. TAR model

We now extend the analysis to study the response of the term spread to major economic developments through the lens of a nonlinear framework. Specifically, we consider the threshold autoregressive (TAR) model (Tong and Lim, 1980), which is well placed to track potential asymmetry. In this class of models, different regimes are activated when the transition variable exceeds (falls below) a certain threshold. Thus, the monetary policy reaction function is nonlinear over the whole sample period, and linear within any specific regime.

Under the assumption of a two-regime framework, the TAR model for the nonstandard monetary policy rule can be formalised as:

$$\begin{aligned} TS_t &= \alpha'_0 + \alpha'_1 \, INFL_t + \alpha'_2 \, OG_t + \alpha'_3 \, RG_t + \alpha'_4 \, SPG_t + \alpha'_5 \, HPG_t + \varepsilon_{1,t} \quad if \;\; S_t \le c \\ TS_t &= \alpha''_0 + \alpha''_1 \, INFL_t + \alpha''_2 \, OG_t + \alpha''_3 \, RG_t + \alpha''_4 \, SPG_t + \alpha''_5 \, HPG_t + \varepsilon_{2,t} \quad if \;\; S_t > c \end{aligned} \qquad (2)$$

where $\alpha_i', \alpha_i'', \forall_i = 1, ..., 5$ are the estimated parameters in the first and second regimes, respectively, S_t is the threshold variable, the parameter c denotes the value of the threshold, and $\varepsilon_{1,t}$ and $\varepsilon_{2,t}$ are the error terms of the two regimes.

We apply linearity tests to select the transition variable (S_t) and the threshold parameter (c) among all possible candidate variables, and retain the optimal transition variable that strongly rejects linearity. Following Tsay (1989) and Hansen (1996), we start by testing the null hypothesis of linearity against the alternative hypothesis of nonlinearity. This test is related with the

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[4] The inclusion of the sum of leads and lags of the first-differences of the regressors eliminates the effects of regressor's endogeneity on the distribution of the least squares estimator (Stock and Watson, 1993). Despite this, we also employ an IV approach using an IV-2SLS estimator (with normal, robust and HAC standard-errors) and an IV-GMM estimator, where heteroscedasticity and autocorrelation are controlled for using the HAC procedure. The empirical findings do not corroborate the presence of endogeneity. Moreover, they are both quantitatively and qualitatively similar to that based on the DOLS estimator. These results are available from the authors upon request.

Portmanteau test of nonlinearity used by Petruccelli and Davies (1986) and is based on an arranged regression and predictive residuals. Thus, we specify the linear model. Next, we specify arranged autoregressive models and apply a threshold nonlinearity test (CUSUM test) while ordering observations according to the increasing values of the threshold variable. Finally, we run a regression for the lowest k observations of the threshold variable, and another one for the highest k observations. The arranged auto-regressions have the advantage of placing observations into two groups without requiring knowledge of the precise value of the threshold.

As for the TAR model estimation, we apply the sequential conditional least squares (LS) method (Tong and Lim, 1980). This procedure is based on a recursive method for each value of S_t. More specifically, the linearity hypothesis tests the equality between the AR coefficients of the two regimes under consideration. If linearity is rejected, the optimal value of S_t should maximise this statistic, and the value of the threshold (c) is determined graphically, as the graph provides useful information about its location. In particular, when plotting the values of the t-ratio of recursive estimates of the AR model coefficients versus the threshold regime, the optimal threshold value should correspond to the first observed structural break and should belong to the interval [Min S_t, Max S_t].

3.2.2. MSR model

Another alternative approach to test for nonlinearity in nonstandard monetary policy rules is the estimation of a Markov-Switching Regression (MSR). The idea behind this modelling strategy is that many economic series might obey to different regimes associated with events, such as financial crises (Jeanne and Masson, 2000) or abrupt policy changes (Hamilton, 1988). Thus, we assess if the term spread dynamics is regime-dependent, that is, whether it changes across different regimes associated with the growth rate of central bank reserves.[5]

[5] There are, at least, two important conceptual differences between the MSR and the TAR approaches. First, the former incorporates less prior information than the latter. Indeed, while the regime probabilities of a MSR model can be

We consider the following MSR model:

$$TS_t = \Psi L^k Z_{1t} + \Gamma(s_t) L^k Z_{2t} + \varepsilon_t \quad (3)$$

where TS_t is the term spread, Z_t denotes the vector of explanatory variables (including the intercept), Ψ is the vector of non-switching parameters, $\Gamma(s_t)$ represents the vector of parameters that vary across different regimes s_t, with $s_t \in \{1, \dots, m\}$, L^k is the lag operator, and ε_t is the error term with a variance that may also be regime-dependent, i.e. $\varepsilon_t | s_t \sim N(0, \sigma^2(s_t))$.

Let us denote by p_{ij}, the unconditional transition probability that $s_t = i$ given that $s_{t-1} = j$, i.e. $p_{ij} = P\{s_t = i \,| s_{t-1} = j\}$. The MS model assumes that the transition probability matrix, P, is time-invariant and sums up all time-dependence between states, that is, $p_{i1} + p_{i2} + \cdots + p_{im} = 1$. Under these conditions, the model can be estimated using a Maximum-Likelihood Estimator (MLE) and an Expectation-Maximization (EM) algorithm as discussed by Hamilton (1990).

From an empirical point of view, we consider that only the coefficient associated to the growth rate of central bank reserves is regime-switching, while the response of the term spread to all the remaining variables is linear. Therefore, equation (3) can be rewritten as

$$TS_t = \sum_i \psi_{1i} \, \mathrm{INFL}_{t-i} + \sum_i \psi_{2i} \, \mathrm{OG}_{t-i} + \sum_i \psi_{3i} \, \mathrm{SPG}_{t-i} + \sum_i \psi_{4i} \, \mathrm{HPG}_{t-i} + \sum_i \gamma_i(s_t) \, \mathrm{RG}_{t-i} + \varepsilon_t, \quad (4)$$

where s_t is the regime, and *i* denotes the number of lags.

3.2.3. TVPMS model

A basic assumption of the Markov-Switching modelling strategy is that the probabilities governing the transition between states of the world are fixed. However, relaxing this assumption and allowing for time-varying transition probabilities, that is, modelling them as functions of certain

interpreted as a transition function that is directly estimated from the data, the TAR framework requires the selection of the transition variable. Second, the MSR model allows one to infer from the data the timing of significant changes in the dependent variable, whereas the TAR model accounts for the possibility of abrupt changes occurring when the transition variable is below or above a certain threshold.

state variables may be more appropriate, as these variables can be relevant to explain regime switches (Kim et al., 2008).

From a theoretical perspective, Time-Varying Probability Markov-Switching (TVPMS) models are particularly attractive for exploring the linkages between the conduct of monetary policy and asset price dynamics. First, central bank actions can change over the business cycle and asset prices usually move in tandem (Dufrénot and Malik, 2012). Second, the uncertainty about the effectiveness of policy interventions generally accrues to the a stochastic shift in monetary regimes that can be identified as active or passive, and low or high financial stress. Moreover, the nature of monetary adjustments can depend on features, such as adjustment costs, credit and liquidity constraints, informational constraints, leverage effects and market imperfections. Third, the selected state variable explaining the transition from one regime to another often exhibits a strong correlation with the business cycle. Consequently, rather than mapping the evidence of a nonlinear behaviour of monetary policy into regimes that are defined *ex-ante* in accordance with a prior belief - as in the case of a Markov-switching model with *fixed* transition probabilities -, it may be more plausible to use an approach whereby economic agents make a probabilistic inference regarding the future policy rule and the state of the economy. In this context, monetary policy reaction functions associated with smoother (thereby, less frequent) regime-switches are more prone to stabilize the economy and to provide a better understanding of how the central bank responds to asset market developments in nonstandard times.

In this context, we model the unconventional monetary policy rule as

$$TS_t = \rho_0(s) + \rho_1 INFL_t + \rho_2 OG_t + \rho_3(s) RG_t + \sigma_t(s)\vartheta_t, \quad (5)$$

where we assume that the coefficients associated with inflation rate (ρ_1) and the output gap (ρ_2) do not change across regimes (s_t), but the coefficient associated with the growth rate of central bank reserves ($\rho_3(s)$) might be different across regimes.

The term spread can switch between two different states, i.e. $s_t \in \{1,2\}$. The observation of either regime 1 or 2 at time *t* depends on the realization of an unobservable Markov chain, that is, s_t

is conditioned by $s_{t-1}, s_{t-2}, \ldots, s_{t-k}$. At any time $\tau < t$, the regime that will be observed at time t is unknown with certainty. Thus, we introduce a probability P of occurrence of s_t, given the past regimes.

Let us assume that s_t is a first-order Markov-switching process. Then, we define $P\{s_t/s_{t-1}, s_{t-2}, \cdots, s_{t-k}\} = P\{s_t / s_{t-1}\}$. We further assume that the transition from one regime to another depends on a transition variable (z_{t-k}) that is observed at time t-k, so that $P\{s_t / s_{t-1}\} = P\{s_t/s_{t-1}, z_{t-k}\}$. The transition probabilities are defined as

$$\begin{cases} p_{11}(z_{t-k}) = \frac{\exp(a_1+b_1 z_{t-k})}{1+\exp(a_1+b_1 z_{t-k})}, \quad p_{22}(z_{t-k}) = \frac{\exp(a_2+b_2 z_{t-k})}{1+\exp(a_2+b_2 z_{t-k})}, \\ p_{12}(z_{t-k}) = 1 - p_{11}(z_{t-k}), \; p_{21}(z_{t-k}) = 1 - p_2(z_{t-k}), \end{cases} \tag{6}$$

where $p_{ij}(z_{t-k})$ is the probability of moving from regime i to regime j, conditional on the dynamics of the transition variable. The fact that $b_1 > 0$ (< 0) indicates that, on average, a positive change in z_{t-k} decreases (increases) the likelihood of a transition from regime 1 to regime 2. Similarly, when $b_2 > 0$ (< 0), then, on average, a positive change in z_{t-k} increases (decreases) the likelihood of a transition from regime 2 to regime 1. Thus, one advantage of this formalization over the standard Markov-Switching model is that the transition probabilities vary with respect to z_{t-k}.

Though the logistic function is commonly used for the transition probabilities, any function that maps the transition variable into the unit interval is a valid choice for a well-defined log-likelihood function. The selection of the transition variable is done by testing the null hypothesis of a standard MS model against a TVPMS model and, when several variables satisfy the test, the final selection is made by considering the information criteria. Thus, we do not impose that the central bank responds directly to the dynamics of asset prices, i.e. we do not include the growth rate of stock and housing prices in the monetary policy reaction function. Instead, we consider that these variables are part of the transition matrix, that is, they are embedded as conditioning information upon which monetary policy is conducted.

The model is estimated via maximum likelihood (ML). We define $\Omega_t = (\mathbf{X}_t, z_{t-k})$ as the vector of observed independent variables and transition variables up to time *t*, and $\xi_t = (y_t, y_{t-1}, \dots, y_1)$ as the vector of historical values of an endogenous variable. Denoting by θ, the vector of parameters to estimate, the conditional likelihood function of the observed data, ξ_t, is defined as

$$L(\theta) = \prod_{t=1}^{T} f(y_t/\Omega_t, \xi_{t-1}; \theta), \tag{7}$$

where

$$f(y_t/\Omega_t, \xi_{t-1}; \theta) = \sum_i \sum_j f(y_t/s_t = i, s_{t-1} = j, \Omega_t, \xi_{t-1}; \theta) \times \\ \times P(s_t = i, s_{t-1} = j/\Omega_t, \xi_{t-1}; \theta). \tag{8}$$

The weighting probability is computed recursively by applying the Bayes's rule to get:

$$P(s_t = i/s_{t-1} = j, z_t) P(s_{t-1} = j/\Omega_t, \xi_{t-1}; \theta) = P_{ij}(z_t) P(s_{t-1} = j/\Omega_t, \xi_{t-1}; \theta) \tag{9}$$

We also have:

$$P(s_t = i \quad /\Omega_{t+1}, \xi_t; \theta) = P(s_t = i \quad /\Omega_t, \xi_t; \theta) \\ \frac{1}{f(y_t/\Omega_t, \xi_{t-1}; \theta)} \sum_j f(y_t/s_t = i, s_{t-1} = j, \Omega_t, \xi_{t-1}; \theta) \\ \times P(s_t = i, s_{t-1} = j/\Omega_t, \xi_{t-1}; \theta). \tag{10}$$

To complete the recursion defined by the equations (9) and (10), we need the regime-dependent conditional density functions:

$$f(y_t/s_t = 1, s_{t-1} = j, \Omega_t, \xi_{t-1}; \theta) = \frac{\phi\left(\frac{y_t - x_t'\beta_1}{\sigma_1}\right)\Phi(a_j + z_t' b_j)}{\sigma_1 P_{1j}(z_t)}, \tag{11a}$$

$$f(y_t/s_t = 2, s_{t-1} = j, \Omega_t, \xi_{t-1}; \theta) = \frac{\phi\left(\frac{y_t - x_t'\beta_2}{\sigma_2}\right)\Phi(a_j + z_t' b_j)}{\sigma_2 P_{2j}(z_t)}. \tag{11b}$$

The parameters of the TVPMS model are, thus, jointly estimated with ML methods for mixtures of Gaussian distributions. As shown by Kiefer (1978), if the errors are normally distributed, then, the ML estimator yields consistent and asymptotically efficient estimates. Furthermore, the inverse of the matrix of second-order partial derivatives of the likelihood function evaluated at the true parameters is a consistent estimate of the asymptotic variance-covariance matrix of the parameters.

4. Data and Empirical Results

4.1. Data

We collect monthly frequency data for the United States over the period 2008:11-2017:12. Our sample refers to the post-Lehman Brothers' collapse period, which marks the beginning of unconventional monetary policy.

We assume that, in nonstandard times, monetary policy actions - i.e. changes in the central bank's policy instrument - are captured by the dynamics of the term spread, i.e. the difference between the long-term (10-year) government bond yield rate and the short-term (3-month) Treasury Bill rate.

The policy instrument responds to macroeconomic (which are embedded in the inflation rate and the output gap) and asset price developments (i.e. the growth rate of the stock price and the growth rate of the housing price index). The growth rate of central bank reserves, which is computed using data for the reserves of depository institutions and is expressed in natural logs of real terms, is also part of the information set of the central bank.

Both the term spread and the growth rate of central bank reserves come from the Board of Governors of the Federal Reserve System. The inflation rate is computed using data for the Consumer Price Index (CPI) - All Urban Consumers (all items less food and energy, 1982-84=100) from the Bureau of Labor Statistics (BLS). The output gap is computed using data for the total industrial production and capacity utilization index, which is obtained from the Board of Governors of the Federal Reserve System. The industrial production index is transformed into natural log terms and the Hodrick-Prescott filter is applied to generate the output gap in percentage of potential industrial production. The stock price index corresponds to the S&P500 index. The housing price index is based on the median sales price for new houses sold in the United States, which is gathered by the Federal Reserve Bank of St. Louis. Both asset price indices are expressed in natural logs of real terms.

4.2. Linear framework

A summary of the results using the DOLS approach can be found in Table 1. We note that the macroeconomic environment plays an important role in the conduct of unconventional monetary policy. Indeed, both the inflation rate and the output gap enter negatively and significantly in the model. This means that the monetary authority further expands its stance - i.e. it puts in place additional asset purchases that lead to a compression in the term spread - in response to a recovery of the inflation rate or an improvement in real economic activity. In doing so, it aims at guaranteeing that these macroeconomic developments are sustained over time. Stock prices also appear to influence the term spread but the effect is weak, as it is only significant at the 10% level.

Table 1. Unconventional monetary policy rule - DOLS model.

VARIABLES	(1)
Constant	3.9043***
	[25.474]
INFL	-0.9089***
	[-10.516]
OG	-0.1185***
	[-7.592]
RG	0.0358***
	[2.783]
SPG	-0.0323*
	[-1.737]
HPG	0.0044
	[0.160]
Observations	107
R-squared	0.797

Notes: Robust *t*-statistics in brackets. *** p<0.01, ** p<0.05, * p<0.1.

Finally, the growth rate of central bank reserves enters positively and significantly in the policy rule. On the one hand, the amount of aggregate reserves is largely determined by policy actions operating on the asset side of the central bank's balance sheet. On the other hand, the motivation behind reserves accumulation by banks is a function of the impact of changes in the economic environment on these institutions. In this case, precautionary motives might play an important role. As a result, the positive link between the term spread and the growth rate of central bank reserves suggests that an increase in the size of large-scale asset purchases by the monetary authority creates the expectations of further purchases in the future. It is also a signal that the large injection of liquidity by the Fed started to restore the functioning of interbank market and promoted credit expansion, encouraging banks to minimize their holdings of excess reserves.

4.3. Nonlinear frameworks

4.3.1. TAR model

We estimate an AR model of order *p*, recover its estimated residual and consider possible values for S_t. Second, we apply a Multiplier Lagrange linearity test for each value of *d* and compute the *LM* statistics for different values of *c*, i.e. $LM(c)=S(c)'I(c)S(c)$, where $S(c)$ measures the estimated model score under the null hypothesis and $I(c)$ refers to the Fisher matrix of information.

As for the Tsay (1989) test, if linearity is rejected, the optimal value of S_t should minimize the *p*-value of this test. The threshold parameter is then estimated by minimizing the residual variance of estimated TAR models for various possible values of S_t. Finally, we estimate the threshold model using the LS method.

Our empirical findings suggest that the term spread dynamics exhibits nonlinearity and switching regimes (Tables 2-3). The linearity is strongly rejected when the output gap is considered. A two-regime TAR model appears to appropriately fit the data and the transition between regimes occurred in October 2015, that is, amidst the bond market reaction to the unwinding of the unconventional monetary policy put in place by the Fed and the normalisation of its balance sheet (i.e. the so-called 'taper tantrum'). In fact, in December 2015, the Fed increased the Federal Funds Rate for the first time since June 2006.

Table 2. General linearity tests and structural break tests.

Equation	Statistic	Keenan (1985) test (*p*-value)	Bai and Perron test [a]
TS	12.86	0.00	2015:10

Notes: [a] Break date.

Table 3. Specific threshold tests.

Equation	S_t	Tsay (1989) test [a]	Hansen (1996) test [b]	Tsay (1989) test [a]	Threshold date [c]	Model
TS	*OG*	0.10	0.01	0.44	2015:10	TAR(2)

Note: [a] Bootstrap *p*-value. [b] *p*-value of Fisher statistics for the Tsay tests. s_t refers to the optimal transition variable. The number in parentheses (2) indicates the number of regimes for each model. [c] Threshold date denotes the date associated with the transition from one regime to another.

Next, we estimate a two-regime TAR model and report its main results in Table 4. Our results point to some interesting observations. In the regime 1 - i.e., when the output gap is low -, the Fed strongly responds to the dynamics of inflation. In particular, an increase in the inflation rate is accompanied by a large compression of the term spread.

Table 4. Unconventional monetary policy rule - TAR model.

	Regime 1 ($OG < 0.3021$)
Constant	5.3695***
	[14.4493]
INFL	-1.5873***
	[-8.6572]
OG	-0.0514**
	[-2.0222]
RG	0.0113***
	[2.5374]
SPG	0.0224*
	[1.6731]
HPG	0.0007
	[0.0525]
	Regime 2 ($OG \geq 0.3021$)
Constant	3.5250***
	[18.0985]
INFL	-0.7754***
	[-7.3497]
OG	0.1424**
	[2.1029]
RG	0.0362***
	[2.9522]
SPG	-0.0310***
	[-2.5868]
HPG	0.0021
	[0.2372]
Adj. R-squared	0.6877
Log Likelihood	-31.9143
Durbin-Watson Statistic	0.8716
Threshold variable	*OG*
Threshold value	$C = 0.3021$

Notes: Robust *t*-statistics in brackets. *** p<0.01, ** p<0.05, * p<0.1.

In regime 2, which corresponds to the case of a high output gap, the term spread also falls when inflation rises. However, the scale of central bank's reaction is about half of that in the first regime. Interestingly, the coefficient associated with the output gap is positive, which suggests that the central bank tightens monetary conditions in response to an improvement in real economic activity. By contrast, the monetary authority appears to accommodate the dynamics of stock prices, as an increase in the growth rate of this variable is associated with a compression of the term spread.

Finally, it should be noted that in none of the regimes does the house price growth play a significant role. And the growth rate of central bank reserves exerts a significantly positive impact on the term spread, which is larger in the second regime than in the first regime.

Overall, these results show that the dynamics of the term spread is regime-dependent, as its behaviour responds differently to the various drivers in accordance with the level of the output gap. This is particularly visible in the reaction of the term spread to variation in the inflation rate.

4.3.2. MSR model

In this Section, we present the main findings associated with the estimation of the two-stage Markov-Switching Regression (MSR). Our model embeds a regime-specific mean and the empirical evidence gives support to a common error variance across regimes instead of regime-specific error variances. Since regime transition probabilities are time-invariant, the only probability regressor is the constant.

Table 5 presents the (constant) transition probability matrix. It shows that there is considerable state dependence in the transition probabilities, with a relatively higher probability of remaining in regime 1 (0.9133) than in regime 2 (0.8942).

Table 5. (Constant) Transition probability matrix.

	Regime 1	*Regime 2*
Regime 1	0.9133	0.0867
Regime 2	0.1058	0.8942

Notes: $p_{ij} = P\{s_t = i\,|s_{t-1} = j\}$, where *i*=column, *j*=row.

Table 6 summarises the results of the MSR model estimation. From an empirical point of view, our specification assumes that the term spread (*TS*) responds to the growth rate of central bank reserves (*RG*) in a nonlinear fashion (i.e. the panel of 'switching parameters' in the Table) and linearly vis-à-vis the inflation rate (*INFL*), the output gap (*OG*) and the growth rate of stock prices (*SPG*) and housing prices (*HPG*) (i.e. the panel of 'non-switching parameters' in the Table).

Looking at the estimates of non-switching parameters, we note that the term spread is negatively and significantly associated with the output gap, the inflation rate and the growth rate of stock prices. Thus, the term spread is compressed when these variables increase. Moreover, there is very little evidence supporting the inclusion of asset price growth rates in the monetary policy reaction function. In fact, the stock price growth rate is only significant at the 10% level and the housing price growth rate is not statistically significant.

Table 6. Unconventional monetary policy rule - MSR model.

	Non-switching parameters
INFL	-0.8827***
	[-11.7029]
OG	-0.1210***
	[-9.7782]
SPG	-0.0118*
	[-1.8347]
HPG	0.0029
	[0.4870]
Log(σ)	-1.5421***
	[-20.2236]
	Switching parameters
	Regime 1 (*S=1*)
Constant	4.1879***
	[31.5169]
RG	0.0131***
	[4.0407]
	Regime 2 (*S=2*)
Constant	3.5843***
	[25.5089]
RG	-0.0034
	[-0.6410]
	Transition matrix parameters
p_{11} - *Constant*	2.3551***
	[4.6291]
p_{21} - *Constant*	-2.1347***
	[-4.4542]

Notes: Robust *z*-statistics in brackets. *** p<0.01, ** p<0.05, * p<0.1.

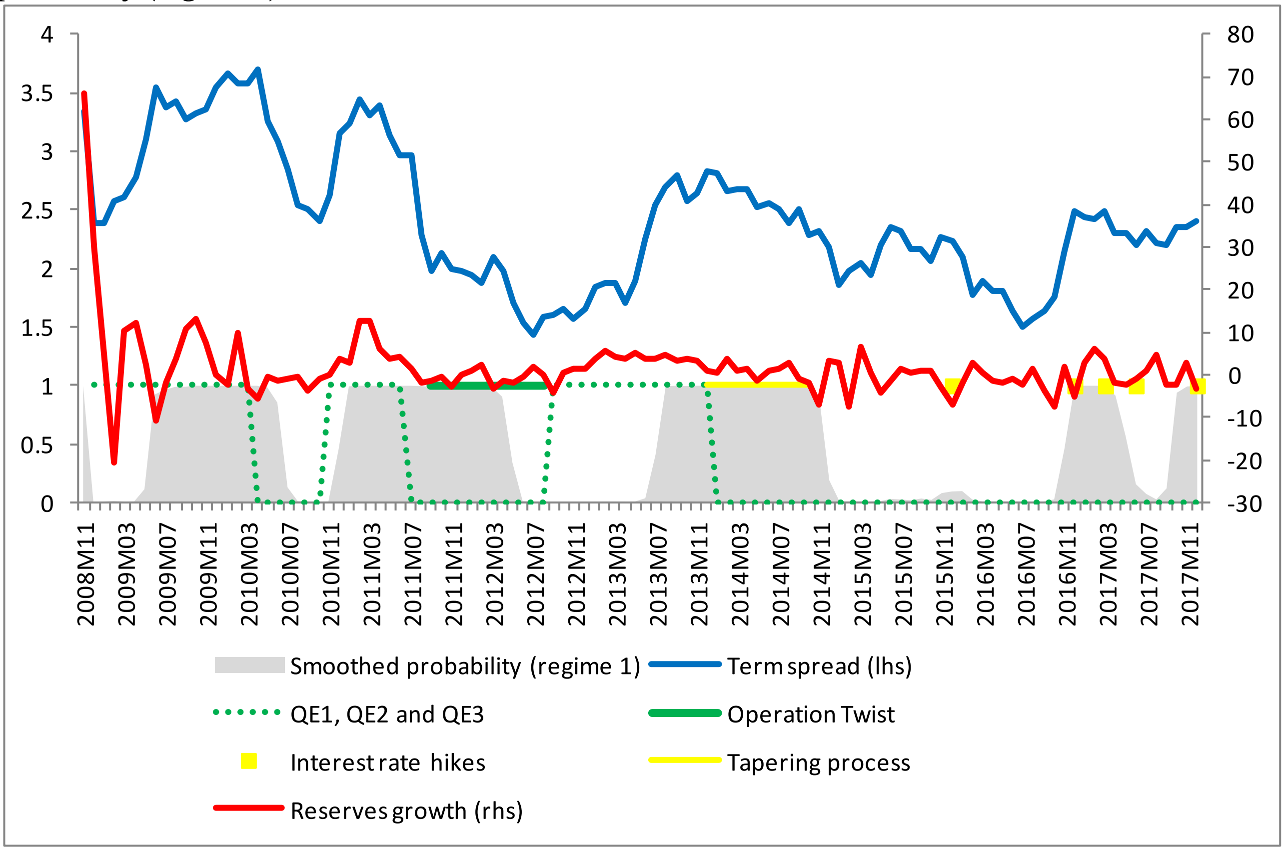
Turning to the estimates of regime-dependent parameters, we find that changes in the supply of banking reserves play a key and asymmetric role in shaping the dynamics of the term spread. More specifically, in regime 1, the growth rate of central bank reserves exerts a positive and significant impact on the term spread. By contrast, in regime 2, the effect is not statistically significant.

The explanation for this asymmetric impact can be drawn from the inspection of Figure 1. It plots the two series of interest (i.e. term spread (red solid line) and the growth rate of central bank reserves (blue solid line)) and the dating of regime 1, which is embedded in its smoothed probability (grey shaded area). It also depicts the timing of Federal Open Market Committee (FOMC) actions, namely, the three quantitative easing programs (i.e. QE1, QE2 and QE3 (green dotted line)), the Operation Twist (green solid line), the tapering process (yellow solid line) and the interest rate hikes since the historical decision taken in December 2015 (yellow square markers).

We remark that the QE1 program ran from December 2008 until March 2010; the QE2 program was launched in November 2010 and concluded in June 2011; and the QE3 program began in September 2012 and ended in December 2013. Between the QE2 and QE3 programs, the Fed launched the Operation Twist, which was initially announced in September 2011 and further extended in June 2012. In December 2013, the FOMC started the tapering process and, in October 2014, the Fed ended its large-scale asset purchase program. Towards the end of 2016 and the beginning of 2017, government bond yields started to rise as a result of the normalisation of the Fed's balance sheet and various interest rate hikes that were put in place.

All in all, with the exception of the first half of the QE3 program, regime 1 captures well the timing of FOMC actions, thus, it can be labelled as the regime of "active" monetary policy. These were associated with reasonably large movements in the term spread and sharp variation in the growth rate of central bank reserves. By contrast, regime 2 tracks periods where the monetary authority adopted a "wait and see" type of strategy. As a result, it can be denoted as the regime of "passive" monetary policy.

Figure 1. Term spread, growth rate of central bank reserves, FOMC actions and smoothed probability (regime 1).



4.3.3. TVPMS model

In the light of the relevance of asset market developments for the conduct of monetary policy, a pertinent issue is the extent to which asset markets are viewed as embedding information that can be useful to assess the nonlinear response of the term spread to the growth rate of central bank reserves. From a modelling perspective, this implies that variables, such as stock and housing price growth rates, are not directly incorporated in the central bank's reaction function. Instead, they are considered as conditioning variables entering the transition probability matrix.

In this context, we adjust the MSR model to account for time-varying transitions across regimes. More specifically, we still assume that the term spread (*TS*) responds to the growth rate of central bank reserves (*RG*) in a nonlinear manner, while the response to the dynamics of inflation (*INFL*) and the output gap (*OG*) is linear. However, we no longer include the growth rate of stock prices (*SPG*) and the growth rate of housing prices (*HPG*) among the set of 'non-switching variables'. Instead, they are used as transition variables in the TVPMS model that we estimate.

Table 7 reports the (time-varying) transition probability matrix. It can be seen that the transition probabilities are significantly lower than those of the MSR model. Despite this, there is a reasonable degree of state dependence, and the probability of remaining in regime 1 (0.5615) is slightly lower the probability of remaining in regime 2 (0.6334).

Table 7. (Time-varying) Transition probability matrix.

	Regime 1	*Regime 2*
Regime 1	0.5615	0.4385
	(0.4029)	(0.4029)
Regime 2	0.3666	0.6334
	(0.4493)	(0.4493)

Notes: $p_{ij} = P\{s_t = i \,|s_{t-1} = j\}$, where *i*=column, *j*=row. Standard deviations in brackets.

The empirical results associated with the estimation of the TVPMS model are summarised in Table 8. All in all, they are both quantitatively and qualitatively similar to those obtained for the MSR model. Thus, in what concerns the non-switching parameters, we find that the term spread is significantly compressed in response to an increase of the output gap or the inflation rate. This implies that the central bank responds to the developments in these variables in an accommodative way.

Regarding the regime-dependent parameters, we replicate the finding of an asymmetric reaction of the term spread to the growth rate of central bank reserves: in regime 1, the growth rate of central bank reserves has a positive and significant effect on the term spread; but, in regime 2, the impact is not statistically significant.

Interestingly, the empirical evidence also suggests that the central bank uses the dynamics of the asset markets as conditioning information for the design of nonstandard monetary policy actions. In fact, we find that, in regime 1, an increase in the growth rate of stock and housing prices contributes, albeit weakly, to the adoption of unconventional monetary policies that are restrictive in nature, i.e. that lead to a rise in the term spread. In contrast, in regime 2, asset price growth does not convey significant conditioning information.

Table 8. Unconventional monetary policy rules - TVPMS model.

	Non-switching parameters
INFL	-0.9767***
	[-10.7838]
OG	-0.1081***
	[-6.6692]
Log(σ)	-1.1120***
	[-13.7389]
	Switching parameters
	Regime 1 (*S=1*)
Constant	4.2544***
	[25.0635]
RG	0.0150***
	[2.9788]
	Regime 2 (*S=2*)
Constant	3.9019***
	[24.1866]
RG	0.0011
	[0.1435]
	Transition matrix parameters
p_{11} - *SPG*	0.7116*
	[1.6389]
p_{11} - *HPG*	0.7920*
	[1.7254]
p_{21} - *SPG*	-2.8819
	[-1.5572]
p_{21} - *HPG*	-1.0840
	[-1.4484]

Notes: Robust *z*-statistics in brackets. *** p<0.01, ** p<0.05, * p<0.1.

5. Conclusion

This paper estimates unconventional monetary policy rules using monthly data for the United States over the post-Lehman Brothers' collapse period. We rely on both linear and nonlinear econometric frameworks.

The linear model (which is based on a DOLS estimator) shows nonstandard monetary policy actions largely react to developments in the inflation rate and the output gap. Additionally, large-scale asset purchases by the central bank seem to generate expectations of further purchases in the future. Moreover, asset prices do not have a significant impact on unconventional monetary policy measures.

In what concerns the nonlinear frameworks, the empirical evidence based on the TAR model reveals the presence of threshold effects in the unconventional monetary policy reaction function.

Thus, there is a substantial degree of monetary accommodation vis-à-vis inflation when the output gap is low, but such degree is significantly reduced when the output gap is high.

The results associated with the MS regression also corroborate the existence of an asymmetric (switching-type of) response of the term spread to the growth rate of central bank reserves that captures particularly well the main FOMC actions since the global financial crisis.

Finally, the empirical evidence emerging from the estimation of a TVPMS model shows that asset prices are used as conditioning information in the design of nonstandard monetary policy measures. Indeed, they affect the probability of transition across policy regimes.

From a policy perspective, our work highlights that when the central bank cannot rely on standard policy instruments (either because the zero lower bound has been reached or these instruments are no longer effective), it still systematically responds to a panoply of macro-financial developments. More specifically, the term spread reacts to the dynamics of inflation and the output gap as a way of boosting the former and stimulating the latter.

In addition, our results emphasise that, in nonstandard times, the conduct of monetary policy is guided by a close track of fluctuations in the growth rate of central bank reserves, with the monetary authority closely monitoring the dynamics of stock and housing prices to substantiate their changes in policy responses.

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