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U.K. MONETARY POLICY UNDER INFLATION TARGETING

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Abstract

This paper considers a variety of reaction functions in the context of real time data to analyse U.K. monetary policy under inflation targeting adopted in 1992. In order to deal with lack of current and future data in real time, we construct the forecasts of expected variables in the first step and use the constructed data for the estimations of contemporaneous- and forward-looking rules. Moreover, we employ the impulse-indicator saturation method to deal with the issue of outliers and therefore obtain robust estimates of policy parameters. Our results show that the robust characteristics of monetary policy during the inflation targeting regime are forward-looking and raising the interest rate by more than one-to-one to movements in inflation, thereby satisfying the Taylor principle.

JEL Classification : C22, C52, C53, E52, E58
Keywords: Real-time data, Taylor rule, Forecasting, Impulse indicator saturation, Autometrics.

Non-technical summary

This paper aims to investigate the characteristics of U.K. monetary policy under the inflation targeting regime which was adopted in the early 1990s. To do so, we consider a variety of Taylor rules, including backward-, contemporaneous-, and forward-looking models in order to find the one that best describes interest rate movements. Our work contributes to the literature on U.K. monetary policy in two ways. The first contribution is that we take the real-time nature of data into account, as emphasized by Orphanides (2001). In order to estimate the contemporaneous-, and forward-looking monetary policy rules, we follow the two-step strategy introduced by Nikolsko-Rzhevskyy (2011). The first step is to construct the required forecasts. The second step is to use the constructed forecasts to estimate the contemporaneous- and forward-looking monetary policy reaction functions. The two-step approach has a dual appeal: it matches the real-time nature of data, and it bypasses the problem of endogeneity, along with the related problem of identifying instruments to deal with endogeneity. Thus, this approach is an alternative to using ex-post realized data in a framework with instrumental variables.

Regarding the second contribution, we consider carefully the issue of outliers, which could be caused, say, by sporadic deviations of the interest rate from its 'normal' rule, and then conduct policy evaluations based on the estimates that are robust to such a problem. This is done by employing the impulse-indicator saturation (henceforth IIS) approach, which is introduced by Hendry (1999). Specifically, impulse indicators, one for every observation, are embedded into the standard Taylor-rule type model to create a new model that produces robust estimates to outliers (see, Hendry, Santos and Johansen 2008, Johansen and Nielsen 2009). In this framework, the number of variables (N) equals the number of observations (T) plus four (an intercept and coefficients on inflation, output gap, and the lag of interest rate). Because the proposed model involves more variables than observations, it cannot be estimated by standard econometric methods. We instead use Autometrics, which is a method that handles the $N > T$ problem by implementing a mixture of expanding and contracting searches in order to seek the relevant indicators (Doornik 2009).

Our results show that the robust characteristics of U.K. monetary policy under inflation targeting are forward-looking and raising the interest rate by more than one-to-one to movements in inflation. Specifically, the best-fitting rule responds to one-year-ahead inflation forecast and output growth, instead of output gap as often assumed. In addition, the rules that deal with the issue of outliers, compared to standard Taylor rules, better explain interest rate movements.

1 Introduction

Since the early 1990s, the U.K. has experienced low and stable rates of inflation. This price stability has been mainly attributed to improvements in the conduct of monetary policy associated with the adoption of inflation targeting in 1992. Notably, Nelson (2003) estimates U.K. monetary policy reaction functions with ex-post data, and finds that the post-1992 conduct of monetary policy can be characterized by a forward-looking rule with an inflation coefficient above unity. Therefore, when inflation increases, monetary policy raises the real interest rate, leading to a reduction in inflationary pressures. This feature is known as the Taylor principle (Woodford 2001). Meanwhile, the $1972-1976$ period of extremely high inflation is captured by a near-zero response of nominal interest rate to inflation. Also using ex-post data, Cukierman and Muscatelli (2008) and Martin and Milas (2004) affirm the anti-inflationary stance of monetary policy under the inflation targeting regime.

Our study contributes to this literature on U.K. monetary policy in two ways. First, we take the real-time nature of data into account, as emphasized by Orphanides (2001), using the estimation strategy suggested by Nikolsko-Rzhevskyy (2011). This approach is an alternative to using ex-post realized data in a framework with instrumental variables for the estimations of contemporaneous and forward-looking models.[1] Second, we consider carefully the issue of outliers, which could be caused, say, by sporadic deviations of the interest rate from its 'normal' rule, and then conduct policy evaluations based on the estimates that are robust to such a problem. Our results show that the robust characteristics of U.K. monetary policy under inflation targeting are forward-looking and raising the interest rate by more than one-to-one to movements in inflation. Specifically, the

[1] Orphanides (2001) and Orphanides and van Norden (2002) show that the estimate of U.S. output gap with real-time data differs from that estimated by ex-post revised data. The same conclusion is obtained for the U.K. by Garratt, Lee, Mise and Shields (2009). In addition, Orphanides (2001) argues that using ex-post revised data might misrepresent the description of past policy and conceals the behaviour proposed by the information available to central bankers in real time.

best-fitting rule responds to one-year-ahead inflation forecast and output growth, instead of output gap as often assumed. In addition, the rules that deal with the issue of outliers, compared to standard Taylor rules, better explain interest rate movements.

On the rationale of the real-time nature of data, we consider a variety of Taylor rules, including backward-, contemporaneous-, and forward-looking models in order to find the one that best describes interest rate movements. While estimating the backward-looking model is straightforward, complications related to a lack of contemporaneous- and forward-looking data arise in the estimation of the other two types of models. For the estimation of U.S. monetary policy rules, Orphanides (2002) uses the Greenbook forecasts, which are prepared by the Federal Reserve Board staff for the Federal Open Market Committee before every regularly scheduled meeting. For the U.K. economy, we note that since 1993 the Bank of England (henceforth BoE) has produced quarterly forecasts of inflation. Unlike the Greenbook forecasts, the BoE forecasts "represent the MPC's best collective judgment about the most likely paths for inflation and output, and the uncertainties surrounding those central projections" (*Inflation Report*, August-2006, p.1). Britton, Fisher and Whitley (1998, p.31) also note that "the final forecast, published in the Report, includes adjustment in response to the advent of market-related data in the period up to the relevant monthly MPC meeting, and reflects any change in interest rates made by the Committee in that meeting."[2] In the context of forecasting performance, there is evidence that judgments help to improve forecasts, particularly in the case of BoE's inflation forecasts, as shown in Groen, Kapetanios and Price (2009). However, those forecasts are likely the 'expected effect' of policy, not the 'cause' of changes. Therefore, they might not be appropriate to incorporate into the interest rate policy reaction function in the first place.[3]

[2]Since 1997, the Bank has also published inflation forecasts conditioned on the market path. However, the series are not consistent: they are RPI (excluding mortgage interest payments) inflation forecasts for the pre-2004Q1 period and CPI inflation forecasts after that. It is also not clear how the judgments of the MPC affect these forecasts.

[3]When using BoE forecasts for the period 1992Q4-2007Q4, we find the inflation coefficients are wrongly

To deal with this data-related issue, we follow the two-step strategy introduced by Nikolsko-Rzhevskyy (2011). The first step is to construct the required forecasts. The second step is to use the constructed forecasts to estimate the contemporaneous- and forward-looking monetary policy reaction functions. The two-step approach has a dual appeal: it matches the real-time nature of data, and it bypasses the problem of endogeneity, along with the related problem of identifying instruments to deal with endogeneity.[4]

In a standard Taylor rule, the interest rate is characterized by a linear function of a constant term, the deviation of inflation from its target and the deviation of output from the potential level. Policy makers, however, may desire to deviate from such a rule at some points in time, say, to moderate the economy under unfavourable global conditions or to respond to some other variables besides inflation and the output gap, such as exchange rates, credit growth, or asset prices.[5] These deviations can be considered as outliers from the 'normal' policy rule. To obtain reliable estimates of coefficients of interest, such as the response of interest rate to inflation, we need to take the issue of outliers into consideration when evaluating the historical conduct of monetary policy. One proposal is to add dummies over the periods of deviations; however, this approach requires prior knowledge concerning the timing of deviations, which are too diversified in the real world to identify properly. Another proposal is to incorporate other variables in addition to inflation and the output gap into the reaction function. However, unless policy makers take those variables as their policy's objectives, it is unwise to expand the framework to include all of them because the inclusion could misrepresent the estimates of interest. In addition, it is difficult to identify what 'other' variables are.

signed or positively small and statistically insignificant.

[4] Using real-time output in the estimation of U.K. monetary policy has been considered in a few studies such as Kharel, Martin and Milas (2010), Mihailov (2006), and Lee, Olekalns and Shields (2013). However, these papers use ex-post realized data for the estimation of forward-looking rules and deal with endogeneity by using instrumental variables.

[5] For example, Kharel et al. (2010) investigate the response of monetary policy to exchange rate fluctuations, and Chadha, Sarno and Valente (2004) consider monetary policy reactions to asset prices and exchange rates.

In order to deal with the above-mentioned issue, we employ the impulse-indicator saturation (henceforth IIS) approach, which is introduced by Hendry (1999). Specifically, impulse indicators, one for every observation, are embedded into the standard Taylor-rule type model to create a new model that produces robust estimates to outliers (see, Hendry et al. 2008, Johansen and Nielsen 2009). In this framework, the number of variables (N) equals the number of observations (T) plus four (an intercept and coefficients on inflation, output gap, and the lag of interest rate). Because the proposed model involves more variables than observations, it cannot be estimated by standard econometric methods. We instead use Autometrics, which is a method that handles the $N > T$ problem by implementing a mixture of expanding and contracting searches in order to seek the relevant indicators (Doornik 2009). The method is analogous to using dummies, without requiring advance knowledge about break points.

The remaining study is structured as follows. The next section provides an overview of Taylor-rule based model specifications. Section 3 outlines the methodology used to estimate the model and describes inflation forecasts and real activity measures. Section 4 presents the results and provides some possible explanations for the stability of inflation observed under the inflation targeting regime. The last section concludes.

2 Taylor Rule Specifications

The Taylor (1993) interest rate rule has the following simple formula

$$r_t = R^* + \pi^* + \phi_\pi(\pi_t - \pi^*) + \phi_x x_t, \tag{1}$$

in which the interest rate r_t responds to the deviation of inflation rate π_t from its target π^* and the output gap x_t, and R^* is the equilibrium level of the real interest rate. According to Taylor (1993), this rule specified with $R^* = 2$, $\pi^* = 2$, $\phi_\pi = 0.5$, and $\phi_x = 0.5$ closely approximates the movements of federal fund rates during the 1984-1992 period.

The original Taylor rule, however, does not take into account the forward-looking behaviour which is a prominent feature in policy-making at major central banks around the world.[6] This forward-looking dimension can be seen most clearly among inflation-targeting countries, an example of which is the United Kingdom. In these countries, the forecasts of inflation are a key factor in the policy decision-making process. In addition, on a theoretical ground, the forward-looking rule is shown to have a close (approximate or exact) form with the optimal rule for a central bank that has a quadratic loss function in deviations of inflation and output from their respective targets, given a generic macroeconomic model with nominal price inertia (e.g. Clarida, Galí and Gertler 1999). Moreover, it ignores the policy maker's tendency to smooth changes in interest rates. Such policy rate persistence may be endogenous to the bank, i.e. reflecting partial adjustment and monetary policy inertia, or exogenous due to the slow cyclical fluctuations in the key macroeconomic driving variables of monetary policy (Rudebusch 2001). Clarida, Galí and Gertler (2000) therefore modify (1) to capture the forward-looking behaviour and the gradual adjustment of the interest rate:

$$r_t = \rho r_{t-1} + c + \phi_\pi E_t \pi_{t-1+h} + \phi_x E_t x_{t-1+q} + \varepsilon_t, \tag{2}$$

in which the interest rate responds to the expected changes of inflation and output gap at the $t-1+h$ and $t-1+q$ period by ϕ_π and ϕ_x, respectively; ρ is the smoothing parameter; and ε_t is the policy shock which is assumed to have mean zero and variance σ^2. This type of rule reflects the 'leaning against the wind' view in macroeconomic management. Note that the specification in (2) also nests the backward-looking (i.e.,

[6] Orphanides (2003) finds that forward-looking policy rules are more successful than the original backward-looking specification in describing the historical movements of monetary policy. Batini and Haldane (1999) also report that forecast-based rules, compared to backward-looking interest rate rules, can better control both current and future inflation.

$h = 0$) and contemporaneous-looking rules (by setting $h = 1$).

Additionally, to apply the Taylor rule framework as in Taylor (1993) and Clarida et al. (2000), a measure of output gap, which is the difference between actual and potential output, is required. However, the main challenge to its application is the inability to observe potential output directly. Consequently, policy makers need to rely on imperfect measures of potential output, indicating the uncertainty in the estimates of output gap. For instance, the HP filter is notorious for its unusual behaviour of cyclical components near the end of the sample (Baxter and King 1999). According to Orphanides and van Norden (2002), the primary challenge to the estimate of potential output in real time arises from the fact that when data in subsequent quarters become available, hindsight may help to clarify our position in the business cycle. This includes the update/revision of the model in view of the arrival of new data. In addition, output data is often subject to revision. As such, the estimate of output gaps from real-time data may differ from those estimated with revised data. For these reasons, we consider different measures of real activity, as will be discussed below, to control for the uncertainty of the real activity measures. Another advantage of considering different measures is that we can identify the measure that adds the highest value in explaining interest rate dynamics.

The standard Taylor rule is characterized by a linear function of a constant intercept and measures of inflation and output. However, as mentioned above, policy makers may be motivated to respond as well to other (domestic and/or global) variables in addition to output and inflation. Particularly, in the two-step approach proposed by Nikolsko-Rzhevskyy (2011), forecasts are based on past information, i.e. from period $t-1$ (month or quarter) backward; hence, they do not take into account information available to policy makers when making decisions at time t . The additional information might be important enough to prompt the policy maker to take an action that "leans against the wind," thereby deviating from the interest rate suggested by the forecast-based rules. Also, factors affecting supply and demand evolve over time, likely causing movements in the natural real interest rate R^* and rendering changes in the intercept.[7] Thus, obtaining reliable estimates of coefficients of interest, such as the response of interest rate to inflation, demands that these issues be taken into consideration when evaluating past monetary policy.

To deal with this problem, we employ the impulse-indicator saturation (henceforth IIS) approach, which is introduced by Hendry (1999). Specifically, impulse indicators, one for every observation, are embedded into the set of candidate regressors. Therefore, we propose a Taylor rule with IIS by placing impulse indicators into the Clarida et al. (2000)'s monetary rule as follows

$$r_t = \rho r_{t-1} + c + \phi_\pi E_t \pi_{t-1+h} + \phi_x E_t x_{t-1+q} + \sum_{i=1}^{T} \beta_i 1_{i=t} + \varepsilon_t, \tag{3}$$

in which $1_{i=t}$ is the impulse indicator which has the value of 1 for every $i = t$ and 0 elsewhere, other notations are remained as in (2). In this framework, the number of variables (N) equals the number of observations (T) plus four (an intercept and coefficients on inflation, output gap, and the lag of interest rate). As the proposed framework contains more variables than observations, it cannot be estimated by standard econometric methods. We instead use Autometrics, a method proposed by Doornik (2009) to handle the $N > T$ problem by implementing a mixture of expanding and contracting searches in order to retain the relevant indicators. The method is similar to using dummies but does not require advance knowledge about break points. Hendry et al. (2008) and Johansen and Nielsen (2009) derive the asymptotic distributions of the mean and variance of this estimator. In addition, Johansen and Nielsen (2009) analyse the indicator saturation algorithm as a robust estimator and Castle, Doornik and Hendry (2012) provide evidence in favour of the use of Autometrics with IIS in model selection when there are multiple breaks.

[7] See Woodford (2001) for a discussion.

The long-run implied responses of interest rate to inflation and economic activity, $\xi_\pi = \frac{\phi_\pi}{1-\rho}$ and $\xi_x = \frac{\phi_x}{1-\rho}$, are important from the policy-making perspective. To gain the intuition of these parameters, consider the corresponding implied real rate rule of (2) and (3) as follows:

$$R_t^* = R^* + (\xi_\pi - 1)(E_t\pi_{t-1+h} - \pi^*) + \xi_x E_t x_{t-1+q} \tag{4}$$

where $R_t^* = r_t - E_t\pi_{t-1+h}$ is the (ex ante) real rate target. As can be seen in (4), interest rate policy rules with $\xi_\pi > 1$ will tend to be stabilizing, i.e., raise the real interest rate when expected inflation is above its target, while those with $\xi_\pi \leq 1$ are likely to be destabilizing or accommodative of shocks to the economy. This property is also known as the Taylor principle (Woodford 2001).[8]

3 Methods

In this section, we first present the method to select the terminal model from an initial model that has more variables than observations. Second, we describe how we construct the expected values of inflation in order to estimate contemporaneous- and forward-looking Taylor rules. Finally, we discuss the measures of real activity considered in this study. Details of data sources are presented in Appendix A.1.

[8]By estimating (2), Clarida et al. (2000) find that in the pre-Volcker period monetary policy was greatly accommodative, with interest rates rising less than expected inflation, thus violating the Taylor principle; in the Volcker-Greenspan era, however, monetary policy became strongly anti-inflationary with increases in expected inflation associated with larger increases in the policy instrument. For the U.K., Nelson (2003) finds that the 1972-76 period of extremely high inflation was characterized by a near-zero response of nominal interest rates to the inflation rate; meanwhile, the low-inflation period from 1992 on is characterized by a Taylor rule with a response parameter above unity. In addition, Woodford (2003) shows that the Taylor principle (or some close variant forms of it) must be satisfied for the determinacy of most existing macroeconomic models.

3.1 Autometrics: Model Selection with More Variables than Observations

We first explain the Autometrics approach, proposed by Doornik (2009), for model selection in the standard case $N << T$, i.e. the number of variables are smaller than the number of observations. Starting from a general unrestricted model (hereafter GUM), which is the initial model for the reduction procedure and provides sufficient information on the process that is modelled, Autometrics uses a tree path search on the model space (i.e. all possible sets of the variables in the GUM) to detect and eliminate statistically insignificant variables. At any stage, the removal of a variable is only accepted if the new model is a valid reduction of the GUM in the sense that the new model must encompass the GUM at the chosen significance level. A path terminates when it cannot be reduced any further on the selected criteria. More than one terminal model is possible: all are congruent, un-dominated, mutually encompassing representations. If so, the search is terminated by using a tie-breaker, such as the Schwarz Criterion (SC) used as the default, with the Akaike Information Criterion and the Hannan-Quinn criterion as well as the union of the terminal candidate models as an option.

We now discuss the case of model selection with IIS. Recall that impulse saturation includes an indicator for every observation. Due to this inclusion, there are more variables than observations, i.e. $T + 4$ against T. To estimate this model, impulses are entered in large blocks in the first step with two sets of $T/2$ in the simplest case, but perhaps in smaller combinations in practice. We then add half the indicators into the core model (including an intercept and coefficients on inflation, output gap, and the lag of interest rate). The new model has fewer variables than observations, so we select the relevant indicators following the steps described above when $N << T$, record the outcome, then drop that set of impulses and add the other half, conducting the selection again. The next step is to combine the significant impulses and select as usual. By using a relatively tight significance level, retention rates for irrelevant variables are small on average, which helps to avoid the over-fitting problem.

3.2 Inflation Forecasts

Nikolsko-Rzhevskyy (2011) also applies the two-step method to several countries, including the U.K. Specifically, to construct the forecasts for the U.K. Nikolsko-Rzhevskyy (2011) uses the method that produces the best forecasts for the U.S., which is a Phillips-curve based model. Not only is this assumption of the transferability of the U.S. models to the U.K. questionable, the forecasting performance in Nikolsko-Rzhevskyy (2011) based on the Root Mean Square Forecast Error for a long time-span from 1974Q1 to 2001Q4 is also likely misleading. Stock and Watson (1999) consider forecasts computed over two subsamples, 1970-1983 and 1984-1996, and find that the Phillips-curve based forecast model performs better in the former, while the AR model dominates in the latter. Fisher, Liu and Zhou (2002) document that Phillips curve forecasts do relatively poorly in periods of low inflation volatility and after a regime shift in monetary policy. Camba-Mendez and Rodriguez-Palenzuela (2003), Stock and Watson (2008) and Marcellino (2008) also provide considerable evidence to support the univariate model in forecasting inflation at least since the early 1990s. Therefore, if the transferability is guaranteed, as in the spirit of Nikolsko-Rzhevskyy (2011), it appears that a univariate framework better suits forecasting inflation from the early 1990s.

Instead of assuming the transferability from U.S. models to the U.K., we use the model that has been credited as the most competitive forecasting model of U.K. inflation. Kapetanios, Labhard and Price (2008) consider the forecasting performance, over the period of Bank independence, of a suite of statistical forecasting models constructed at the Bank of England, including AR, VAR, Markov-Switching, STAR, Factor model, as well as other time-varying and nonlinear models. They point out that most models fail to outperform the AR, although some models perform well for several horizons. Given the dominance of autoregressive models in forecasting, particularly over the past 20 years, we employ this approach to construct the expected values of inflation in order to estimate contemporaneous- and forward-looking Taylor rules.[9]

It is known that the inflation rate of the reference month is released with a one-month delay. In other words, at time t (month), only the inflation rates of time $t-1$ and earlier are observed. We aim to forecast the inflation at time t (nowcasting) and the next 24 months ($t+24$)- a two-year horizon in line with the horizons of BoE projections, using the dynamic (ex-ante) forecasting method. The general unrestricted model specification at each forecast origin is given by

$$\pi_t = c + \sum_{k=1}^{L} \alpha_k \pi_{t-k} + \sum_{i=1}^{T} \beta_i 1_{i=t} + \varepsilon_t,$$

in which $t = 1, ..., T$; $1_{i=t}$ is the impulse indicator saturation which has the value of 1 for every $i = t$ and 0 elsewhere; $\varepsilon_t = IID\{0, \sigma^2\}$. The number of lags L is of 13 as in Hendry and Hubrich (2011). In the practice of forecasting, forecasters often use dummies to capture local shifts in order to avoid systematic forecast failure (see, Castle, Clements and Hendry 2013, Castle, Fawcett and Hendry 2009). For this reason, we incorporate the impulse indicator saturations and use Autometrics to select the forecasting model from a general unrestricted model (Doornik 2009). As mentioned above, this method is analogous to using dummies, without the requirement of advance knowledge about the timing.

To illustrate the process of constructing the quarterly series of $E_t\pi_{t-1+h}$ for $h = 1$ to $h = 9$, we use as an example the forecasts obtained at the 1992M12 forecast origin. It should be noted that the inflation rate of 1992M10 and 1992M11 are observed at 1992M12.

[9] We show in Appendix A.2 that our forecast series, compared to the Phillips-curve based forecasts , better explain the conduct of U.K. monetary policy.

At that origin, there are 25 forecasts carried out, including the year-on-year inflation of that month, 1992M12, and the next 24 months from 1993M1 to 1994M12. We choose the (nowcasted) forecasted inflation rate of 1992M12 to be the expected contemporaneous inflation rate of 1992Q4, $E_t\pi_t$. Meanwhile, the expected one-quarter-ahead inflation rate, $E_t\pi_{t+1}$, equals the forecasted inflation rate of 1993M3. The expected two-to-eight-quarter-ahead inflation rates are computed in a similar way.

3.3 Real Activity Measures

The real-time dataset for GDP contains seasonally adjusted quarterly data covering the vintages from 1992Q4 to 2012Q1. For each vintage, the starting point is the same at 1955Q1; the ending points differ, however, reflecting the information available at that vintage. For example, the 1992Q4 vintage series includes the data of real GDP from 1955Q1 to 1992Q3, and the 2000Q4 vintage series starts from 1955Q1 but ends in 2000Q3. Note that GDP data is only available with a lag of one quarter.

We consider three different measures of economic activity. First, we follow Orphanides and van Norden (2002) to use GDP growth, so there is no need to calculate the unobserved potential output. The second measure is the quadratic output gap, which is obtained by detrending the log of real GDP with a linear and quadratic trend. This measure of output gap is popular in U.K. monetary policy literature, for instance Clarida, Galí and Gertler (1998), Nelson (2003), Srinivasan, Mahambare and Ramachandran (2006), Adam, Cobham and Girardin (2005) and Lee et al. (2013).[10] The third measure is the popular Hodrick-Prescot filtered output gap.[11]

[10]The log of real GDP is regressed on a constant term, a linear timetrend and a quadratic time trend. We use a rolling window estimation to improve its ability to capture possible changes in the trend.

[11]The output gap series is derived by minimizing the loss function $L = \sum_{t-1}^{T} \hat{y}_t^2 + \lambda \sum_{t=2}^{T-1} [(\tau_{t+1} - \tau_t) - (\tau_t - \tau_{t-1})]$, where $\hat{y}_t = y_t - \tau_t$ and $\lambda = 1600$ for quarterly data. To solve the end-of-sample problem of the HP filter, we extend the data at each vintage based on the output growth forecasted over a one-year horizon using an autoregressive model.

4 Results

4.1 Taylor Rules with IIS

The Taylor rules embedded with IIS are estimated over the sample from 1992Q4 to 2007Q4. As mentioned above, to take into account the uncertainty of real activity's measures, we consider three different measures relating to output, including: output growth, quadratic output gap, and HP filtered output gap. For each measure, we estimate ten different model specifications, including one backward-looking rule ($h = 0$ - corresponding to observed $(t-1|t)$ data), one contemporaneous-looking rule ($h = 1$), and eight forward-looking rules responding to the expected inflation up to eight quarters ahead ($h = 2, ..., 9$).

We start with Taylor rules using output growth whose estimates are presented in Table 1. The results suggest that BoE behaviour is pro-active. Not only are the responses of interest rate to inflation in both backward- and contemporaneous-looking rules not statistically significant at 5 percent, they also have wrong signs, implying a decrease of interest rate given a rise in inflation. On the other hand, the response to inflation in the forward-looking rule is positive and significant. Based on the Schwarz criterion,[12] the forward-looking reaction function appears to explain interest rate movements better than the other two types of policy rule. Such a notion is robust when we use the quadratic output gap as well as the HP filtered gap, therefore confirming our finding. In Table 2, we group the results of the best-fitting models corresponding to their measure of real activity.[13] For the rules with quadratic output gap and output growth, the best-fitting rule responds to the four-quarter-ahead expected inflation; for the case of HP output gap, it is the rule responding to the three-quarter-ahead expected inflation. These results are in line

[12] The Schwarz criterion is normalized by dividing its value by the number of observations.

[13] The results of backward and contemporaneous-looking rules with the quadratic and HP output gap measures are not presented but are available upon request.

Table 1: Output-growth-based Taylor Rule with IIS Estimates: 1992Q4-2007Q4

	Policy Behaviour		
	BL	CL	FL
Smoothing ρ	0.90***	0.86***	0.86***
	[0.03]	[0.03]	[0.02]
Constant c	0.01	0.11	-0.01
	[0.16]	[0.15]	[0.12]
Inflation ϕ_π	-0.07*	-0.01	0.18***
	[0.04]	[0.04]	[0.04]
Real Activity (RA) ϕ_x	0.30***	0.29***	0.12***
	[0.04]	[0.04]	[0.04]
Implied LR-Inflation $\xi_\pi = \frac{\phi_\pi}{1-\rho}$	**-0.65**	**-0.08**	**1.29**
Implied LR-RA $\xi_x = \frac{\phi_x}{1-\rho}$	**2.87**	**1.94**	**0.90**
SC	0.16	0.11	-0.16

Notes: The table presents the estimates of Taylor rules with IIS:

$$r_t = \rho r_{t-1} + c + \phi_\pi E_t \pi_{t-1+h} + \phi_x E_t x_{t-1} + \sum_{i=1}^{T} \beta_i 1_{i=t} + \varepsilon_t,$$

for $t = 1993Q1, ..., 2007Q4$. Standard errors are given in [.]. *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$.SC-Schwarz criterion. Implied long-run coefficients are highlighted in bold type. The columns correspond to different types of behaviour: BL (Backward-looking) - responding to the previous quarter's inflation $h = 0$, CL (Contemporaneous-looking) - responding to the current quarter's inflation $h = 1$, and FL (Forward-looking)- the best-fitting rule among the group of forward-looking reaction functions based on Schwarz criterion, i.e. in this case $h = 5$: the policy rule responds to the expected inflation of 4 quarters ahead.

with Batini and Haldane (1999), who analyse the output-inflation volatility frontier for the U.K. and find that the optimal policy rule responds to the expected inflation of about one year ahead. The authors argue that a rule responding to a distant inflation forecast horizon can worsen policy performance because it does too little to smooth inflationary shocks, while a rule responding to a too-near inflation forecast horizon can be too late to offset effectively any build-up of inflationary pressures.

In terms of the estimated policy parameters, both the responses to output and inflation are reasonable, with positive signs and significant at the 5 percent level, implying increases in the interest rate given positive deviations of inflation and/or output from their targets.

Table 2: Taylor Rule with IIS Estimates: 1992Q4-2007Q4

	Quadratic OG [h=5]	HP filter OG [h=4]	Output Growth [h=5]
Smoothing ρ	0.82***	0.84***	0.86***
	[0.04]	[0.03]	[0.02]
Constant c	0.42*	0.13	-0.01
	[0.22]	[0.16]	[0.12]
Inflation ϕ_π	0.22***	0.25***	0.18***
	[0.04]	[0.03]	[0.04]
Real Activity (RA) ϕ_x	0.04**	0.16**	0.12***
	[0.02]	[0.07]	[0.04]
Implied LR-Inflation $\xi_\pi = \frac{\phi_\pi}{1-\rho}$	**1.24**	**1.62**	**1.29**
Implied LR-RA $\xi_x = \frac{\phi_x}{1-\rho}$	**0.20**	**1.04**	**0.90**
SC	0.04	-0.02	-0.16

Notes: The table presents the estimates of Taylor rules with IIS:

$$r_t = \rho r_{t-1} + c + \phi_\pi E_t \pi_{t-1+h} + \phi_x E_t x_{t-1} + \sum_{i=1}^{T} \beta_i 1_{i=t} + \varepsilon_t,$$

for $t = 1993Q1, ..., 2007Q4$. Standard errors are given in [.]. $^{*}p < 0.1$, $^{**}p < 0.05$, and $^{***}p < 0.01$. *SC*-Schwarz criterion. Implied long-run coefficients are highlighted in bold type.

Most importantly, we find that the implied long-run responses of interest rate to inflation are above one in all these three rules, thereby satisfying the Taylor principle. Although the estimates are not far from the value of 1.5 reported in Taylor (1993) and Nelson (2003), we find some heterogeneities, with a value of 1.6 in the HP-gap-based rule and about 1.3 in the other rules.

The long-run response to output gap in the rule with quadratic gap, $\xi_x = 0.2$, is similar to the one obtained in Clarida et al. (1998), who use the same measure. Meanwhile, the implied long-run response to the HP filtered output gap is 1.04. Kharel et al. (2010) estimate the U.K. Taylor rule for the 1992Q4-2005Q4 sample with both measures of real time output gap and also find that the long-run response to HP output gap is above one, while the response to quadratic gap is far below one. Regarding the rule with output growth, the results imply an increase by 0.9 percent in the interest given a one percent deviation of output growth from its target.

The smoothing parameter is also found statistically significant, around 0.8, thus suggesting a degree of gradualism in the conduct of monetary policy at BoE. Combined with further assumptions, the equilibrium level of the real interest rate R^* can be derived from the estimate of the intercept. For the rules using output gap, the value of intercept c implies a combination of the equilibrium level of the real interest rate R^* and the inflation target π^* given by $c = (1-\rho)(R^* + \pi^* - \phi_\pi \pi^*)$. Meanwhile, in the rule with output growth, the interpretation of c involves not only R^* and π^*, but also the growth target g^*. Under this context, $c = (1-\rho)(R^* + \pi^* - \phi_\pi \pi^* - \phi_x g^*)$. Assume that $\pi^* = 2.5\%$ and $g^* = 1.8\%$ (the average of output growth over the sample), R^* can be obtained. Specifically, we find that R^* varies between 2% and 3%, which appears reasonable for the U.K. economy over the 1992-2007 sample. For a comparison, we calculate the real interest rate as $r_t - E_t \pi_{t+4}$, where $E_t \pi_{t+4}$ is the four-quarter-ahead expected inflation constructed above, and use the HP filter to obtain the natural real interest rate denoted by r_t^N. Then we get an estimate of R^* as the average of r_t^N. For our period, $R^* = 2.8\%$, thus confirming our results.

Does our model with IIS, compared to the standard model, better explain interest rate movements? To answer this question, we first estimate the standard Taylor rules for the 1992Q4-2007Q4 period using three different measures of real activity: output growth, quadratic output gap, and HP filtered gap. For each measure, as in the case with IIS, there are ten different specifications considered, containing one backward-looking rule, one contemporaneous-looking rule, and eight forward-looking rules, which respond to the expected inflation up to eight quarters ahead. Thus, a total of thirty standard monetary policy rules are estimated. For purposes of brevity, we present in Table 3 the best-fitting rule, based on Schwarz criterion, for each measure of economic activity. Specifically, we find that the best-fitting rule is the forward-looking one that responds to the three-quarter-ahead expected inflation regardless of the measures of economic activity. In all cases, the interest rate responses to economic activity and inflation are positive and

Table 3: Standard Taylor Rule Estimates: 1992Q4-2007Q4

	Quadratic OG [h=4]	HP filter OG [h=4]	Output growth [h=4]
Smoothing ρ	0.76***	0.80***	0.85***
	[0.06]	[0.05]	[0.04]
Constant c	0.80**	0.46*	0.05
	[0.33]	[0.25]	[0.22]
Inflation ϕ_π	0.17***	0.19***	0.10*
	[0.05]	[0.05]	[0.06]
Real Activity (RA) ϕ_x	0.06***	0.28***	0.20***
	[0.02]	[0.10]	[0.06]
Implied LR-Inflation $\xi_\pi = \frac{\phi_\pi}{1-\rho}$	**0.72**	**0.97**	**0.64**
Implied LR-RA $\xi_x = \frac{\phi_x}{1-\rho}$	**0.27**	**1.42**	**1.31**

Notes: The table presents the estimates of standard Taylor rules:

$$r_t \quad = \quad \rho r_{t-1} + c + \phi_\pi E_t \pi_{t-1+h} + \phi_x E_t x_{t-1} + \varepsilon_t,$$

for $t = 1993Q1, ..., 2007Q4$. Standard errors are given in [.]. *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$. Implied long-run coefficients are highlighted in bold type.

Table 4: Standard *versus* IIS (1992Q4-2007Q4)

	Quadratic OG	HP filter OG	Output growth
Mis-specification Tests			
Standard Taylor Rule	*No*	*No*	*No*
Taylor Rule with IIS	*Yes*	*Yes*	*Yes*
Schwarz Criterion			
Standard Taylor Rule	0.60	0.60	0.54
Taylor Rule with IIS	0.04	-0.02	-0.16

Notes: Four mis-specification tests considered include: the autocorrelation test is the F-test suggested by Harvey (1990), normality test of Doornik and Hansen (2008), unconditional homoscedasticity test of White (1980) and *ARCH* (Autoregressive conditional heteroscedasticity) test of Engle, Hendry and Trumble (1985). *No*: the corresponding model does not pass at least one of the four mis-specification tests at 5% significance level; *Yes*: the model passes all the mis-specification tests at 5% significance level.

significant. However, none of the implied long-run inflation coefficients ξ_π, including both best-fitting and the remaining rules, is above unity.[14] As such, the Taylor principle is

[14] Also in all other standard Taylor-rule-based models, including backward-,contemporaneous- and other forward-looking ones, the implied long-run inflation coefficients ξ_π are below one.

violated. This result may be surprising given the stability of inflation rates under the inflation-targeting regime. Nevertheless, such a result is not unprecedented in the context of real-time data. For instance, Mihailov (2006) obtains a corresponding value of 0.81 for the $1992Q4 - 1997Q1$ period and 0.5 for the $1997Q2 - 2001Q4$ period. It is also worth noting that Nikolsko-Rzhevskyy (2011) uses the two-step approach to estimate the U.K. Taylor rule over the $1983Q3 - 2007Q1$ period and finds that the response of interest rate to inflation is above unity in the contemporaneous and forward-looking rules.[15] However, when we use the same data set but exclude the sample prior to inflation targeting (i.e. the pre-1992Q4 sample), the implied long-run inflation coefficient falls below one, with the maximum value being 0.8, which is similar to those recorded in Table 3.

Nevertheless, as shown in Table 4, the mis-specification tests for the best-fitting standard rules, including the autocorrelation test, ARCH test, normality test, and White test, reject the validity of the standard Taylor-rule-based models.[16] In contrast, we find that the policy rules with IIS pass all mis-specification tests, indicating that the results of the rules with IIS are more reliable. In addition, Table 4 suggests the rules with IIS fit the data better than the standard ones, thus supporting our approach of embedding IIS into Taylor rules to deal with the issue of outliers and then to obtain robust estimates of policy parameters. Moreover, the one-year-ahead forward-looking and output-growth-based rule embedded with IIS appears, among all considered, to best explain interest rate dynamics.

[15] Nikolsko-Rzhevskyy (2011) considers six different policy horizons: one backward-looking rule, one contemporaneous-looking rule and five forward-looking rules.

[16] Note that the mis-specification tests also reject the validity of all other standard Taylor-rule-based models, including backward-,contemporaneous- and other forward-looking ones. The autocorrelation test is the F-test suggested by Harvey (1990), normality test of Doornik and Hansen (2008), unconditional homoscedasticity test of White (1980) and $ARCH$ (Autoregressive conditional heteroscedasticity) test of Engle et al. (1985).

4.2 Estimation Including the Recent Crisis Period

In the above analysis, we exclude the recent crisis period, the post-2007 sample, in order to highlight the important characteristics of U.K. monetary policy under inflation targeting. During most of 2008 the interest rate fell, quickly reaching the effective zero lower bounds (0.5%) in March 2009 and remaining there. The BoE subsequently launched quantitative easing. Thus, the crisis period emerges as a different regime compared to the pre-crisis sample. This point is illustrated in Figure 1, which plots the actual interest rate and the rate suggested by the best-fitting pre-crisis rule, i.e. the forward-looking rule with output growth, with two-standard-error bars. Since 2008, the interest rate has deviated from the pre-crisis rule. Specifically, the actual rate in 2008 was mainly below the pre-crisis-rule-based suggested rate, which can be explained by the loosening of monetary policy in order to respond to the projected contraction of U.K. and global economic activity associated with credit tightening and increasing uncertainty, thus weakening consumption and investment. The most noticeable period is at 2008Q4, when the gap between the suggested rate and the actual rate was more than 3%. The year 2009 tells the opposite story. While the rates of inflation and output growth declined substantially, the actual rates remained higher than the suggested rates because the zero lower bound prevented further decreases of the policy rate. From 2010 till the end of the sample, the actual rate stayed around 0.5%, but the pre-crisis-rule-based suggested rates increased. A similar pattern of the post-2007 U.S. interest rate is reported in Nikolsko-Rzhevskyy, Papell and Prodan (2014). Briefly, Figure 1 shows that the best-fitting pre-crisis rule is not able to capture the actual rate at 11 points in time, i.e. the actual rate lies out of the error bars. This raises the question if these 11 points can be identified as outliers when estimating the Taylor rule with indicators using both the pre-crisis and crisis sample together. This exercise is a powerful check for the approach used in the paper.

We estimate the forward-looking Taylor rule with IIS using the 1992Q4-2012Q1 sample

Figure 1: Actual and Suggested Rate: 2008-2012 Period

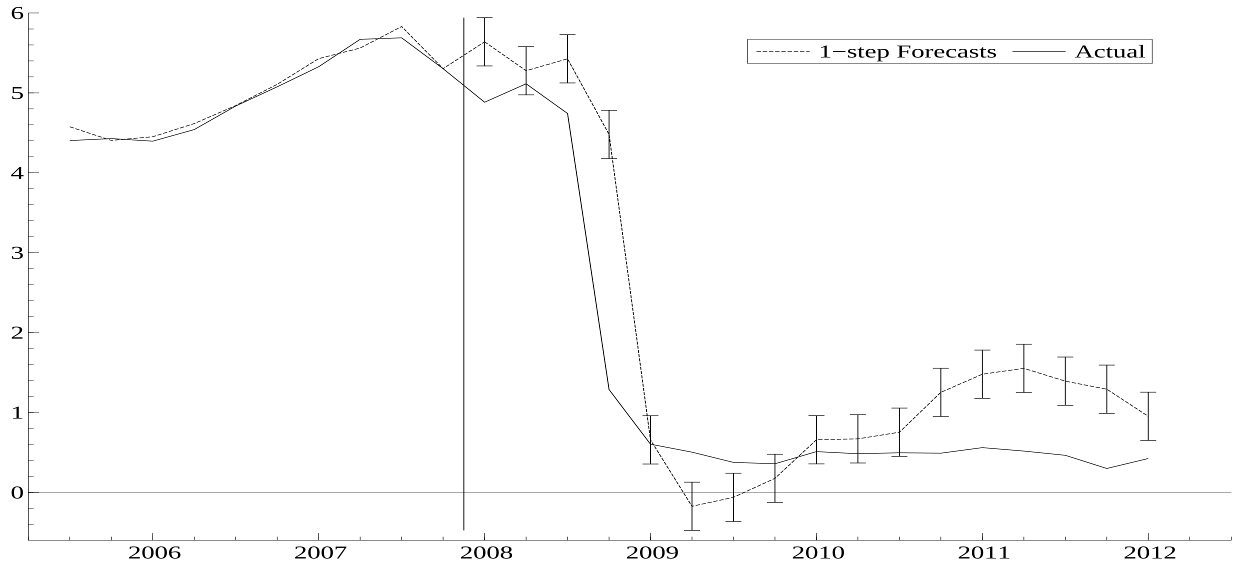

Table 5: Taylor Rule Estimates with IIS for the 1992Q4-2012Q1 Period

	Output growth [h=5]
Smoothing ρ	0.89***
	[0.02]
Constant c	-0.11
	[0.08]
Inflation ϕ_π	0.18***
	[0.02]
Real Activity (RA) ϕ_x	0.11***
	[0.02]
Implied LR-Inflation $\xi_\pi = \frac{\phi_\pi}{1-\rho}$	**1.59**
Implied LR-RA $\xi_x = \frac{\phi_x}{1-\rho}$	**0.95**
Mis-specification tests	Yes

Notes: The table presents the estimates of Taylor rules with IIS for the 1992Q4-2012Q1 Period. Standard errors are given in [.]. *$p < 0.1$, **$p < 0.05$, and ***$p < 0.01$. No: the corresponding model does not pass at least one of the four mis-specification tests at 5% significance level; Yes: the model passes all the mis-specification tests at 5% significance level. Implied long-run coefficients are highlighted in bold type.

and present the results in Table 5. In addition to indicators of the pre-crisis sample, the model successfully identifies as outliers 11 indicators in the crisis. The timings of these

Table 6: Impulse Indicators Associated with the Crisis Period

IIS	**2008Q1**	**2008Q3**	**2008Q4**	**2009Q2**	**2009Q3**	**2010Q4**
Coeff	-0.75	-0.69	-3.2	0.68	0.43	-0.64
IIS (cont)	**2011Q1**	**2011Q2**	**2011Q3**	**2011Q4**	**2012Q1**	
Coeff	-0.82	-0.93	-0.84	-0.91	-0.44	

Notes: The negative sign of coefficient implies that the actual interest rate is smaller than the rate suggested by the rule and vice versa.

11 indicators, which are recorded in Table 6 together with their associated coefficients, are identical to those suggested by Figure 1. The model performs well and passes all mis-specification tests. The success of the model in identifying the crisis-related outliers, then, corroborates our confidence in the method applied and the results obtained. In addition, the responses to economic activity and inflation are similar to those obtained when using only the pre-crisis sample. Specifically, the results confirm that the long-run response to inflation is above unity, thus satisfying the Taylor principle.

4.3 Discussion

Based on these results, the stability of the post-1992 inflation can be explained. First, as discussed in section 2, the magnitude of the long-run inflation parameter γ_π is key to evaluate a central bank's policy rule. If $\gamma_\pi > 1$, when inflation rises, the real interest rate increases, thus slowing the economy and reducing inflationary pressures. Contrariwise, with $\gamma_\pi < 1$, though the central bank raises the nominal rate to respond to an unexpected rise in inflation, it is not increased sufficiently to prevent the real rate from declining; consequently, self-fulfilling bursts of inflation and output may occur. An effective policy rule, then, should have $\gamma_\pi > 1$. Clearly, our results show that this principle is satisfied for U.K. monetary policy under inflation targeting. Second, the finding that forward-looking rules capture interest rate movements better than backward-looking and contemporaneous-looking ones suggests post-1992 monetary policy 'leans against the wind'. This is another important characteristic of an effective monetary policy, as discussed by Taylor and Williams (2011). Third, the smoothing parameter is found to be large and significant, which helps monetary authorities avoid the loss of credibility from sudden large policy reversals (Clarida et al. 1998).

5 Conclusion

The study analysed U.K. monetary policy under inflation targeting based on a real-time Taylor-rule framework. We embedded the IIS into standard rules to produce estimates of interest, such as the response of policy to inflation, which are robust to outliers. A wide range of rules, including backward-, contemporaneous-, and forward-looking policy functions were considered in order to identify which rule best describes the post-1992 conduct of monetary policy. Specifically, to estimate contemporaneous and forward-looking monetary policy reaction functions, we follow the two-step strategy introduced by Nikolsko-Rzhevskyy (2011). We construct the forecasts required in the first step and then use the constructed forecasts for estimation. Our results show that the rules with IIS explain better than standard Taylor rules interest rate movements. In addition, we find that the best-fitting rule responds to one-year-ahead inflation forecast and output growth. Most importantly, the response of interest rate to inflation is larger than one and robust with different measures of real activity. These features of monetary policy can account for the price stability under inflation targeting in the U.K.

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A Appendix

A.1 Data

The estimation is executed by using the following data:

- *Interest rate*: The actual interest rate that is the instrument of the Bank of England has varied three times since 1992, including the *minimum band 1 dealing rate* (August 1981- April 1997), the *repo rate* (May 1997 - July 2006) and the *official bank rate* (since August 2007). Meanwhile, the treasury bill rate has moved very closely with these actual rates over time and is available for the period considered; thus, we follow Nelson (2003) to use the Treasury bill rate as a proxy of the policy rate. The end-of-quarter series is collected from the International Financial Statistics (IFS) for the 1992Q4-2012Q1 period.

- *Real Time Output*: The quarterly real GDP data is obtained from the real-time GDP database of the Office for National Statistics (ONS). It covers the vintages from 1992Q4 to 2012Q1.

- *Inflation rate*: The *inflation rate* is the annual percentage change of the quarterly Retail Price Index (RPI) published by the ONS. We use both quarterly and monthly frequency. The former is used in backward-looking models and covers the period from 1992Q3 to 2011Q4; whereas the latter spans from 1988M1 to 2012M2 and is used to make forecasts of inflation.

A.2 Inflation Forecasts: A Comparison

Nikolsko-Rzhevskyy (2011) constructs inflation forecasts for the U.K. with quarterly data using the model that produced the best forecasts of inflation for the U.S., i.e. the Phillips-curve-based model. We denote this series as $PCBF$. Alternatively, we use an autoregressive model combined with indicator-impulse saturation and utilize monthly data to construct inflation forecasts, denoted as $ARBF$. This section aims to investigate which inflation forecasts better explain interest rate movements. For this purpose, we consider a simple model of interest rate using the first lag of interest rate and inflation forecast as explanatory variables:[17]

$$r_t = (1-\rho)r_{t-1} + c + \phi_\pi E_t \pi_{t-1+h} + \varepsilon_t.$$

The model is estimated for the 1992Q4-2007Q1 period with different forecast horizons $h = 1, 2, ..., 6$, where $h = 1$ corresponds the forecast of the current period (or nowcast) and $h = 6$ the five-quarter ahead forecast which is the maximum forecast horizon of h constructed in Nikolsko-Rzhevskyy (2011). The initial period is at 1992Q4 - the start of the inflation-targeting regime in the U.K., while the last period at 2007Q1 is the last forecasting origin constructed in Nikolsko-Rzhevskyy (2011).

Table 7: Inflation Forecasts: A Comparison

	$h=1$	$h=2$	$h=3$	$h=4$	$h=5$	$h=6$
R^2						
PCBF	0.865	0.865	0.867	0.869	0.872	0.879
ARBF	0.884	0.894	0.898	0.903	0.901	0.901
SEE						
PCBF	0.364	0.364	0.360	0.358	0.353	0.344
ARBF	0.338	0.321	0.315	0.308	0.312	0.311
SC						
PCBF	0.976	0.974	0.955	0.941	0.918	0.860
ARBF	0.825	0.728	0.688	0.639	0.666	0.663

Notes: PCBF - Phillips-curve based forecasts, ARBF- Autoregressive based forecasts.

Table 7 presents the values of R^2, standard errors SEE, and Schwarz Criterion SC corresponding to each forecast series at different horizons. Larger R^2, smaller SEE, and smaller SC suggest better fit to data. It is clear that our inflation forecast series better

[17] Our results remain if we add a measure of real activity.

explain the variation of interest rate in terms of all three criteria.