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ABSTRACT

The Zero Lower Bound, ECB Interest Rate Policy and the Financial Crisis*

This paper estimates a monetary policy reaction function for the ECB over the period 1999-2009. To allow for a potential shift in interest rate setting during the financial crisis, we permit a smooth transition from one set of parameters to another. The estimates show a swift change in the months following the collapse of Lehman brothers. They suggest that the ECB cut rates more aggressively than expected solely on the basis of the worsening of macroeconomic conditions, consistent with the theoretical literature on optimal monetary policy in the vicinity of the zero bound.

JEL Classification: C2 and E52
Keywords: ecb, reaction function, smooth transition and zero lower bound

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1. Introduction

Following the collapse of Lehman Brothers in September 2008, central banks across the world initiated a series of large interest rates cuts. Two related factors may have placed a role in this episode. Most obviously, the sharp falls in headline inflation and economic activity warranted a correspondingly strong policy response to support growth and to ensure that inflation would return to the desired level. Furthermore, and more interestingly, central banks may have perceived a risk that policy rates may eventually reach the zero lower bound (ZLB) and therefore altered their interest rate setting behaviour.[1]

Whether and how monetary policy should change in the run-up to the ZLB has been the subject of intense debate. On the one hand, some have argued that the prospect of reaching the ZLB calls for central banks to "keep their gun powder dry" and be more cautious in cutting rates (Bini Smaghi, 2008). On the other hand, the theoretical literature on optimal monetary policy argues that if the ZLB may bind in the future, then interest rates should be cut faster and more aggressively than suggested by macroeconomic conditions (e.g., Reifschneider and Williams, 2000).

The recent experiences therefore provide an opportunity to gauge whether the predictions of the existing theoretical literature are consistent with observed interest rate setting behaviour in the vicinity of the lower bound. In this paper we seek to perform such an evaluation, focussing on the ECB in the period 1999-2009, that is, before and during the current financial crisis. We follow Mankiw, Miron and Weil

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1 In the theoretical literature, the notion of a "zero lower bound" is interpreted literally. In practice, however, central banks appear to push interest down to a very low but positive level, say 10-30 basis points. It may therefore be more appropriate to refer to a "lower bound."

(1987) and estimate a reaction function using a smooth transition methodology that allows for a gradual shift between a pre-crisis, during with the ZLB was not an issue, and a crisis regime, during which it was. This enables us to estimate whether a shift in reaction function took place, and if so when and how rapidly that occurred.

We begin by modelling the switch as a function of time and find strong evidence for a shift in the autumn of 2008 and that it occurred gradually over a period of several months. Testing against the nested alternatives of a discrete break in October 2008 or no change at all, we find that a smooth transition model, according to which the timing and speed of the shift depends on time, fits the data better. We then extend this analysis and allow the transition between regimes to depend on real GDP growth. This approach provides an economic explanation for the switch and, unlike the case in which it is modelled as a deterministic function of time, allows for the switch to be reversed.

Since the transition between the two regimes must now match the behaviour of economic growth, this model fits the data less well, but the worsening of fit is trivial and the estimated timing and speed of the transition are very similar to those of the first model. The switch is estimated to have occurred when the annual growth rate of real GDP fell to -1.4%, that is, during the autumn of 2008.

In both cases, we find robust evidence that interest rates were cut faster and more aggressively than the pre-crisis reaction function would have predicted, even given the sharp deterioration of macroeconomic fundamentals. The results are thus compatible with the notion that at least some of the 22 members of the ECB's Governing Council grew concerned that the ZLB might be reached in the near future. The rapid interest rate cuts are thus broadly consistent with the theoretical literature on optimal monetary policy near the ZLB.

Many macroeconomic variables, in particular those capturing real economic conditions, have by now recovered to levels similar to those observed before the massive interest rate cuts in the end of 2008, suggesting that the ECB might have returning to setting interest rates in the way captured by the pre-crisis reaction function. The fact that this has not happened should not necessarily be interpreted as evidence against the model since theory suggests an important asymmetry regarding the entry and exit from crisis regime. In particular, while central banks can be expected to cut interest rates rapidly if they become concerned about the ZLB, once the economy starts to recover they may wish to maintain low interest rates for a while in order to prevent long-term interest rates from rising too rapidly. This suggests that the variables that predict a shift in the reaction function into a "crisis mode" may not be useful for predicting a return to the original reaction function. In any case, it is too early to study the return to the pre-crisis regime since the ECB has maintained interest rates at very low level.

The paper contributes to two distinct strands of the literature. First and foremost, we provide an empirical exploration of the main implication of theoretical literature on optimal monetary policy in the vicinity of the zero bound. Secondly, we update the existing empirical literature on ECB interest rate setting behaviour to include an analysis of the crisis period.

The paper is organised as follows. In Section 2, we briefly review the literatures on monetary policy in the presence of the ZLB and the estimation of reaction functions for the ECB. We also provide a short overview of ECB interest rate setting during the crisis. In Section 3 we outline the empirical model, our estimation strategy, explain our choice of data and discuss how we model the structural change in the reaction function. Section 4 presents the results of our estimations. Finally, Section 5 offers some tentative conclusions.

2. Preliminaries

In this section we briefly review the relevant literature on the ZLB, provide a short review of the literature estimation reaction functions for the ECB, and review ECB's interest rate decisions from July 2007 onwards – that is, the month before the financial crisis started with a tightening of liquidity in interbank markets worldwide.

2.1 The ZLB

Central banks are unable to reduce interest rates (much) below zero since agents can avoid negative nominal rates by holding money rather than interest bearing assets.[2] This places a floor on interest rates at or around zero.[3] This issue has been noted as far back as Keynes (1936) and Fischer (1896) and was first emphasised in the modern literature by Summers (1991).[4] While the ZLB was initially seen as of largely academic interest, the decline in inflation across the world in the late 1990s and the accompanying fall in nominal interest rates triggered a renewed interest in its potential relevance for monetary policy. The resulting literature focuses on three questions.

A first question concerns the likelihood that the ZLB would be reached. It is easy to see that the lower the central bank's inflation objective and the lower the neutral real interest rate, defined as the real interest rate that would desirable if inflation was at target and the output gap was zero, the greater the likelihood that a contractionary

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[2] While in theory agents will immediately switch to cash when interest rates turn negative, in practice storage costs mean that interest rates may have to fall somewhat below zero before such a substitution occurs.

[3] For ease of reading, we use the term "zero lower bound" to denote the lower bound throughout this paper, regardless of its exact numerical value.

[4] See Ullersma (2002) for a survey of the literature on the ZLB.

shock would push the policy rate below zero.[5] The resulting literature concluded that an inflation objective of two percent seemed appropriate.[6] Not surprisingly, after the onset of the crisis it has been argued that a somewhat higher inflation target, say four percent, would have been preferable since it would have permitted central banks to cut interest rates by more before reaching the zero lower bound.[7]

The second question concerns what other monetary policy tools can be used to expand aggregate demand if policy rates reach zero. A number of authors have argued that even if short-term interest rates have reached zero, a massive expansion of the monetary base is likely to raise aggregate demand, for instance by increasing the prices of financial assets, in particular on the prices of longer-term bonds.[8] The possibility of depreciating the exchange rate to raise inflation expectations and reduce real interest rates has also received much attention.[9] The importance of non-monetary policies, in particular fiscal policy, has also been noted. But while this literature has generally concluded that monetary and fiscal policy could be used to expand aggregate demand at the ZLB, there is great uncertainty about the effectiveness of these policies. Furthermore, at the time those papers were written, the only recent episode observed instance of a bank facing the ZLB was that of the Bank of Japan, which did not instil confidence in the efficacy of such non-conventional measures.

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5 Viñals (2001) contains an overview discussion of the consequences of the ZLB. See also Gerlach et al. (2009).
6 See Reifschneider and Williams (2000), Viñals (2001), Coenen et al. (2004).
7 See Blanchard et al. (2010) and Williams (2010).
8 See Orphanides and Wieland (2000).
9 See, for instance, Svensson (2001) or Coenen and Wieland (2003, 2004).

In light of this, the third issue addressed is how interest rate policy should be conducted in a situation in which the central bank anticipates that the ZLB might become binding. To clarify the argument, consider the stylised representation in Figure 1. In the absence of a non-negativity constraint on the policy rate, the unconstrained optimal policy rate depends on the state of the macro economy and is denoted by i*. The best the central bank can do is to set the actual interest rate, i, equal to i* at all points in time. The actual interest rate may deviate from the optimal interest rate for three reasons: the central bank misperceives economic conditions; it grows concerned about the ZLB and decides to deviate from i*; or the optimal interest rate turns negative.

To understand the implications of the ZLB, suppose that a severe downturn occurs and that the central bank believes that i* may fall below zero as the economy weakens. Faced with this prospect, there are essentially three strategies it can follow.

The first option is to simply follow their current reaction function until the recommended policy rate reaches zero, and then hold rates at zero for as long i* is negative. This means the existence of the ZLB will not affect monetary policy decisions until the policy rate reaches its floor.

The second option is to set an interest rate below i* once it becomes clear that the ZLB may be reached. In that case interest rate cutting will more aggressive than i* would predict, and follow the dotted line in Figure 1.

This strategy is compatible with the recommendations of the literature on optimal monetary policy with a zero bound. Reifschneider and Williams (2000) develop a model in which monetary policy affects aggregate demand through the long interest rate. If i* falls below zero, the actual policy rate will exceed the optimal rate, implying that long interest rates will be too high. To counteract this effect, they argue that the central bank should set rates below i* prior to the ZLB being reached.

Adam and Billi (2005) reach a similar conclusion based on the expectations channel using a standard forward-looking New Keynesian model. At low interest rates, forward looking agents anticipate the possibility that future shocks might push the interest rate down to the ZLB. As a result, output and inflation are lowered today. To counteract this amplification mechanism, the central bank must therefore cut rates pre-emptively in order to raise expectations of future inflation and output.

Compatible with this analysis, Orphanides and Wieland (2000) find, using dynamic programming techniques, that the policy rate becomes increasingly sensitive to inflation as it falls and the likelihood that the ZLB will be reached rises. In their model, the central bank can use other policy instruments when the ZLB is reached, but not costlessly. Hence in non-deflationary times policymakers are willing to trade off some of their other objectives in order to lower the probability of reaching the ZLB.

Before proceeding and to anticipate some of our empirical results, it is worth noting that the analysis of Reifschneider and Williams (2000) implies that policy makers may respond cut interest rates rapidly when they come to believe that the ZLB may become binding but raise interest rates slowly and with a delay once the economy recovers. Such asymmetric behaviour would imply that the variables that predict a switch to a "crisis regime" predict too early a return to the pre-crisis regime.

A third option is for the central bank to behave more cautiously, cutting interest rates by less than reaction function estimated on pre-crisis data would predict. In that case the interest rate will follow the dashed line in Figure 1. By so doing, the central bank keeps some of its "ammunition" and hence retains the option of interest cuts at a later date. This view is sometimes expressed by policymakers (e.g., Bini Smaghi, 2008). Its proponents argue that aggressive rate cuts may be taken as a sign that the central bank has a more pessimistic view of the economic outlook than market participants and hence induce a worsening of market sentiment. In addition, transmission mechanisms may become much weaker nearer the lower bound, rendering monetary loosening less effective. Finally, keeping rates low for a sustained period of time can fuel future imbalances which are painful to unwind in the tightening phase.

Each of these has a distinct implication for interest rate setting. Under the first strategy, the central bank will set i = i* until the ZLB is reached. Under the second strategy, i will fall below i* as the likelihood that the ZLB will be reached rises and rise only after i* has turned positive. Finally, under the third strategy, i will rise above i* as the likelihood that the ZLB will be reached increases.

This suggests that it is possible to discriminate between these approaches by comparing i and i* as the latter falls towards zero. Of course, doing so is complicated by the fact that we do not observe i* directly. However, we can compute a model-dependent estimate of i* and study how this compares to the observed i as the likelihood that the ZLB will be reached increases. Thus, it is principle possible to explore empirically whether central banks behaved as suggested by the literature on optimal monetary policy at the ZLB.

This approach requires us to develop a model for i. We do so by estimating a reaction function for monetary policy and therefore next review the literature estimating reaction functions for the ECB to help guide the choice of specification of our reaction function.

2.2 Empirical reaction functions for the ECB

The bulk of the existing literature on the interest rate decisions of the ECB estimates reaction functions on a monthly basis, since this corresponds to the frequency with which rates are set. Another reason why monthly data is desirable to quarterly data in this setting is that it allows us to study with greater precision the timing and speed of any shift of the reaction function.

Of course, the frequency chosen has consequences for the data which are used. Whilst inflation is available at a monthly frequency, data for GDP – and therefore estimated output gaps – are only available quarterly. For this reason some studies use data for industrial production, which is available monthly, to capture the state of the business cycle. However, industrial production data are only available with significant lags.[10] Alternatively, one can use subjective measures of real economic conditions which are available on a monthly basis. Gerlach (2007) notes that the latter accords with the ECB's own statements which typically stress the importance of "economic sentiment" or "business confidence" rather than output gaps and goes on to show that Eurostat's Economic Sentiment Index is highly significant in an empirical reaction function for the ECB.

The early literature typically focussed on comparing ECB rate-setting behaviour after EMU with the average behaviour of the national central banks in the run-up to EMU, on estimated single reaction function or the two periods.[11] Several of these papers found that the reaction to inflation was below unity, implying that real interest rates fell in response to rising inflation. Another common finding was that the variables that capture real economic conditions are typically highly statistically significant. As suggested by the analysis in Svensson (1997), there are two possible reasons for this. First, the central bank may be concerned about smoothing the business cycle. Second,

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[10] The data available in the data appendix to the ECB's Monthly Bulletin suggests that the lag is three months.

[11] For space reasons we omit a detailed discussion of this literature (e.g. Gerlach and Schnabel, 2000; Peersman and Smets, 1999; Gerdesmeier and Roffia, 2003). See Gerlach (2007) for an overview.

real economic conditions impact on future inflation through the Phillips curve, implying that even if monetary policy makers were not concerned about output stabilization, they would change interest rates in response to economic activity. Gerlach (2007) argues that measures of the state of the real economy in the euro area are strongly correlated with concerns about inflation expressed in the editorials of the ECB's Monthly Bulletin, which suggests that this is second mechanism is operative.

Several papers have found a role for monetary variables, consistent with the second pillar, in ECB interest rate setting. Carstensen (2003) argues that a monetary overhang – but not money growth – has an important role to play. Gerlach (2007) detects a significant influence of monetary growth. In addition, he finds that the ECB has responded to the rate of depreciation of the nominal effective exchange rate of the euro. Since both money growth and the exchange rate have fluctuated sharply during the crisis, it seems desirable to include them in the model we estimate below.

On the question of whether and how reaction functions estimated for the ECB have changed since the current financial crisis the empirical literature is scarce. To our knowledge the only existing work is Gorter et al. (2009). They compare reaction functions estimated prior to the crisis with those estimated over a full sample and find that adding crisis observations to the sample increases the estimated coefficient on inflation. This suggests that the ECB reacted strongly to the decline in inflation in 2008, as suggested by the analysis in Orphanides and Wieland (2000).

2.3 ECB interest rate decisions, 2007-2009

How did the ECB's interest rate policy evolve during the crisis? The ECB influences interest rates principally by changing its main refinancing rate (commonly known as the "repo rate"), which is shown in Figure 2 together with the overnight rate since

2007. One striking feature of the figure is that the ECB refrained from cutting rates during the episode of severe money market turbulence in the second half of 2007. For the next 12 months rate the repo rate was kept at 4%, on the grounds of a relatively high rate of HICP inflation, as shown in Figure 3 where we have shaded the crisis period. Furthermore, the ECB raised interest rates to 4.25% in July 2008 as oil prices continued to rise, putting upward pressure on HICP inflation.

The ECB began reducing rates only in October 2008 when it took part in a co-ordinated 50 basis point cut by a number of central banks. This cut was explicitly motivated by the ECB in terms of the downside risks to price stability. Subsequent interest rate reductions in late 2008 and early 2009 were also justified by the ECB on the basis of falling inflationary pressures and the apparent fall in survey based measures of economic sentiment.[12] These cuts amounted to a very large relaxation of monetary policy – a cut of 325 basis points – in the space of seven months.

Interestingly, Figure 2 shows that the overnight rate fells much below the repo rate from January 2009 onward. A likely technical reason for this behaviour is that banks took advantage of the ECB's generous provision of term liquidity policy by borrowing more than they needed in order to hedge the risk that tensions in interbank markets would intensify further. In turn, they recycled the funds in the overnight market, depressing the overnight rate. But whatever the reason, the ECB appeared not to be concerned by this additional easing of monetary conditions. In

[12] In the question and answer session on January 15, 2009 President Trichet stated that "[t]his decrease of 50 basis points not only takes into account hard data to date, but also takes into account a continued slowdown of the economy and further alleviation of inflationary expectations.."

what follows we therefore use the overnight rate as the measure of the ECB's monetary policy stance.[13]

Throughout this time the ECB also emphasised that interest rate policy and liquidity operations have different objectives.[14] As before the crisis, interest rate decisions were guided by the inflation outlook. Liquidity operations, by contrast, were influenced by the state of money markets and were devoted to ensuring their smooth functioning. That separation suggests that financial variables should not feature in an empirical specification of the ECB's reaction function, a conclusion that is supported by the fact that interest rates were not cut until October 2008 despite the earlier tensions in the money markets.

In explaining its interest rate decisions, the ECB has consistently emphasised the importance of the medium-term inflation outlook. While this is significantly influenced by the current inflation rate, the ECB has stressed that it takes a "broad-based" approach when considering potential risks to price stability. Such an outlook does not exclude considering the problem of hitting the ZLB as a potential downside threat to price stability, and therefore incorporates the possibility of altering monetary policy to respond to such a threat.

On a number of occasions the issue of the ZLB has been raised in the monthly question and answer sessions during the press conferences that follow the policy

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[13] This interpretation is compatible with the view that also in "ordinary" times the Governing Council conducts monetary policy by setting the repo rate in order to steer the overnight rate to the desired level.

[14] For example, on 11 September 2007, President Trichet told the European Parliament: "I would like to emphasize that our primary mandate calls for our monetary policy stance to deliver price stability in the medium term. Once the level of interest rates is decided we have the responsibility to ensure the smooth functioning of the segment of the money market that we influence. The two responsibilities are clearly separated and should not be mixed."

meetings. On more than one occasion President Trichet has spoken of his desire to avoid a "liquidity trap", but has not elaborated further on how this may affect the ECB's monetary stance, or at what level of rates it sees as a floor.[15] Moreover, the ECB has never explicitly stated that it does not consider the ZLB to be a problem. That said, so far the ECB has refrained from directly discussing the ZLB problem or the appropriate response to it in its official publications.

Individually some members of the ECB's Governing Council have been more forthcoming on how the ZLB should affect monetary strategy although they appear to have reached different conclusions. Bini Smaghi (2008) has spoken of the need to cut cautiously in order to preserve the option of future cuts; whereas Orphanides (2008) has been supportive of a more aggressive response to the economic downturn in the face of the ZLB, consistent with the conclusions in academic research.

Taken together, the evidence on whether and how the ZLB has affected ECB monetary policymaking is unclear. That suggests that empirical analysis might be of help in understanding how the ECB has set interest rates during the current financial crisis and whether the possibility that the desired level of the repo rate might become negative has influenced its policy decisions.

3. The Model

Our empirical approach can be summarised as follows. We begin by estimating a reaction function for the ECB that is allowed to change over the course of the estimation period. This yields two sets of parameters, one for the first period (before

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[15] "…[T]aking into account our own economic and financial environment, we are very keen to avoid ending up in a situation that, for us, would not be appropriate, namely a liquidity trap.", Jean Claude Trichet 15th January 2009.

the crisis) and one for the second period (during the crisis), as well as estimates of the speed and timing of the switch.

To see why this is helpful, note that the ZLB played no role during the pre-crisis period. We can therefore use the estimated parameters from the pre-crisis period to compute an estimate of i* for the full sample. This gives us a sense of what overnight rate would have been if the ECB continued to respond to macroeconomic conditions throughout the sample in the same manner as it did before the crisis erupted. Comparing actual and predicted interest rates then allows us to explore whether the ECB's interest rate setting changed during the crisis when the ZLB was potentially an issue.

3.1 Interest Rate Setting

The starting point for the econometric analysis is a version of the model proposed by Judd and Rudebusch (1998) to study interest rate setting by the Federal Reserve. Let i_t denote the EONIA overnight rate and i_t^T the ECB's "target" for the overnight rate. Let π_t, y_t, μ_t and ε_t denote inflation, real economic activity, money growth and the rate of appreciation of the nominal effective exchange rate.[16] The target level for the interest rate is given by:

$$(1) \qquad i_t^T = \alpha_0 + \alpha_y y_t + \alpha_\pi \pi_t + \alpha_\mu \mu_t + \alpha_\varepsilon \varepsilon_t$$

[16] Note that the inclusion a variable in the ECB reaction function does not necessarily imply it appears in ECB objective function. Svensson (1997) shows that even if the sole objective of policy is to stabilise inflation around a target, the central bank should react to any variable which may have forecasting power for future inflation

where α_0, α_y, α_π and α_μ are expected to be positive and α_ε negative. Next, the overnight rate is allowed to move gradually towards the target:

(2) $$i_t - i_{t-1} = \beta_0\left(i_t^T - i_{t-1}\right) + \beta_1 \Delta i_{t-1} + e_t$$

where e_t is a residual. Using equations (1) and (2) we have that:

(3) $$i_t = \tilde{\alpha}_0 + \tilde{\alpha}_y y_t + \tilde{\alpha}_\pi \pi_t + \tilde{\alpha}_\mu \mu_t + \tilde{\alpha}_\varepsilon \varepsilon_t + \tilde{\alpha}_i i_{t-1} + \beta_1 \Delta i_{t-1} + e_t$$

where $\tilde{\alpha}_j \equiv \alpha_j \beta_0$ and $\tilde{\alpha}_i \equiv (1-\beta_0)$. Before proceeding, we rewrite equation (3) as:

(4) $$i_t = \Theta Z_t + e_t,$$

where Θ is a row vector of parameters and Z_t a column vector containing the regressors.

To proceed, one may think of the fitted value equation (4) as a measure of i*. However, in estimating this equation, one must take into account the fact that the central bank may have deviated from i* during the sample period because it is concerned that the policy rate may reach the ZLB in the future. To avoid that problem, we estimate the reaction function but allow the parameters in Θ to change during the crisis period when concerns about the ZLB may have been relevant.

3.2 Modelling Structural Change

As discussed above, we assume that there are two reaction functions, one in force before, and the other during the financial crisis. During the transition the central bank follows a weighted average of the two with the weights evolving over time in a way we estimate below. Using obvious notation we have that:

(5a) $$i_t = \Theta_I Z_t + e_t \text{ where } e_t \sim N\left(0, \sigma_I^2\right)$$

(5b) $\quad i_t = \Theta_{II} Z_t + e_t$ where $e_t \sim N(0, \sigma_{II}^2)$

Next we turn to the question of how to model any change of the monetary policy reaction function around the time of the onset of the financial crisis. A simple and obvious approach would be to estimate equation (4) with OLS over the full sample and perform Chow tests for a break at plausible dates such as the beginning of the crisis in August 2007 or at the time of the collapse of Lehman Brothers in September 2008. Alternatively, we could use an Andrews test for a break at an unknown date. If we reject the hypothesis of parameter constancy, we can then estimate a reaction function for the two subsamples. One unattractive aspect of the first approach is that the date of switch is imposed by the modeller, rather than being estimated. Moreover, both approaches assume that the break is instantaneous and therefore preclude the possibility that the switch from one regime to another occurred smoothly.

To avoid these shortcomings, we follow Mankiw, Miron and Weil (1987) and use a logistic switching model in which both the timing and the speed of the transition occurred are estimated.[17] Thus, we assume that the full model can be written as:

(6) $\quad i_t = (1 - \omega_t)\Theta_I Z_t + \omega_t \Theta_{II} Z_t + e_t$,

[17] The focus of their study was how the link between short-term and long-term interest rates was affected by the founding of the Federal Reserve in 1914. An alternative approach would be to employ a Markov switching model. Assenmacher-Wesche (2006) estimates monetary policy reaction functions the Federal Reserve, Bank of England and the Bundesbank using Markov switching. However, estimating a such a model requires that one observes switches from regime I to regime II and back again. Given the short sample of our data, it is difficult to believe that there was a switch back to the pre-crisis regime within the span of our dataset.

where the variance of the errors is given by $\sigma^2 = (1-\omega_t)^2 \sigma_I^2 + \omega_t^2 \sigma_{II}^2$, implying that the errors are heteroscedastic. The weights obey the logistic function, L(•):

(7) $$\omega_t = L(\kappa, \lambda, \tau_t) \equiv \frac{\exp(\kappa(\tau_t - \lambda))}{1 + \exp(\kappa(\tau_t - \lambda))}$$

where τ_t denotes a time trend. This choice of transition function warrants several comments.

First, since the time trend is deterministic and increases monotonically, this specification only permits one change between regimes. This seems appropriate in the current sample, in which the ECB arguably remained in the crisis regime at the end of the sample. Second, the parameters λ and κ capture the timing and the speed of the transition respectively. When $\tau_t = \lambda$ the logistic function takes the value of ½, and hence the transition is exactly half completed – we refer to this as the "switching date". The parameter κ captures the duration of the change. As discussed by Mankiw, Miron and Weil (1987), the time between one quarter and three quarters of the adjustment has occurred is given by log(9)/κ. This specification also nests the case of a discrete break: as κ tends to infinity, the speed of adjustment tends also to infinity.

3.3 Data

The review of the literature on estimating reaction functions for the ECB indicated that inflation, money growth, the rate of depreciation of the nominal effective exchange rate and measures of real economic activity are all potential regressors. For inflation, we use the annual percentage change in the Harmonised Index of Consumer Prices (HICP). For money growth, we take the annualised growth rate of M3, and for the nominal exchange rate take the change in the nominal effective exchange rate index over the previous twelve months. The source for all three variables is the ECB's website.

To measure economic activity we use the Purchasing Managers Index (PMI) produced by Markit. Although the empirical literature frequently utilises output gaps in empirical reaction functions, the ECB's monthly bulletin rarely refers to these and instead lays much greater stress on subjective indicators of economic sentiment or confidence.[18] Figure 3 plots the euro area PMI together with real GDP growth over four quarters and shows that the two series are strongly correlated. One important difference, however, is that real GDP growth has recovered much more slowly than the PMI.

While the two series thus contain similar information, using the PMI in reaction functions for the ECB has three important advantages over real GDP growth. First, it is available monthly whereas real GDP data are only available on a quarterly basis. Second, the publication lag is much shorter: while real GDP data is typically available with a lag of several months, the PMI is released in the beginning of each month for the previous month. Third, the PMI is not revised, whilst national accounts are subject to repeated revisions. These reasons suggest that the PMI is likely to be more strongly correlated with the ECB's view of real economic activity than real GDP, and therefore more suitable for inclusion in the reaction function.

For inflation and the M3, each issue of the monthly bulletin reports provisional data for the previous month, and thus the definitive data are only available with a two

[18] See the discussion in Gerlach (2007).

month lag. Data more than two months old are subject to negligible revisions.[19] Exchange rate data are available with a month's lag, and are not subsequently revised. Accordingly, we lag inflation and M3 growth by two months and the PMI and the exchange rate by one month.

4. Estimation

One important feature of the logistic switching model presented above is that the variance of the errors evolves over time in the same way as the parameters. Mankiw, Miron and Weil (1987) propose to estimate the model using maximum likelihood, but in fact use a grid search procedure to determine the parameters in the logistic switching function. Here instead we estimate the full model with maximum likelihood. As starting values, we use the coefficient estimates obtained from estimating the reaction function with OLS.

4.1 Model estimates: Regime switch as a function of time

The model estimates are presented in Table 1. The columns headed "pre-crisis" show the reaction coefficients in the first period, Θ_I. The columns headed "crisis" show the coefficients in the second period, Θ_{II}. Standard errors and p-values are reported under each coefficient.

We began by estimating an unrestricted model which included the lagged interest rate, the lagged change in the interest rate, HICP inflation, the Purchasing Managers

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[19] Coenen et al. (2005) examine in detail the revisions to both inflation and M3 growth data. They find the former has a mean absolute revision (from time t+2 to the final data) of two basis points and the latter has a mean absolute revision of eight basis points.

Index (PMI) for the euro area, M3 growth, and the rate of appreciation of the nominal effective exchange rate of the euro area enter.[20] Since this function is likely to be heavily overfitted, in particular in the crisis period, we do not comment on it in detail. That said, the coefficients are all significant and have the expected signs in the pre-crisis period, except money growth which is insignificant. Overall, the estimates suggest that monetary policy was tightened in response to higher inflation, higher economic activity and a depreciation of the nominal effective exchange rate. The model locates the switch date in October - November 2008, but cannot identify the speed with any precision.[21]

In the second period, only the lagged interest rate is significant, implying that the interest rate follows a first-order autoregressive process. One way to think of this finding is that the ECB has pushed the overnight rate as far down as is easily possible. The interest rate consequently doesn't decline further if economic conditions weakens and is prevented from rising if they strengthen. Thus, the market rate fluctuates over time at a very low level in response to changes in supply and demand conditions in the overnight market.

We then explored suitable restrictions of the model. Based on the p-values reported for second period coefficients in the restricted case, a natural candidate was to drop in the second period all variables bar the constant and the lagged interest rate. This choice was supported by a likelihood ratio test.[22]

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[20] Inflation, money growth and the rate of depreciation are all measured over 12 months.

[21] The switching point is estimated as 225.4 and time trend takes the value 225 in October and 226 in November.

[22] A likelihood ratio test of these restrictions yields a p-value of 0.416, so the restrictions are accepted.

Given the wide standard errors in the unrestricted model, it is possible that quite a range of alternative restrictions could also be accepted. For that reason, we also estimated an alternative model where all coefficients bar that on the lagged interest rate were equal to the first period values (see Appendix, Table A1 for details). However, the value of likelihood function then falls and the posterior odds ratio of such an alternative model is 0.056. That means that given the observed data our specification with the zero reactions in the post-crisis period is around 20 times more likely to be the correct one than where only the lagged interest rate and intercept change across regimes. We interpret this as clear evidence in favour of the former.

Given the debate about the importance of the monetary pillar of ECB's strategy, we also estimated variants of the reaction function which replace inflation with money growth, and which include both inflation and money growth (see appendix for results). These yielded very similar estimates of the coefficients and of the timing and speed of the switch, suggesting that our headline results are robust to the inclusion of money. However, posterior odds ratios suggested using inflation rather than money growth, and hence we omit this variable from our preferred specification.

Our preferred model is presented on the right hand side of Table 1. In the pre-crisis period, the results are as follows. The lagged interest rate is significant and the point estimate suggests quite a high degree of gradualism in rate setting behaviour. The lagged change in the interest rate is also significant, with a negative sign which is consistent with the finding of Gerlach (2007): ceteris paribus, the ECB is less likely to cut (raise) rates if it did so in the previous month. The coefficient on inflation is positive and strongly significant. The PMI also enters with a positive and highly significant coefficient, which is consistent with the findings elsewhere in the literature that the ECB reacts strongly to measures of capacity utilisation as predictors of future inflation. Lastly, there is a significant response to the change in the nominal exchange rate, suggesting the ECB reacts to inflationary pressures generated via the exchange rate channel.

The switching date is estimated to have occurred at a trend value of 225.6, which places the midpoint of the switch around October - November 2008. The speed parameter implies that the going from 5 to 95% on the switching function took around four months, that is, from September 2008 to January 2009. Since the weight attached to the two regimes is a non-linear transformation of κ and λ, it is not easy to see directly how uncertainty about these parameters translates in uncertainty about the weight function.

To assess the degree of confidence we can have in our point estimates of the switching function, we compute a confidence band for ω using simulations. To do so, we take 10,000 draws from the joint distribution of λ and κ and compute the weights implied by each pair. Note that as the model now stands, there is a lack of identification in that $L(\kappa_0;...) \equiv 1 - L(-\kappa_0;...)$ and therefore the two models with $\kappa = \kappa_0$ and $\kappa = -\kappa_0$ will fit the data equally well. Given the starting values we used, we did not experience any problem in the estimation stage. However, in simulating the model we only consider draws for which $\kappa > 0$.

Figure 4 shows the median of the distribution together with a 95% confidence band, for the period August 2007, when the crisis first erupted, to December 2009. The figure indicates that the transition took place in the aftermath of the collapse in Lehman Brothers, that is, more than a year after the turbulence in the interbank market in August 2007 which constituted the first sign of the crisis.

To further explore how plausible our estimates for the smooth transition model are, we also estimated two alternative versions. The first of these is a single regime model (which thus assumes that $\omega_t = 0$), and the second model allows for a discrete break in

October 2008 (so that $\kappa \rightarrow \infty$). In both cases, likelihood ratio tests strongly reject the restrictions implied (see appendix A2 for details). These results imply that there was a structural break and that it was gradual.

The coefficient estimates point to a clear change in the ECB's reaction to economic variables, but they do not tell us directly by how much the interest rate implied by the two reaction functions differs. To better understand the magnitude of the difference in interest rates between regimes, we compute dynamic forecasts from our smooth transition model. In doing so we assume that Regime I remained in force throughout the sample period. We think of these forecasts as an estimate of what interest rates would have been if the ECB had not been concerned by the risk of hitting the ZLB and had simply reacted to the sharp deterioration of economic conditions in the same way as it responded to economic conditions before the crisis. These forecasts are our estimates of i*.

We obtain these forecasts by drawing 10,000 realisations of the estimated parameters using their estimated means and variances, and compute dynamic forecasts of the path of the interest rate.[23, 24] The point forecast is given by the median value for the interest rate, and a 95% confidence interval around this is obtained by dropping the upper and lower 2.5% of the realisations.

In constructing these forecasts, we make two crucial assumptions. First, we assume that the reaction function is correctly specified. Second, we assume that the ECB

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23 To ensure that the non-negativity constraint on interest rates is respected, if the predicted level of the interest is negative, we set it to zero. Repeating the exercise without the non-negativity constraint on forecast errors does not significantly change the results in this, or other dynamic forecasts considered here.

24 Thus, in constructing these forecasts we use the actual value of all the regressors, except past values of the interest rate, for which we use forecasted values.

reacts in a linear fashion to the variables in the reaction function also in cases when they take values that are quite different from those that prevailed in the estimation period. Needless to say, if either of those assumptions are incorrect the actual and the forecasted values for the interest rate can differ.

The forecasts are shown in Figure 5. Two features stand out. First, immediately after the outbreak of tensions in euro area money markets in August 2007, the overnight interest rate was somewhat lower than one would have predicted. This presumably reflects the massive liquidity-enhancing operations undertaken by the ECB. Second, while the interest rate subsequently remained in the forecast interval, it rose towards the top of the interval after the collapse of Lehman Brothers in September 2008.

Third, whilst these estimates of i* imply a considerable relaxation monetary policy in response to the sharp worsening macroeconomic conditions, the predicted fall in interest rates is much more gradual and the (vertical) difference between the forecast and actual interest rate is substantial. For instance, in early 2009 the interest rate predicted under the assumption of no change in regime was roughly 200 basis points above the actual rate. Moreover, for most of the period since the collapse of Lehman brothers, the actual rate lay (well) outside the 95% confidence interval, indicating that the discrepancy between the two is both statistically and economically significant.

Given the difference between our estimate of i* and i, we argue that the ECB's interest rate setting was consistent with the theoretical literature on the ZLB: rates have been cut more aggressively when the possibility of the ZLB looms into view. By the same token, these results seem incompatible with the hypothesis that the ECB exhibited greater caution in rate cutting in order to "keep its gun powder dry."

Overall, our estimates of the timing of the shift accord well with real-time perceptions of the fall-out from the crisis. During the first year of the crisis, i.e. from August 2007 to August 2008, many commentators argued that the ramifications of the crisis for the real economy would be relatively small. In this period therefore, one would not expect to see ZLB considerations play a significant role and hence would expect no departure from the regular reaction function. Following the collapse of Lehman Brothers, however, there was a steady deterioration in the outlook over the autumn in 2008 and into early 2009. This led to increased attention to the problem of the ZLB binding in the future, and hence to a change of the monetary policy reaction function.

4.2 Model estimates: Regime switch as a function of real GDP growth

So far we have assumed that the weights attached to the reaction functions in the pre-crisis and the crisis periods evolve as a function of time. While our estimates indicate when and how fast the change occurred, they provide no explanation for why the change occurred. As noted earlier, it appears eminently plausible that the shift in the reaction function was triggered by the sharp weakening of the real economy following the collapse of Lehman Brothers in September 2008. Therefore, we now refine the model by making the switch a function of economic activity rather than time.[25]

One candidate measure of economic activity is the PMI but, as already discussed, it recovered very rapidly after the crisis while the ECB maintained interest rates at a low level. Below we instead use GDP growth over twelve months as proxy for whatever considerations may have led the ECB to worry about the risk that the ZLB

[25] We also estimated a version of the model in which the regime in force dependent on the lagged level of the interest rate, but did obtain any useful estimates.

would be reached.[26] Denoting real GDP growth with y_t, our weighting function becomes:

$$(8) \qquad \omega_t = L(\mu, \gamma, y_t) \equiv \frac{\exp(\mu(y_t - \gamma))}{1 + \exp(\mu(y_t - \gamma))}$$

where γ denotes the switching level of GDP growth.

The resulting estimates are shown in Table 2. We began with an unrestricted model. As before, this is likely to be heavily overfitted, so we do not comment in detail on the results. For the pre-crisis period, the reaction coefficients are very similar to those presented in the models in Table 1. Moreover, the post-crisis reaction to all variables (bar the lagged interest rate), is highly insignificant. That again argues in favour of a similar restricted form to that presented in Table 1.

The restriction that the second period reaction to all variables bar the lagged interest is zero is comfortably accepted.[27] Therefore we once again model interest rate setting in the second period as a function of a constant and the lagged rate. The switching point is estimated to have been located at an annual growth rate of real GDP of -1.4%.

The implied dynamics of the switch are best seen by graphing the implied transition function over time, along with a confidence band which we compute in the same way as earlier. As Figure 6 shows, the timing and speed of the switch look similar to those estimated when the switch is a function of time, but are naturally somewhat

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[26] Of course, real GDP is not available on a monthly basis so we interpolated the quarterly data. In future work we will consider observed monthly time series that can account for the shift in the reaction function.

[27] A likelihood ratio test of these restrictions yields a p-value of 0.967, so the restrictions are accepted.

less precise since the shift must now match the behaviour of real GDP growth. Importantly, the estimates suggest a rapid, though not instantaneous, shift in the autumn of 2008.

Dynamic forecasts of the interest rate assuming no shift in the reaction function are provided in Figure 7. These estimates of i* are very similar to those reported in Figures 5. Thus, the ECB cut rates faster than one would have expected if there had been no change in its interest rate setting behaviour. The ZLB thus appears to have mattered.

5. Concluding Remarks

In this paper we have studied the ECB's interest rate setting behaviour during the financial turmoil of 2007-2009. We draw several conclusions.

First, the interest rate setting behaviour of the ECB appeared to shift after the collapse of Lehman in September 2008. The shift can be tied to the rapid fall in real GDP growth in that period.

Second, in the pre-crisis regime, the ECB tightened monetary policy in response to stronger economic conditions, higher inflation and a depreciation of the effective exchange rate. In the crisis regime, the ECB pushed the overnight rate down to a low level of about 30 basis points. The month-to-month fluctuations of the interest rate appear uncorrelated with the variables of importance in the pre-crisis regime, consistent with the view that the ECB had pushed the rate down as far as possible and resisted any market-induced tightening of monetary conditions.

Third, while the rapid worsening of economic conditions in the fall of 2008 suggests a series of quick cuts in interest rates, the ECB in fact cut interest rates even more rapidly. Thus, it appears that i was cut below i*.

This finding is compatible with the theoretical literature on optimal monetary policy in the presence of the ZLB, which suggests that the central bank should cut more aggressively than its regular reaction function would suggest if it can foresee the ZLB binding in the future. Equally, they clearly reject the hypothesis that rate cutting has been more cautious in the vicinity of the zero bound.

But while encouraging, the results are also compatible with other interpretations. In particular, Orphanides (2010) argues, but provides no estimates, that the ECB's interest rate setting during the crisis is compatible with a stable reaction function in which forecasts of economic growth and inflation enter. Under that interpretation, the shift in the ECB's reaction function that we identify above may instead be evidence of a shift in the relationship between current economic conditions and near-term forecasts of inflation and output.

Another possibility is that the true reaction function in non-linear and entails "recession aversion" in the sense of Gerlach (2003) and Gerlach and Cukierman (2003). This hypothesis holds that central banks are more concerned – for reasons unrelated to the zero lower bound – by economic activity being below than above the objective. Thus, as economic activity slowed, the ECB started to cut interest rates increasingly aggressively to support growth.

It is also possible that the estimated shift of our reaction function captures important variables that we have omitted from the analysis, such as measures of the state of the banking system. Overall, more work is needed before we can conclude that the ZLB played an important role in the ECB's interest rate setting during the crisis.

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Tables and Figures

Figure 1: Alternative rate setting strategies

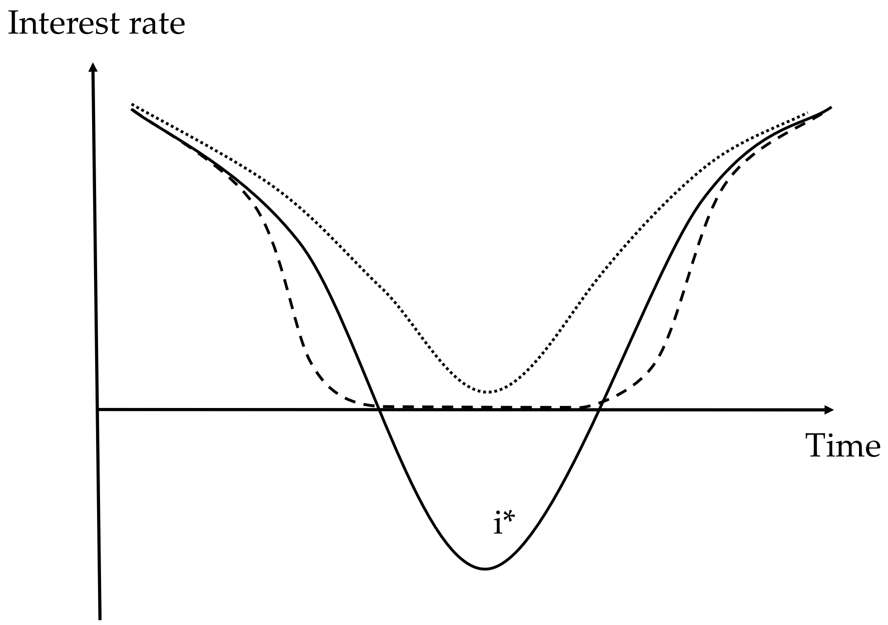

Figure 2: Repo Rate 2007-2009

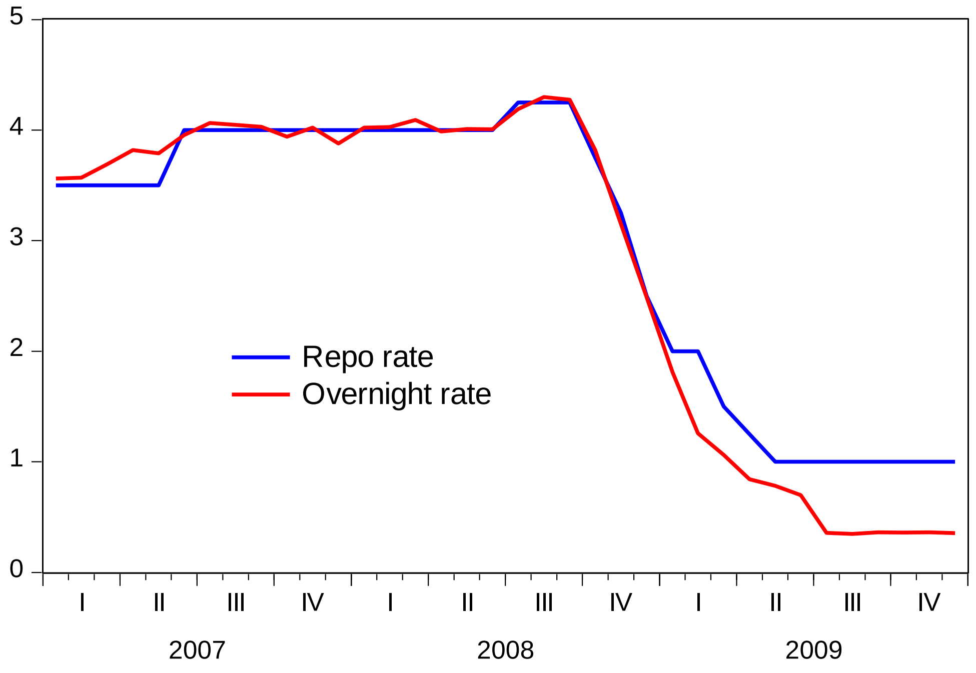

Figure 3: PMI and Real GDP Growth

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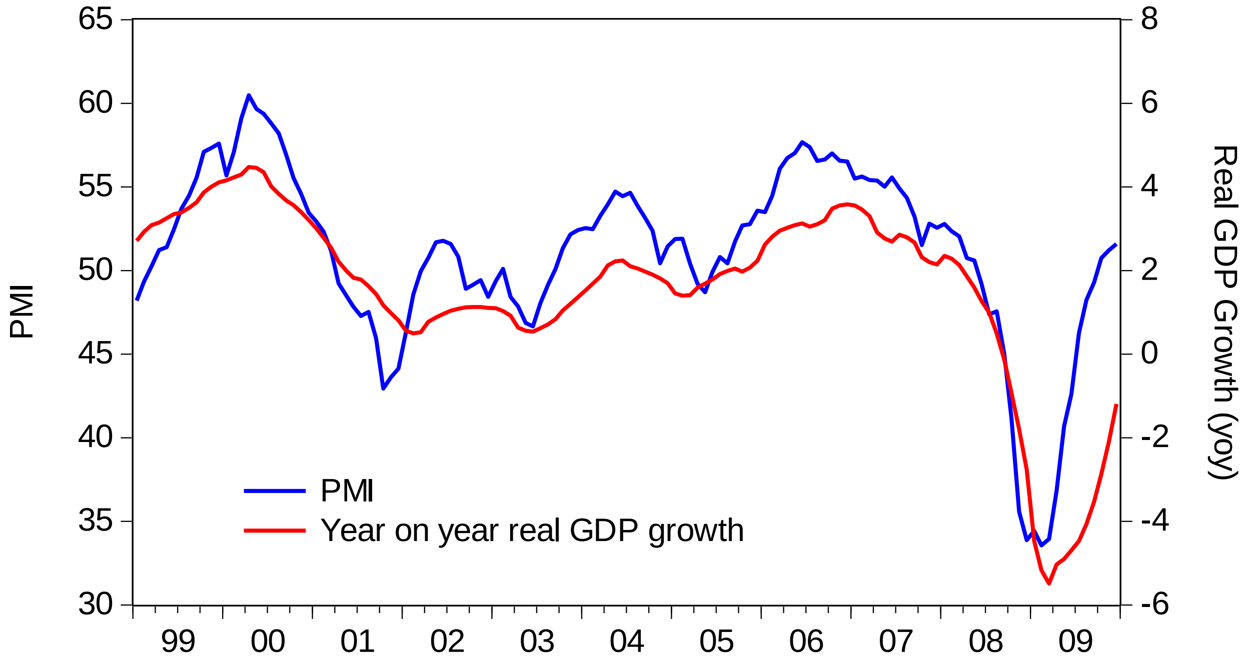

Figure 4: Logistic weights

(Switch as a function of time; with 95% confidence band)

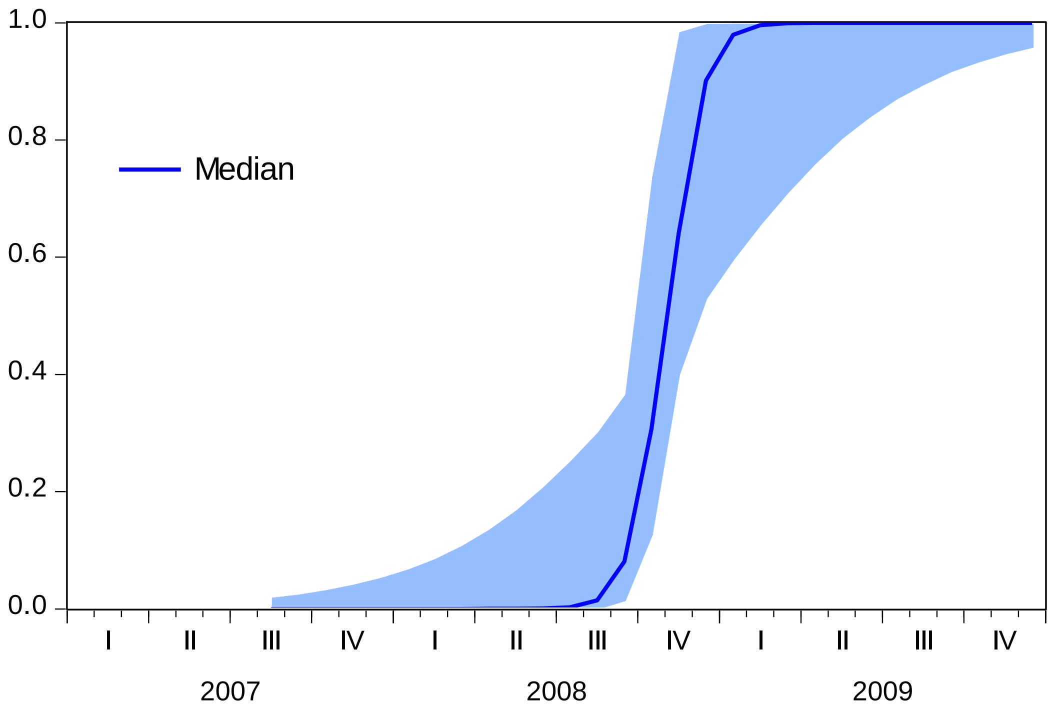

Figure 5: Dynamic out-of-sample forecasts/estimates of i*

(Switch as a function of time; with 95% confidence band)

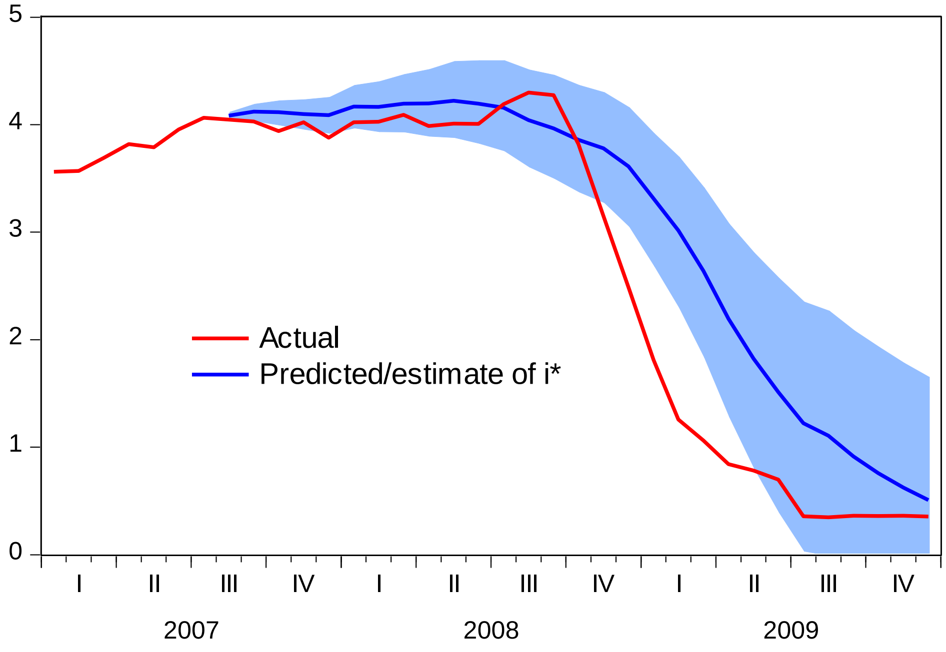

Figure 6: Logistic weights

(Switch as a function of real GDP growth; with 95% confidence band)

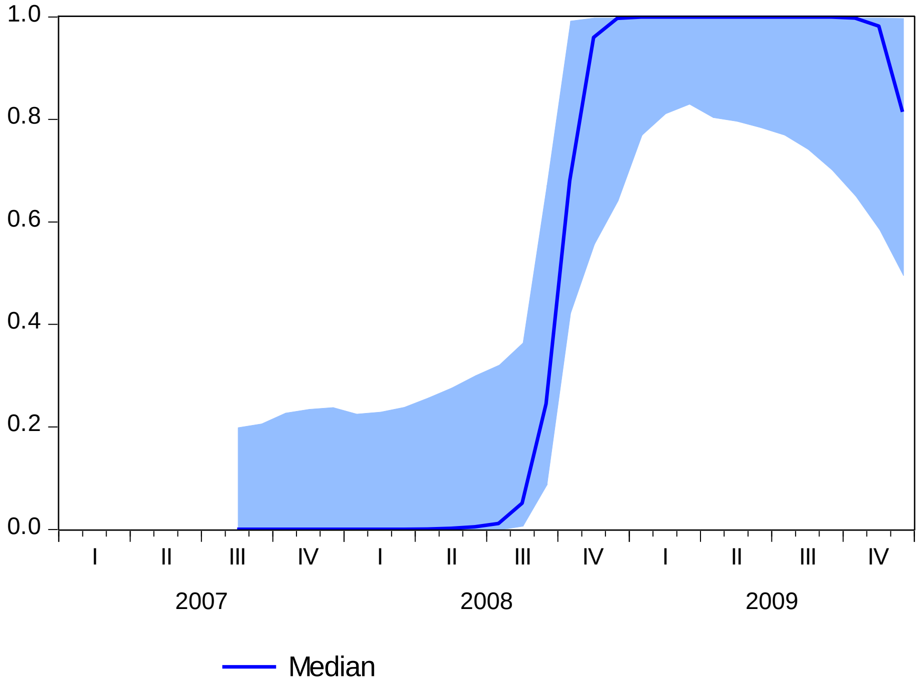

Figure 7: Dynamic out-of-sample forecasts/estimates of i*

(Switch as a function of real GDP growth; with 95% confidence band)

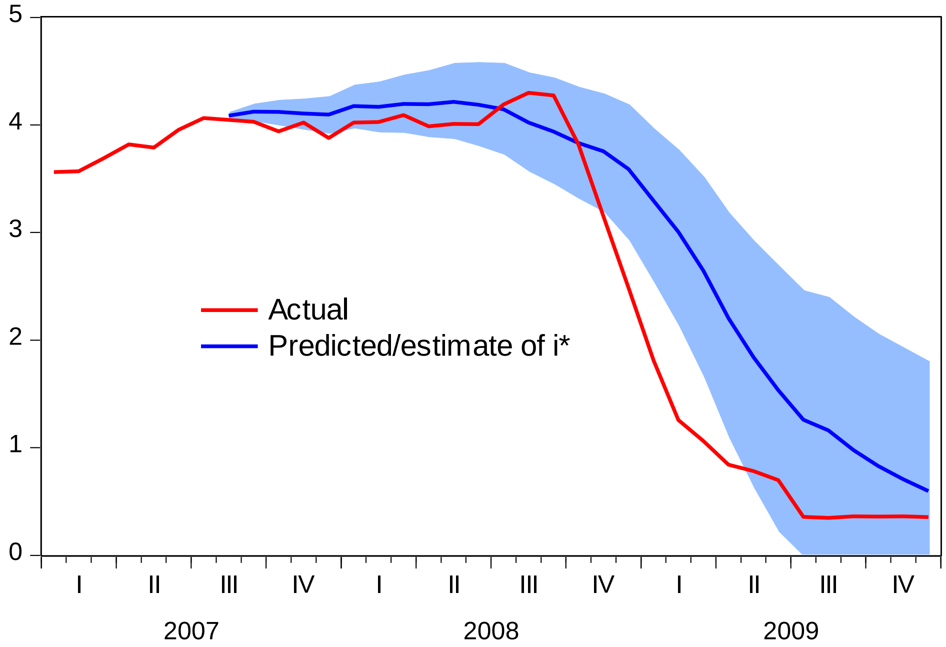

Table 1: Maximum likelihood estimates (Switch as a function of time)
Sample period January 1999 – December 2009

	Unrestricted model		**Restricted model**	
Regime	**Pre-crisis**	**Post Crisis**	**Pre-crisis**	**Post Crisis**
Constant	**-1.337**	**-0.284**	**-1.392**	**0.085**
	(0.272) *0.000*	(0.820) *0.729*	(0.265) *0.000*	(0.093) *0.361*
Lagged interest rate	**0.979**	**0.543**	**0.979**	**0.714**
	(0.014) *0.000*	(0.390) *0.163*	(0.013) *0.000*	(0.060) *0.000*
Lagged change in interest rate	**-0.287**	**-0.014**	**-0.277**	
	(0.079) *0.000*	(0.366) *0.966*	(0.077) *0.003*	
PMI	**0.024**	**0.011**	**0.026**	
	(0.005) *0.000*	(0.018) *0.546*	(0.004) *0.000*	
Inflation	**0.042**	**0.198**	**0.052**	
	(0.019) *0.031*	(0.204) *0.333*	(0.017) *0.002*	
M3 growth	**0.008**	**-0.004**		
	(0.006) *0.184*	(0.101) *0.966*		
Nom. eff. exchange rate	**-0.007**	**-0.009**	**-0.005**	
	(0.003) *0.023*	(0.025) *0.720*	(0.002) *0.049*	
Standard deviation of error term	**0.105**	**0.076**	**0.106**	**0.085**
	(0.006) *0.000*	(0.024) *0.002*	(0.006) *0.000*	(0.026) *0.001*
Speed (K)	**0.664**		**1.624**	
	(0.746) *0.374*		(0.836) *0.052*	
Switching date (λ)	**225.399**		**225.646**	
	(0.838) *0.000*		(0.516) *0.000*	
Log likelihood	**115.716**		**112.672**	

Notes: Standard errors in parenthesis; p-values in italics

Table 2: Maximum likelihood estimates (Switch as a function of GDP growth)
Sample period January 1999 – December 2009

	Unrestricted model		**Restricted model**	
Regime	**Pre-crisis**	**Post Crisis**	**Pre-crisis**	**Post Crisis**
Constant	**-1.369**	**-0.554**	**-1.375**	**0.078**
	(0.271) *0.000*	(0.828) *0.504*	(0.284) *0.000*	(0.10) *0.42*
Lagged interest rate	**0.979**	**0.641**	**0.979**	**0.724**
	(0.014) *0.000*	(0.233) *0.006*	(0.014) *0.000*	(0.05) *0.00*
Lagged change in interest rate	**-0.303**	**0.303**	**-0.282**	
	(0.079) *0.000*	(0.080) *0.000*	(0.079) *0.000*	
PMI	**0.025**	**0.013**	**0.026**	
	(0.005) *0.000*	(0.013) *0.345*	(0.005) *0.000*	
Inflation	**0.037**	**0.165**	**0.048**	
	(0.019) *0.049*	(0.251) *0.512*	(0.017) *0.005*	
M3 growth	**0.008**	**0.041**		
	(0.006) *0.182*	(0.12) *0.73*		
Nom. eff. exchange rate	**-0.007**	**0.003**	**-0.005**	
	(0.003) *0.001*	(0.024) *0.880*	(0.002) *0.000*	
Standard deviation of error term	**0.105**	**0.094**	**0.108**	**0.087**
	(0.006) *0.000*	(0.034) *0.005*	(0.006) *0.000*	(0.03) *0.00*
Speed (G)	**-528.190**		**-2.735**	
	(21149.320) *0.98*		(1.558) *0.079*	
Switching level of GDP growth (μ)	**0.489**		**-0.665**	
	(0.076) *0.000*		(0.334) *0.047*	
Log likelihood	**111.525**		**110.835**	

Appendix: Additional Empirical Results

Table A1: Reaction Functions with Monetary Growth

	I. Benchmark Model (*Restricted Model* of table 1)		**II. Replace inflation with money growth**		**III. Include both inflation and money growth**	
Regime	**Pre-crisis**	**Post Crisis**	**Pre-crisis**	**Post Crisis**	**Pre-crisis**	**Post Crisis**
Constant	**-1.392** (0.264) *0.000*	**0.085** (0.093) *0.361*	**-1.166** (0.280) *0.000*	**0.085** (0.093) *0.36*	**-1.338** (0.273) *0.000*	**0.085** (0.093) *0.358*
Lagged interest rate	**0.979** (0.013) *0.000*	**0.714** (0.060) *0.000*	**0.986** (0.012) *0.000*	**0.713** (0.060) *0.000*	**0.979** (0.013) *0.000*	**0.713** (0.060) *0.000*
Lagged change in interest rate	**-0.277** (0.077) *0.000*		**-0.261** (0.082) *0.001*		**-0.286** (0.080) *0.000*	
PMI	**0.026** (0.004) *0.000*		**0.022** (0.005) *0.000*		**0.024** (0.005) *0.003*	
Inflation	**0.052** (0.017) *0.002*				**0.042** (0.020) *0.033*	
Money Growth			**0.013** (0.005) *0.018*		**0.008** (0.006) *0.186*	
Nominal eff. exchange rate	**-0.005** (0.002) *0.049*		**-0.008** (0.003) *0.021*		**-0.007** (0.003) *0.025*	
St dev of error term	**0.106** (0.006) *0.000*	**0.085** (0.026) *0.001*	**0.107** (0.006) *0.000*	**0.0850** (0.026) *0.001*	**0.105** (0.006) *0.000*	**0.084** (0.026) *0.001*
Speed (K)	**1.624** (0.836) *0.052*		**1.727** (0.858) *0.044*		**1.633** (0.810) *0.044*	
Switching date (λ)	**225.646** (0.516) *0.000*		**225.685** (0.537) *0.000*		**225.62** (0.493) *0.000*	
Log likelihood	**112.672**		**111.509**		**113.776**	
Posterior Odds Ratio vs benchmark			**0.313**			
Test of restrictions (p-value)					**0.137**	

Notes: p-values in italics, standard errors in parantheses

Blank cell indicates a coefficient restricted to zero; coefficient in the middle of a column indicates common coefficient in first and second periods.

Liklihood test treats I as restricted form of III

Table A2: Alternative Regime Switches

	Benchmark (*restricted model* of table 1)		A. Reaction to Economic Variables Unchanged		B. Single regime	C. Discrete break in October 2008	
Regime	**Pre-crisis**	**Crisis**	**Pre-crisis**	**Crisis**		**Pre-crisis**	**Crisis**
Constant	**-1.392**	**0.085**	**-1.041**	**-0.799**	**-1.248**	**-1.204**	**-0.988**
	(0.262) *0.000*	(0.03) *0.361*	(0.230)*0.000*	(0.180) *0.008*	(0.132) *0.000*	(0.239) *0.000*	(0.182) *0.000*
Lagged int rate	**0.979**	**0.714**	**0.977**	**0.725**	**0.971**	**0.976**	**0.755**
	(0.013) *0.000*	(0.06) *0.000*	(0.013)*0.000*	(0.055) *0.000*	(0.014) *0.000*	(0.013) *0.000*	(0.057) *0.000*
Lagged ch. in int rate	**-0.277**		**-0.193**		**-0.032**	**0.755**	
	(0.077) *0.000*		(0.073) *0.008*		(0.066) *0.627*	(0.058) *0.000*	
PMI	**0.026**		**0.020**		**0.026**	**0.023**	
	(0.004) *0.000*		(0.003) *0.000*		(0.002) *0.000*	(0.004) *0.000*	
Inflation	**0.052**		**0.052**		**0.003**	**0.041**	
	(0.016) *0.002*		(0.017) *0.003*		(0.015) *0.848*	(0.015) *0.007*	
Nominal eff. ex. rate	**-0.001**		**-0.007**		**-0.002**	**-0.006**	
	(0.002) *0.049*		(0.002) *0.003*		(0.002) *0.196*	(0.002) *0.008*	
s.d. of error term	**0.106**	**0.085**	**0.107**	**0.096**	**0.125**	**0.110**	**0.111**
	(0.006) *0.000*	(0.026) *0.001*	(0.006) *0.000*	(0.022) *0.000*	(0.007) *0.000*	(0.006) *0.000*	(0.031) *0.000*
Speed (K)	**1.624**		**2.641**			**100**	
	(0.836) *0.052*		(3.762) *0.483*			**(imposed)**	
Switching date (λ)	**225.646**		**225.112**			**225.5**	
	(0.516) *0.000*		(1.350) *0.000*			**(imposed)**	
Log likelihood	**112.672**		**109.789**		**86.671**	**104.166**	
Post Odds Ratio vs Benchmark			**0.056**				
Test of restrictions (p-value)					**0.000**	**0.000**	

Notes: p-values in italics (for space reasons standard errors are not reported)

Blank cell indicates a coefficient restricted to zero; coefficient in the middle of a column indicates common coefficient in first and second periods.

Odds ratio equals the ratio of the likelihood function for the alternative model to the likelihood function of the benchmark model

Liklihood test treats C and D as restricted forms of benchmark model