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ABSTRACT

ECB Reaction Functions and the Crisis of 2008*

We study ECB's interest rate setting in 1999-2010 using a reaction function in which forecasts of future economic growth and inflation enter as regressors. Allowing for a gradual switch between two reaction functions, we detect a shift after Lehman Brothers failed in September 2008 when the pre-crisis reaction function first indicates that interest rates may become constrained by the zero lower bound. Furthermore, the interest rate cuts in late 2008 were more aggressive than forecast by the pre-crisis reaction function. These findings are compatible with the literature on optimal monetary policy in the presence of a zero lower bound.

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

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1. Introduction

The global financial crisis that started in August 2007 has shown all too clearly that if a large, contractionary shock occurs, reducing inflation to a very low or even a negative level and causing a sharp contraction in economic activity, central banks may be stuck in a situation with interest rates to close to zero, that is, close the to Zero-Lower Bound (ZLB). This raises the risk that if yet another shock occurred, central banks' ability to offset it with interest rate cuts would be exhausted, forcing them to rely on the vagaries of quantitative easing or other non-standard measures to stimulate the economy.

A number of authors have argued that the possibility of reaching the zero-lower bound should affect central banks' interest rate setting also in situations in which interest rates are some distance above zero, although there appears to be disagreement as to precisely how policy should change. On the one hand, the literature on optimal monetary policy suggests that central banks cut interest rates more aggressively than otherwise in response to a contractionary shock if there is a prospect that interest rates may reach zero in the near future (Reifschneider and Williams (2000), Orphanides and Wieland (2001) and Adam and Billi (2005)). On the other hand, in the policy literature the risk of hitting an interest rate floor is sometimes seen as a reason for the central bank to exercise greater caution in cutting rates, so as to preserve the possibility of making cuts in the future (e.g., Bini Smaghi, 2008).

In this paper we estimate monetary policy reaction functions for the ECB in order to explore its interest rate setting behaviour during the crisis. Since there are good reasons to believe that that reaction function may have shifted in the sample, we use an econometric framework which allows the coefficients of the reaction function to change over time. We follow Mankiw, Miron and Weill (1987) and Gerlach and Lewis (2011) in using a smooth transition model that allows for two different monetary policy regimes. An appealing feature of this approach is that both the timing of the regime switch and the speed with which it occurs is estimated rather than imposed. Furthermore, it is straightforward to test whether two regimes are needed to capture the behaviour of interest rates, and whether the transition between them is gradual or instantaneous.

Four main results emerge from our analysis. First, we find that a 95% confidence interval for our estimate of the long-run interest rate target rate (to which the actual short-term rates is moving gradually over time) falls well below zero after the collapse of Lehman Brothers. Subsequently, the interest target rises but a confidence interval includes zero until the end of our sample in December 2010.

Second, a dynamic forecast of the actual short-term interest rate based on pre-crisis estimates of the ECB's reaction function predicts a negative interest rate during the crisis. Taken together, these two findings suggest that the ZLB did appear to be a significant constraint on monetary policy.

Third, following the collapse of Lehman Brothers in September 2008, we detect a rapid but not instantaneous shift of the reaction function we use to characterise the ECB's interest rate setting. Interestingly, the switch was concluded by early 2009, that is, several months before the apparent interest rate floor was reached.

Fourth, in the new regime the ECB cut interest rates significantly more rapidly in response to worsening economic conditions than we would have expected on the basis of the pre-crisis reaction function. Thus, monetary policy became more aggressive. This rapid relaxation of monetary policy is consistent with theoretical work on optimal monetary policy in the presence of the ZLB and is in contrast to the view that policymakers should exercise more caution in rate-cutting when the ZLB nears (the "keeping your powder dry" approach).

We emphasise that although the literature on ECB reaction functions is extensive[1], this paper is one of very few that analyse how the crisis has affected ECB rate setting behaviour. Gorter et al. (2010) estimate reaction functions with rolling coefficients and detect parameter instability in reaction functions over the period 1999-2010. However, they do not propose an alternative specification which resolves the problem of unstable coefficients.

Gerlach and Lewis (2011) and Gerlach (2011) utilise the smooth transition approach adopted here to examine how the ECB's responses to actual macroeconomic data changed during the crisis, and show that interest rate setting became more aggressive after the collapse of Lehman Brothers. However, Orphanides (2010) notes that a calibrated forward-looking reaction function under which the ECB sets monetary policy according to macroeconomic forecasts fits the ECB's observed interest rate setting well throughout the 2008-9 period, suggesting that the reaction function did not shift. It is therefore possible that the non-linearity detected by Gerlach and Lewis (2010) and Gerlach (2011) arises because forecasts of future economic conditions deteriorated unusually fast and to an usual extent compared to the worsening of incoming macroeconomic data, and not because the ECB's reaction function changed. Here we therefore use forecasts of inflation and economic growth as regressors in the empirical reaction function in order to see if our earlier findings are spurious.

The paper is organised as follows. The next section provides an overview of the literature on monetary policy in a low-interest rate environment, Section 3 details our empirical approach and Section 4 presents the results. Section 5 concludes.

[1] For example Castelnuovo (2007), Gerdesmeier and Roffia (2004), Gerlach-Kristen (2003), Surico (2003), Carstensen (2006), Gerlach (2007), Sauer and Sturm (2007), and Gorter et al. (2008).

2. The Lower Bound on the Interest Rate

The problems posed by a floor on the interest rate were revived in the modern literature by Summers (1991).[2] The problem arises because agents can avoid negative nominal rates by holding cash, central banks cannot push interest rates below zero. The precise numerical value of the lower bound is the subject of some debate. Some authors have argued that practical difficulties of holding large sums of cash mean agents may tolerate marginally negative rates (McCallum, 2000). Others have argued that the bound may be positive, reflecting the costs of disruptions to money market of a zero rate (Williams, 2009). Indeed, during the crisis no central bank has pushed rates down to zero, but several have stopped somewhere in the range of 0 - 25 basis points. In what follows we use the term zero lower bound (ZLB) for reasons of brevity.

The revival in interest in the ZLB in the early 2000s inspired several papers that used model-based simulations to estimating the frequency, and extent to which the ZLB may act as a binding constraint on monetary policy. Simulations using Taylor-type rules find that although the ZLB may frequently bind, its effects on macroeconomic volatility will be small, because the gap between the desired (negative) interest rate and the zero lower bound is small (Reifschneider and Williams, 2000; Coenen, 2003; Coenen et al., 2004; and Billi, 2004).

The sharp falls in inflation and output seen during current crisis have led some to question this earlier result. Williams (2009) notes that the earlier studies are typically based on the probability distribution of disturbances during the Great Moderation and hence may underestimate the frequency and severity of tail events such as the crisis that followed the collapse of Lehman Brothers. Studying the current crisis he

[2] The constraint was noted much earlier by authors such as Keynes (1936) and even Fisher (1896). See Ullersma (2002) for a comprehensive survey.

finds that the ZLB did not significantly accentuate the sharp decline in autumn 2008 in inflation and output in the US, because developments were too fast for monetary policy to react pre-emptively, but finds that it has slowed the recovery considerably.

In recent work, Blanchard et al. (2010) raised the possibility of raising inflation targets to reduce the risk that the ZLB becomes a constraint on policy. This option has sparked several papers that attempt to analyse the potential trade-offs between the costs of higher steady-state inflation and the benefits of having the ZLB bind less often (e.g., Schmitt-Grohé and Uribe, 2010; McCallum, 2010; Walsh, 2010). These papers conclude that the costs of higher steady state inflation do not outweigh the benefits of the ZLB binding less frequently and less severely.

Our results contribute to this literature on the frequency and severity of the constraint posed by ZLB by providing an empirical analysis of how long and by how much has the ZLB appeared to constrain interest rates in the euro area.

Other work has analysed the related question of how monetary policy should respond when central banks are concerned that the ZLB may bind in the near future. A common argument in this literature is that faced with the possibility of the ZLB constraining rates in the future, policymakers should cut interest rates more rapidly in response to lower inflation and weaker growth than under “normal” conditions (Reifschneider and Williams, 2000; Orphanides and Wieland, 2000; Adam and Billi, 2005). The intuition of this can be seen from the model of Reifschneider and Williams. If monetary policy works via the long term interest rate (which depends on the expected path of future short term rates), the policy rate will be higher than the central bank would otherwise like when the ZLB binds. To prevent the long term interest rate from rising and choking off aggregate demand, it is optimal for the central bank to set interest rates below the level it would have set in the absence of the ZLB. Interestingly, it should do so as soon as it anticipates that the ZLB will bind and potentially also promise to do so after the crisis has abated.

While theory thus suggests that the prospect of reaching the ZLB makes central banks become more aggressive, many policy makers have argued that the possibility of rates being constrained requires more caution in rate cutting. This common view is outlined by Bini Smaghi (2008) who cites several arguments against rapid rate cuts. The first of these holds that central banks should refrain from interest rate cuts now to retain the option of reducing rates in the future, that is, they should "keep their gun powder dry". Second, sharp rate cuts could be misinterpreted by market participants as a sign that the central bank is more pessimistic about the economic outlook than the market is, and engender negative confidence effects. Third, holding rates "too low for too long" could fuel dangerous financial imbalances.

Given that there are two opposing views about how policy should be conducted in the presence of the ZLB, it is of interest to explore whether the data allows us to distinguish between them. This is what we attempt to do in this paper.

3. Econometric Considerations

To set the stage for the empirical work that follows, in this section we first discuss the data and then discuss the econometric model.

3.1 Data Choice

Several contributions in the literature have argued that central banks respond to forecasts of future economic variables rather than current levels (Orphanides 2001, Orphanides 2010). Using forecasts as explanatory variables has the advantage that they in principle incorporate all information available at the time to the policymaker, including "soft" information, other variables and policy makers' expert judgement. This could be particularly important in crisis times, since central banks might look to a much broader set of variables (such as financial stress indicators or asset prices) to gauge the economic outlook than they would do in normal times.

The ECB commissions its own *Survey of Professional Forecasters* (SPF) which is published in the middle month of each quarter and contains average forecasts for inflation, growth and unemployment at the one and two year time horizons. Since this is the measure the ECB itself uses to assess the macro economic outlook, it represents a natural data choice for our purposes.

While Taylor (1993) in his seminal paper used the output gap and inflation to characterise the interest rate setting of the Federal Reserve, a number of papers have argued that central banks in practice respond more strongly to the growth rate of real GDP than to the output gap. One reason for this is that it is very difficult to estimate the trend level of output with any precision in real time (Orphanides and van Norden, 2001). Indeed, as emphasised by Gerlach (2007), the ECB's own commentary on its policy decisions emphasise the role of business sentiment indicators which are much more closely correlated with real GDP growth rather than the deviation of real GDP from trend. In modelling the policy choices of the ECB's Governing Council, of which he is a member, Orphanides (2010) also uses the differential between (forecast) real and potential GDP growth rather than the output gap.[3]

Since we wish to analyse monetary policy at the monthly frequency at which it is set and the SPF data is only available quarterly, we need to interpolate their values in the months between surveys. One option would be simply to simply take the latest SPF data available in a given month. However, that would be tantamount to assuming that no new information is received by the ECB in the three months between SPF rounds. This is improbable, especially during the recent crisis. The simplest alternative would be to use linear interpolation for the intermediate months,

[3] Using inflation and economic growth in a reaction function can be grounded theoretically in the literature on "speed limit" policy rules. This finds that a monetary policy rule based on economic growth and inflation is a close approximation to the unconstrained optimal rule (Walsh, 2003; McCallum and Nelson, 2004).

but this procedure relies on the use of data (the next round of SPF figures) which was not available in real time.

We therefore use the Chow-Lin (1971) method to interpolate the quarterly SPF series using the monthly expectations data supplied by Consensus Economics. This too is a survey, but unlike the SPF, asks participants to forecast what inflation and growth will be at the end of the current and the following calendar year. Since the forecast horizon is not constant, we use linear interpolation to derive an estimate for forecast inflation 12 months ahead, which we then use to interpolate monthly values for the SPF data.

The raw SPF data together with the interpolated data is shown in Figures 1 and 2. These show that as inflation forecasts started to rise in the second half of 2008, before abruptly falling after the collapse of Lehmann Brothers in September. By the summer of 2009 the fall was arrested, and inflation forecasts started to rise again. Similarly, the collapse of Lehman Brothers had a large impact on forecast real GDP growth, which fell to -2% in the summer of 2009 before rebounding.

[Figures 1 and 2 go here]

An important question that arises when estimating reaction functions for the ECB during the crisis is what interest rate to use as dependent variable. While the literature to date has tended to use the ECB's repo rate, during the crisis the overnight rate (EONIA) fell substantially below the repo rate (Gerlach and Lewis 2011). The ECB had strong incentives to reduce interest rates as much as possible to stimulate the economy and could have prevented the overnight rate from declining below the repo rate if it had felt that it fell too low. We therefore view the rapid decline of EONIA relative to the repo rate as an expression of policy and thus use the EONIA as our dependent variable in the econometric analysis below.

3.2 Modelling Interest Rate Setting

We base our approach on a modified version of the model of Judd and Rudebusch (1998). Let i_t denote the EONIA overnight rate, i_t^T the ECB's "target" for the overnight rate, y_{t+12}^f the forecast of economic growth twelve months ahead and π_{t+12}^f the forecast of inflation twelve months ahead. The target level for the interest rate is given by:

(1) $$i_t^T = \alpha_0 + \alpha_y y_{t+12}^f + \alpha_\pi \pi_{t+12}^f$$

where all coefficients are expected to be positive. The overnight rate is allowed to move gradually towards the target according to:

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

where β_1 governs the gradualism with which this is done and where β_2 captures the extent to which there is inertia in the change in rates.

Combing (1) and (2) we have the following reaction function:

(3) $$i_t = \tilde{\alpha}_0 + \tilde{\alpha}_y y_{t+12}^f + \tilde{\alpha}_\pi \pi_{t+12}^f + \tilde{\alpha}_i + (1-\beta_0) i_{t-1} + \beta_1 \Delta i_{t-1}$$

where $\tilde{\alpha}_j = \alpha_j \beta_0$.[4] For ease of exposition, we re-write this equation more compactly as:

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

where Θ is a row vector of parameters and Z_t as column vector of data.

Estimating a single reaction function for the whole period may be problematic because interest rates may have been constrained by the ZLB during the crisis. First

[4] Elsewhere in the literature other papers including a lagged dependent variable use a slightly different terminology: $\tilde{\alpha}$ is sometimes referred to as the "short-run reaction" and α as the "long-run reaction".

and as discussed above, it is eminently plausible that the ways in which policy makers responds to economic conditions may change if it is plausible that the ZLB might be reached in the near future. Second, the fitted reaction function, which is typically linear, must satisfy the non-negativity constraint on the interest rate. As economic conditions worsen, it is otherwise possible that the target interest rate implied by the pre-crisis reaction function would be negative. While the ZLB constrains the actual interest rate, which adjusts gradually to the target rate, such a situation can only persist for a limited period of time. As the actual interest rate continue to fall towards zero, at some time the reaction function must shift.

In estimating the reaction function we must therefore take into account the possibility that there may have been two regimes in operation during the sample period. The full model can thus be written:

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

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

The simplest way to model the structural change would simply be to assume a discrete break at some point in the sample at a date suggested by the chronology of the crisis such as during the money market tensions in August 2007 or the collapse of Lehman Brothers in September 2008. Alternatively, we could employ an Andrews test to select the appropriate break date. In both cases, however, the break is assumed to be discrete, which rules out the possibility of a smooth transition between regimes that seems eminently plausible.

We therefore employ the smooth transition model of Mankiw, Miron and Weil (1987). In any given period, the interest rate is a weighted average of the two regimes:

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

where the variance of the errors is also a weighted average of the two regime specific variances: $\sigma^2 = (1-\omega_t)^2\sigma_I^2 + \omega^2\sigma_{II}^2$. Note that this means the error terms are heteroscedastic and so this will be an additional source of specification error if one simply estimates a single reaction function.

The weights follow a logistic function, $L(\bullet)$ of time:

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

where τ_t is a time trend.

Since a time trend is deterministic and increases monotonically, this specification permits only one change of regimes, and hence cannot capture any return to the pre-crisis regime. However, in the current sample there does not appear to have been such a shift to the original reaction function so this specification seems appropriate for our purposes.

The speed and timing of the transition is captured by the parameters θ and λ respectively. The parameter λ gives the value of the trend at the mid-point of the switch (i.e. when $\omega = 0.5$) and the parameter θ describes the speed (a higher value implies a faster switch). This functional form also nests the case of a discrete break. In that case, the speed of the change tends towards infinity and the midpoint of the change occurs between months. Testing the restrictions implied allows us to formally test whether the switch was discrete.

It should be noted that the model is not identified as it currently stands. Since $L(\theta_0;\ldots) \equiv 1 - L(-\theta_0;\ldots)$ a model with $\theta = \theta_0$ will be identical to a model with $\theta = -\theta_0$. However, the model we estimate below implies restrictions on parameters in the second period that are sufficient to ensure identification.

4. Empirical Results

As suggested by Mankiw, Miron and Weill (1997), the model can be estimated with maximum likelihood.[5] We begin by estimating an unrestricted version which included forecast growth, forecast inflation, a lagged interest rate and the lagged change in the interest rate. The results are shown below in Table 1.

[Table 1 goes here]

The switching point is located in November 2008. (We therefore refer to the regime in force in the first part of the sample as the pre-crisis period and that in the second part as the crisis regime.) The failure of Lehman Brothers in September will first be felt in the October forecasts and (since the regressors are lagged by one month to capture reporting lags) will only influence policy in November. Mankiw, Miron and Weill 1987) note that the time between one quarter and three quarters of the adjustment has occurred is given by log(9)/θ, and our point estimate thus implies that the switch was rapid.

Turning to the coefficients in the reaction function, the pre-crisis estimates have the expected signs and, with the exception of the lagged change in the interest rate, are significant. In the crisis period, both forecast inflation and real GDP growth are insignificant. This suggests that the appropriate restricted form of the reaction function in the crisis is a model with only a constant and the lagged interest rate, which implies that in the target interest rate was constant in the crisis period and that the actual interest rate converged gradually towards and then fluctuated around this constant target.

We next dropped all the insignificant parameters and show the results for the restricted model on the right of Table 1. In the pre-crisis period, the coefficients are

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[5] Interestingly, they do not estimate the location and speed of the switch but use a grid search procedure to determine these parameters.

consistent with the earlier literature on ECB reaction functions. The lagged rate is significant, as are the reactions to forecasted inflation and economic growth. Importantly, the long run response to forecast inflation and real GDP growth are large (4.35 and 2.35, respectively), indicating that the ECB has responded strongly to inflation and to economic growth, which is an important driver of inflation.

The speed and switching parameters are both quite precisely estimated and locate the mid-point of switch in the autumn of 2008. To quantify this uncertainty, Figure 3 shows the point estimate for the weighting variable over time and together with a 95% confidence interval. The confidence interval was obtained by drawing 10,000 times from the joint distribution of the speed and switching date parameters and computing the weighting function in each case. Discarding the top and bottom 2.5% of realised outcomes then yields a confidence interval.

[Figure 3 goes here]

The solid line shows the median of the estimates of ω_t, which suggests that the switch occurred in around November 2008 and that it took only four months for the weighting parameter to go from 0.1 to 0.9. The vertical distance between the dashed lines give a 95% empirical confidence interval for ω_t. Overall, the switching between regimes seems quite tightly identified. In early 2008, the upper bound of the confidence interval is close to zero, indicating that monetary policy is quite well characterised by the pre-crisis reaction function. By September 2008, when the point estimate is below 0.1, even the upper bound is around 0.25, suggesting that the pre-crisis reaction function continued to explain the ECB's policy decisions quite well.

In addition, this also suggests that the transition was not discrete. If that were the case, the weighting parameter would be either 0 or 1 in any given month, yet figure 1 makes plain that for during the fourth quarter of 2008, the confidence interval lies quite far away from both 0 and 1.

To explore this issue more formally, we estimated a series of alternative specifications where a discrete break is imposed in a given month. The log-likelihood of these is shown in Figure 4 (solid line), together with the log likelihood of the smooth transition model (dashed line) reported in Table 1. The horizontal axis records the month where the break is imposed is in the discrete model. The highest log-likelihood is for the model which has October 2008 as the break point, although other break points in the following months yield log-likelihoods which are almost as high. Since the discrete break in October 2008 is a restricted form of our benchmark smooth transition model, the restrictions implied can be tested formally. A chi-squared test yields a p-value of less than 0.01, strongly rejecting the restrictions and thus provides formal support for modelling the regime change as a smooth transition.[6]

[Figure 4 goes here]

As a robustness check we also investigated several other alternative forms of the model similar to the alternatives considered by Gerlach and Lewis (2010). These included a single reaction function where the coefficients are constant throughout, and one where only the gradualism parameter changes across regime. Log-likelihood based tests strongly rejected these alternatives. (Results are available from the authors on request.)

The above results provide evidence for a change in the ECB's reaction function as the crisis progressed, but they do not say anything directly about the how far actual interest rates were from the those posited by the pre-crisis reaction function. It is to this issue that we now turn.

[6] Of course, this test disregards the fact that the discrete break date was selected on the basis of highest log likelihood amongst alternative models rather than being exogenously given. Correcting for this would further strengthen the rejection of the discrete break model.

We begin with the estimates of the target interest rate, i_t^T. This is the interest rate towards which the EONIA rate would converge if the forecast rate of inflation and real GDP growth remained constant at their current levels. Figure 5 below shows the target interest rate, assuming that the pre-crisis reaction function applied throughout, together with a 95% confidence interval, which is constructed by sampling from the joint distribution of the parameters.[7]

[Figure 5 goes here]

Several features stand out. First, from the start of EMU until the crisis starts, the point estimate of the target rate is always positive, although in the early part of the 2000s the lower bound of the confidence interval went briefly below zero. Second, following the collapse of Lehman Brothers on 15 September 2008, the target rate declines sharply and by November that year is significantly below zero and remains well below zero for a considerable time. Thus, the pre-crisis coefficients suggest that, given the ECB's past way of setting interest rates, the target rate was negative and hence, it was possible that the overnight rate would reach the ZLB in the future, although the actual rate was some way above zero at the time. Third, the rate rose substantially in the second half of 2009, but the confidence interval contains zero throughout. That suggests that as of December 2010 there was still some possibility that the low interest rates observed may still have been above the target rate implied by the pre-crisis reaction function.

Having discussed target rate, we next turn to the overnight rate. In order to see how much of the sharp interest rate reduction after the collapse of Lehman Brothers can be attributed to deteriorating macroeconomic forecasts, we construct a dynamic out-of-sample forecast using coefficients from the pre-crisis reaction function, beginning in September 2008. This forecast is shown below in Figure 6 (solid thin line), together

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[7] As before, we draw 10,000 from the joint distribution of parameters, calculated the path of the interest rate implied by each one, and then discard the upper and lower 2.5% in each period.

with a 95% confidence interval (the dashed line) and the actual path of the interest rate (thick line).[8]

[Figure 6 goes here]

The figure shows that the predicted policy rate falls sharply after the failure of Lehman Brothers and turns negative in the middle of 2009. However, the cuts seen in the final quarter of 2008 represent a significantly larger and more rapid relaxation of monetary policy than predicted by pre-crisis reaction function. By January 2009 this discrepancy was over 100 basis points. Furthermore, the observed policy rate lay outside the 95% confidence interval, indicating both a statistically and economically significant difference. As the interest rates level off, this divergence is closed, and then reversed as the forecast rate goes below zero.

This figure is particularly relevant in the light of the theory on optimal monetary policy in the vicinity of the lower bound. As noted earlier, theory suggests that as the economic outlook worsens, central banks should cut interest rates faster than one would be expected on the basis of their regular reaction function before. Thus, the ECB's behaviour appears fully consistent with the predictions of the theoretical literature which holds that central banks should cut interest rates faster in response to a contractionary shock when there is a likelihood that the ZLB will bind in the future.

5. Conclusions

In this paper we have studied the ECB's interest rate setting during the global financial crisis that started in August2007 and became more severe after the failure of Lehman Brothers in September 2008. Our main findings can be summarised as follows.

[8] This is constructed using the same method as our confidence intervals for the target rate.

First, we find evidence that the ZLB did constrain monetary policy during the financial crisis. We draw this conclusion because the estimated target rate was significantly negative for an extended period from the autumn of 2008 onwards and it did not rise significantly above zero during the rest of the sample (which ends in December 2010). Furthermore, the dynamic forecast of the interest rate based on the estimated pre-crisis reaction coefficients posits a negative interest rate, which furthermore is statistically significant, for a prolonged period.

Second, the ECB's responses to forecasts of inflation and growth shifted shortly after the collapse of Lehman Brothers. The mid-point of this switch happens at almost exactly the same moment as the target interest rate (computed on the basis of the parameters estimate from data from before the crisis) turns negative.

Third, as evidence by the shift of the reaction function, during the crisis interest rates were reduced significantly faster than suggested by pre-crisis estimates of the reaction function. Thus, the shift in the reaction function is not only statistically but also economically significant.

Fourth, the change in the ECB's interest rate setting behaviour is consistent with the findings in the theoretical literature on optimal monetary policy in the presence of the ZLB. Furthermore, the rapid interest cuts appear to be inconsistent with the "keeping your powder dry" approach.

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Table 1: Maximum likelihood estimates

Sample period January 1999 – December 2010

	Unrestricted model		**Restricted model**	
Regime	**Pre-crisis**	**Crisis**	**Pre-crisis**	**Crisis**
Constant	**-0.693**	**-0.483**	**-0.610**	**0.131**
	(0.115) *0.000*	(1.418) *0.733*	(0.097) *0.000*	(0.037) *0.000*
Lagged interest rate	**0.930**	**0.645**	**0.935**	**0.678**
	(0.015) *0.000*	(0.132) *0.000*	(0.015) *0.000*	(0.039) *0.000*
Lagged change in interest rate	**-0.120**	**-0.009**		
	(0.079) *0.131*	(0.280) *0.974*		
Expected GDP Growth	**0.171**	**-0.024**	**0.153**	
	(0.030) *0.000*	(0.114) *0.829*	(0.026) *0.000*	
Expected Inflation	**0.316**	**0.471**	**0.283**	
	(0.055) *0.000*	(1.085) *0.4342*	(0.053) *0.000*	
Standard deviation of error term	**0.117**	**0.082**	**0.117**	**0.087**
	(0.007) *0.000*	(0.013) *0.000*	(0.007) *0.000*	(0.008) *0.000*
Speed (K)	**1.469**		**1.231**	
	(0.969) *0.130*		(0.466) *0.008*	
Switching date (λ)	**225.711**		**226.136**	
	(0.960) *0.000*		(0.504) *0.000*	
Log likelihood	**114.887**		**112.643**	

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

Chi-squared test of implied restrictions yields p-value of 0.344

Figure 1: SPF Data and Interpolated Data, Inflation forecasts

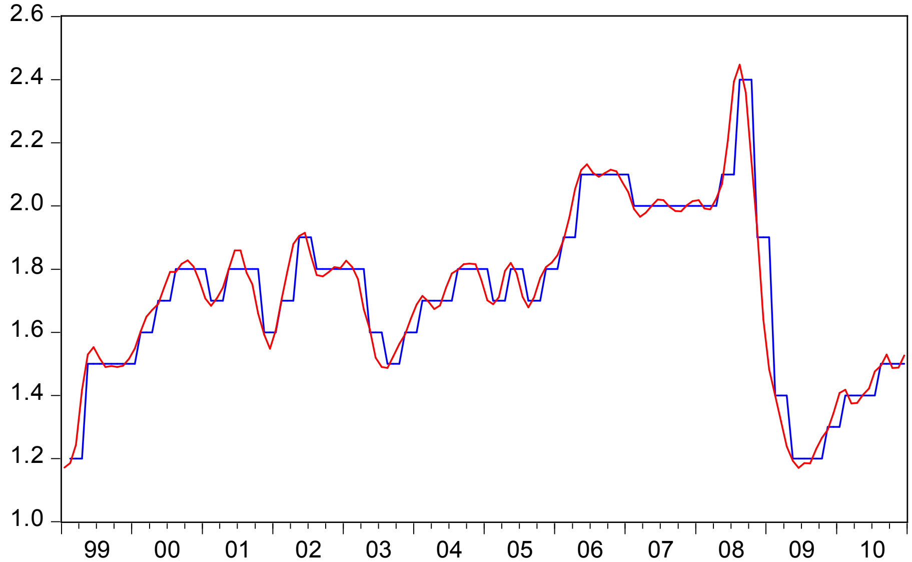


Figure 2: SPF Data and Interpolated Data, real GDP Growth forecasts

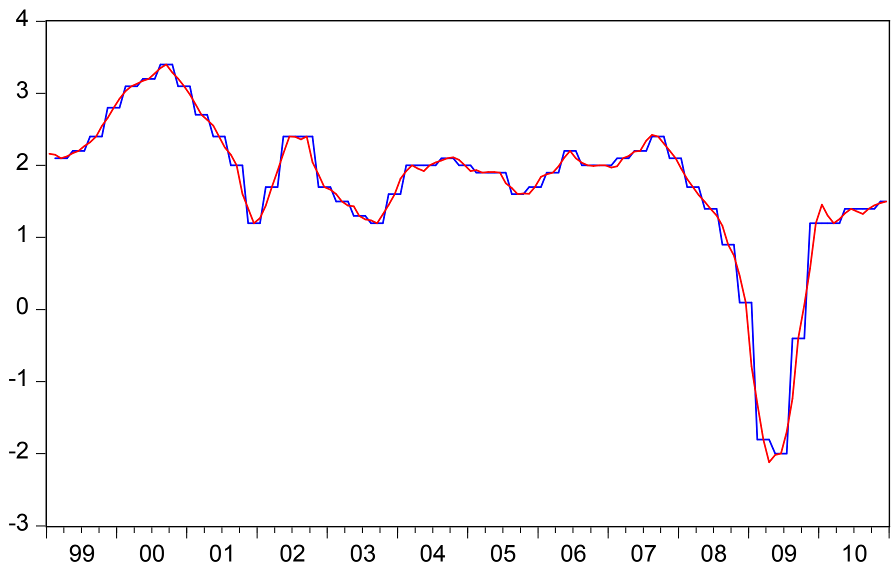


Figure 3: Estimated Weighting Function and 95% confidence band

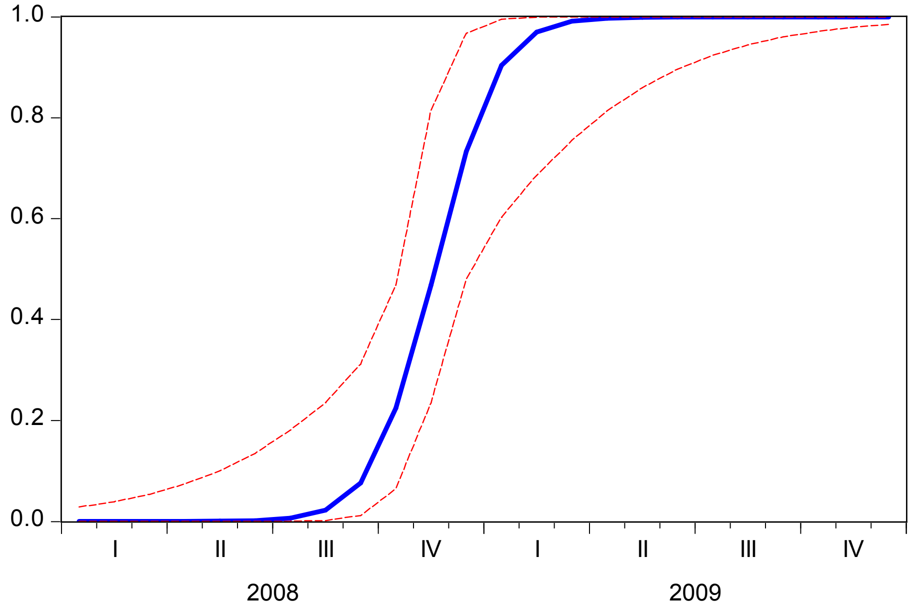


Figure 4: Log Likelihood for Discrete Breaks

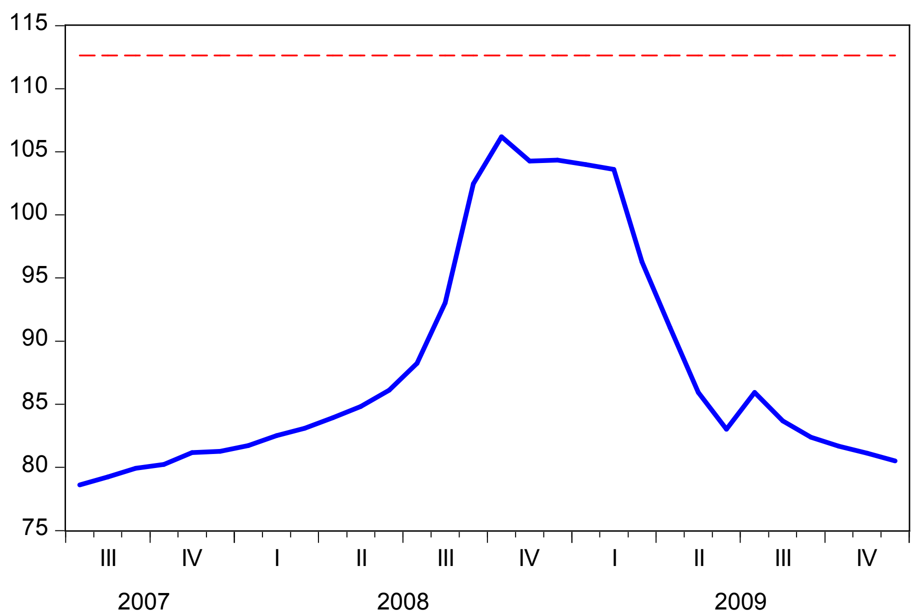


Figure 5: Target Interest Rate with 95% confidence band

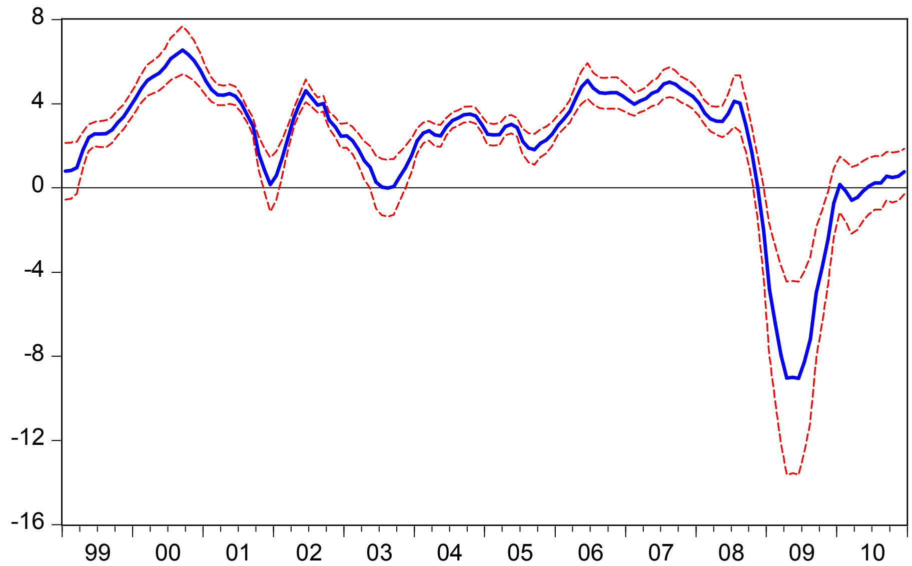
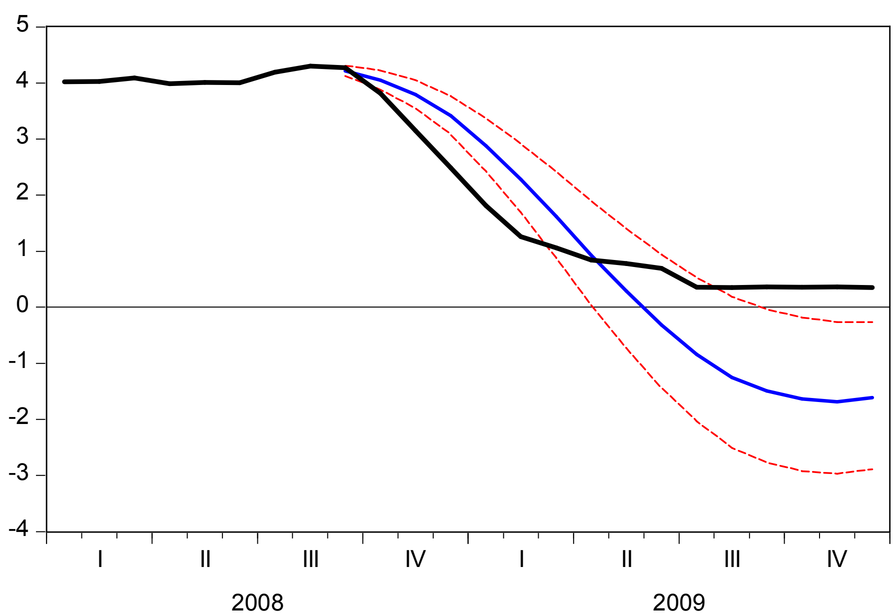


Figure 6: Dynamic out-of-sample forecasts starting in September 2008



Appendix (not for publication)

Appendix 1: Alternative Switches

	Benchmark (“restricted” from table 1)		**A. Reaction to Economic Variables Unchanged**		**B. Single regime:**	**C: Discrete break in November 2008**	
Regime	**Pre-crisis**	**Crisis**	**Pre-crisis**	**Crisis**		**Pre-crisis**	**Crisis**
Constant	**-0.610**	**0.131**	-0.301		-0.093	-0.608	0.140
	(0.097) *0.000*	(0.037) *0.000*	**(0.106) *0.010***		**(0.047) *0.05***	**(0.105) *0.000***	**(0.041) *0.001***
Lagged int	**0.935**	**0.678**	0.972		0.935	0.884	0.662
rate	(0.015) *0.000*	(0.039) *0.000*	**(0.014) *0.000***		**(0.017) *0.000***	**(0.020) *0.000***	**(0.057) *0.000***
Expected GDP	**0.153**		**0.044**		0.044	0.227	
Growth	(0.026) *0.000*		(0.013) *0.001*		**(0.039) *0.259***	**(0.019) *0.000***	
Expected	**0.283**		**0.174**		0.104	0.263	
Inflation	(0.053) *0.000*		(0.064) *0.006*		**(0.010) *0.000***	**(0.053) *0.000***	
s.d. of error	**0.117**	**0.087**	**0.128**	0.096	0.143	0.110	0.085
term	(0.007) *0.000*	(0.008) *0.000*	(0.006) *0.000*	**(0.020) *0.00***	**(0.008) *0.000***	**(0.008) *0.000***	**(0.008) *0.000***
Speed (K)	**1.231**		**1.983**			100	
	(0.466) *0.008*		(1.806) *0.272*			[imposed]	
Switching	**226.136**		225.031			225.5	
date (λ)	(0.504) *0.000*		**(0.514) *0.000***			[imposed]	
Log Lik’hood	**112.643**		97.325		75.283	108.698	
Post Odds			**0.000**				
Log L Test					**0.000**	**0.019**	

Notes: p-value,s in italics; Blank cell indicates a coefficient restricted to zero; coefficient in the middle of a column indicates common coefficient in first and second periods

Posterior Odds shows posterior odds ratio against benchmark (non-nested models) *Log L Test* shows likelihood ratio test of implied restriction

Appendix 2: Results Using Raw SPF Data

Table A2: Maximum likelihood estimates

Sample period January 1999 –December 2010

	Unrestricted model		**Restricted model**	
Regime	**Pre-crisis**	**Crisis**	**Pre-crisis**	**Crisis**
Constant	**-0.578**	**-0.253**	**-0.577**	**0.140**
	(0.134) *0.000*	(0.648) *0.711*	(0.126) *0.000*	(0.039) *0.000*
Lagged interest rate	**0.937**	**0.556**	**0.937**	**0.662**
	(0.015) *0.000*	(0.259) *0.031*	(0.014) *0.000*	(0.052) *0.000*
Lagged change in interest rate	**-0.015**	**-0.009**		
	(0.089) *0.865*	(0.280) *0.865*		
Expected GDP Growth	**0.266**	**-0.016**	**0.148**	
	(0.068) *0.000*	(0.066) 0.806	(0.024) *0.000*	
Expected Inflation	**0.316**	**0.332**	**0.267**	
	(0.055) *0.000*	(0.584) *0.570*	(0.053) *0.000*	
Standard deviation of error term	**0.121**	**0.082**	**0.117**	**0.084**
	(0.007) *0.000*	(0.013) *0.000*	(0.066) *0.000*	(0.008) *0.000*
Speed (K)	**1.158**		**1.146**	
	(0.493) *0.019*		(0.379) *0.003*	
Switching date (λ)	**226.415**		**226.249**	
	(0.960) *0.000*		(0.504) *0.000*	
Log likelihood	**110.241**		**109.201**	

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

Chi-squared test of implied restrictions yields p-value of 0.72

Figure A1: Estimated Weighting Function and 95% confidence band, using SPF Raw Data

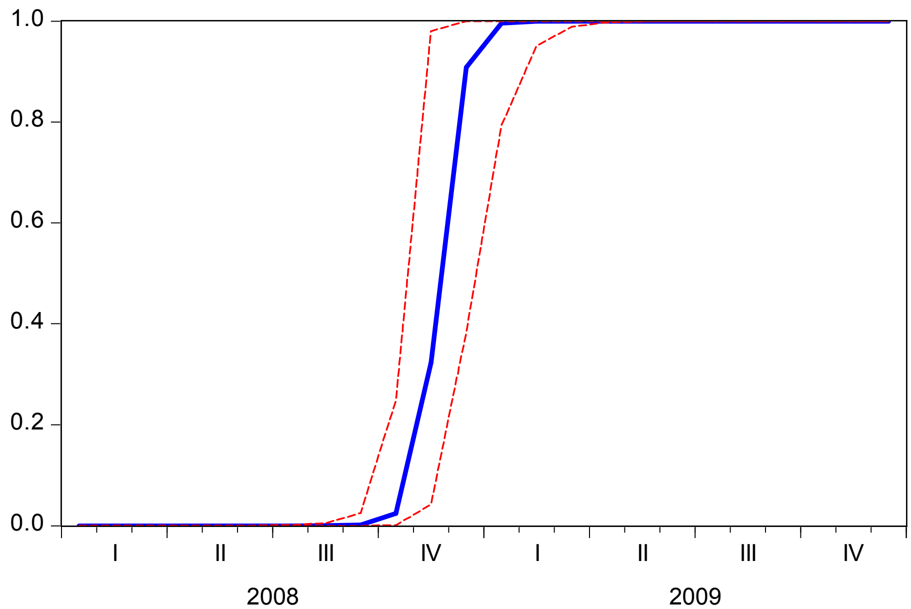


Figure A2: Discrete Break, using SPF Raw Data

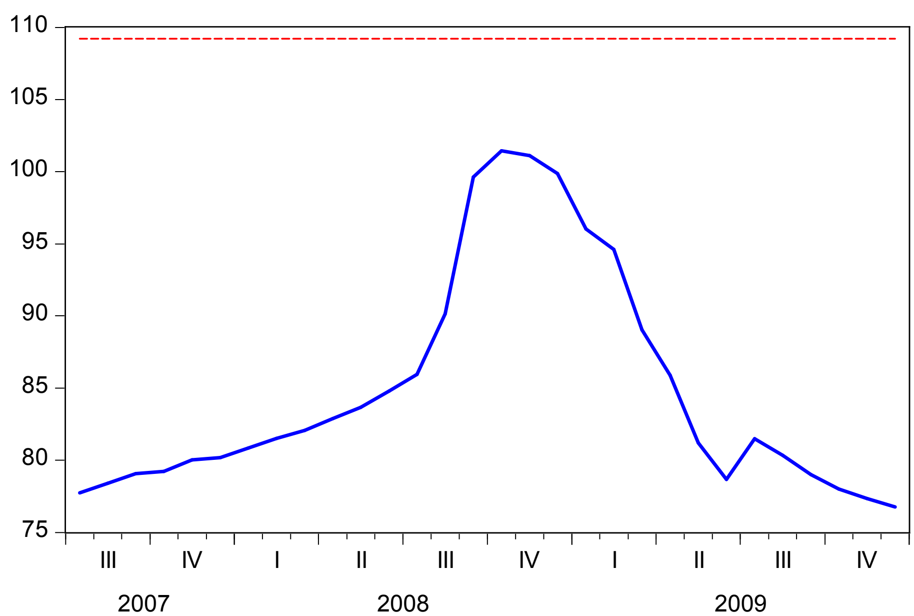


Figure A3: I target and confidence intervals, using Raw SPF Data

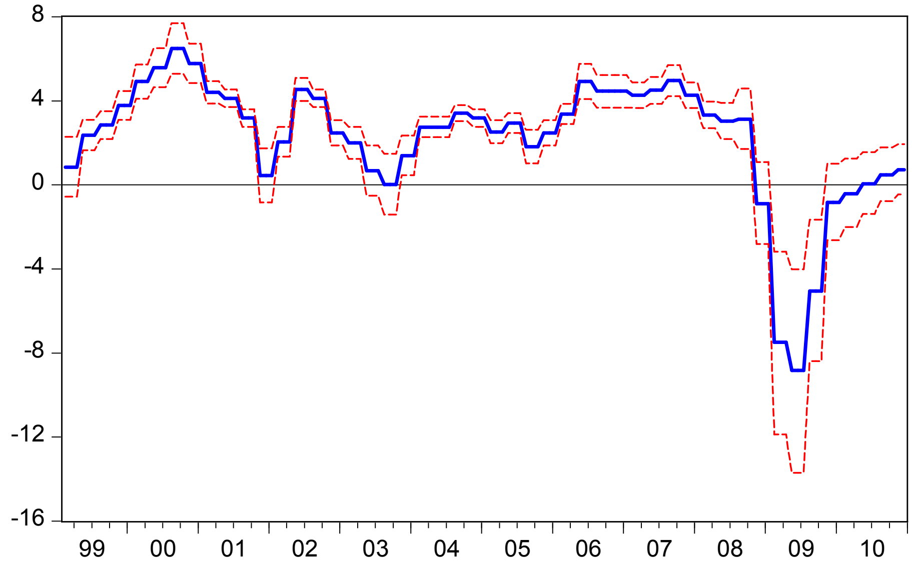


Figure A4: Out of Sample Forecasts, SPF Raw Data