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Evidence for the ECB and the Fed

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Modifying Taylor Reaction Functions in Presence of the Zero-Lower-Bound – Evidence for the ECB and the Fed*

by

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Abstract

We propose an alternative way of estimating Taylor reaction functions if the zero-lower-bound on nominal interest rates is binding. This approach relies on tackling the real rather than the nominal interest rate. So if the nominal rate is (close to) zero central banks can influence the inflation expectations via quantitative easing. The unobservable inflation expectations are estimated with a state-space model that additionally generates a time-varying series for the equilibrium real interest rate and the potential output - both needed for estimations of Taylor reaction functions. We test our approach for the ECB and the Fed within the recent crisis. We add other explanatory variables to this modified Taylor reaction function and show that there are substantial differences between the estimated reaction coefficients in the pre- and crisis era for both central banks. While the central banks on both sides of the Atlantic act less inertially, put a smaller weight on the inflation gap, money growth and the risk spread, the response to asset price inflation becomes more pronounced during the crisis. However, the central banks diverge in their response to the output gap and credit growth.

JEL code: E43, E52, E58

Keywords: zero-lower-bound, Federal Reserve, European Central Bank, equilibrium real interest rate, Taylor rule

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1. Introduction

The reaction of almost all central banks in industrialized countries to the financial crisis was cutting the policy rate aggressively. So also the US Federal Reserve (Fed) and the European Central Bank (ECB) reacted in this manner, although with a different speed. While the Fed cut rates immediately after the first signs of the financial crisis emerged, the ECB did not lower rates until the crisis intensified with the collapse of Lehman Brothers in late 2008. Moreover, the ECB did not lower the rates close to zero as the Fed. Instead it set its target rate to one percent. But this does not make much of a difference since the decisive variable is the interbank lending rate which is significantly lower and takes values closer to the rate of the deposit facility which is set 0.75 percentage points below the rate of the main refinancing operations. Thus, also the room to cut rates for the ECB is limited.

However, if nominal interest rates reach the lower bound of zero, traditional monetary policy which targets the interest rate can no longer be used.[1] Hence, in the recent financial crisis central banks had to find new ways of stimulating the economy. The programs implemented by central banks can be subsumed under the notion of unconventional monetary policy and they cover measures of quantitative and qualitative easing.[2] Using quantitative easing, central banks intend to influence inflation expectations and, by this, also the real interest rate which is generally considered to be the relevant rate for investment and consumption decisions. In this paper, we develop a model which takes this relationship explicitly into account. Moreover, our model generates a time series of potential output and the equilibrium real interest rate which are both time varying and thus needed to estimate Taylor reaction functions precisely. Strictly following McCulley and Toloui (2008) or Tucker (2008), we suspect that there is a break in the equilibrium real interest rate starting with the beginning of the crisis. Hence, holding this variable constant does not appear appropriate within the framework we apply here.

[1] Iwata and Wu (2006) show that the transmission channel between interest rates and output becomes nonlinear in such a situation.

[2] While quantitative easing refers to programs that expand the central bank's balance sheet, measures of qualitative easing cover a broader range of programs with the goal of e.g. increasing the range of collateral for central bank money or the maintenance period. Since measures of qualitative easing are hard to quantify in our framework, we will only use a measure of quantitative easing here.

The generated time series will be used in a second step to estimate whether there are significant differences in the reaction coefficients of the ECB and the Fed before and after the crisis begun as Gerlach (2011) suggests. Moreover, we check if other variables can explain the differences in the reactions of monetary policy before and after the crisis started. These additional variables in the spirit of Tucker (2008) are credit and money growth, an interest rate spread variable and (overall) asset price inflation, the latter being represented by stock and real estate price inflation.

The remainder of this paper proceeds as follows. In section 2 we provide our model that is used to estimate inflation expectations, the equilibrium real interest rate and the potential output. Section 3 explains the modifications needed to model the standard Taylor reaction functions properly in the recent financial crisis. Estimations of the accordingly modified Taylor reaction functions are presented in section 4. Section 5 concludes.

2. The equilibrium real interest rate and inflation expectations – construction and estimation

In this section we will explain how the time series of the equilibrium real interest rate and the inflation expectations are constructed. For this purpose we will merge two models. The first one is proposed by Laubach and Williams (2003) who estimated a state-space-model for the equilibrium real interest rate using quarterly data.[3] The second model developed by Klose (2011a) estimates a system of equations using a similar specification as Laubach and Williams (2003) but focuses on the estimation of inflation expectations. Moreover, the second model is developed using monthly data, which generates more data in the still short period of the recent financial crisis. We will also rely on this monthly specification but estimate a state-space-model with a time-varying equilibrium real interest rate as Laubach and Williams (2003) did.

To construct our model, we start with the formulation of inflation expectations which consist of observed inflation rates and a measure of quantitative easing. The natural candidate for this is the size of the central banks balance sheet. We use this measure but specify a so

[3] Several other papers have applied this model for various industrial countries. See Clark and Kozicki (2005), Trehan and Wu (2006) for the US, Wintr et al. (2005), Mesonnier and Renne (2007), Garnier and Wilhelmsen (2008) for the euro area and Larsen and McKeown (2004) for the UK.

called *balance sheet gap* being the deviation of the balance sheet from its "natural" level. The "natural" or equilibrium balance sheet is constructed by taking the end-of-month size of the balance sheet[4] for each month from 1996M6 to 2008M8 for the Fed and for each month from 1997M9 to 2008M8 for the ECB. The starting dates are chosen in an unbalanced way just according to the criterion of maximum data availability. It seems advisable to us to rely on the longest possible sample period in order not to bias our results by sticking to a shorter period which does not cover the overall trend. However, since the Fed balance sheet size evolved smoothly before the financial crisis started, our results are not influenced by our choice of the sample period. In case of the ECB, the starting date is chosen using balance sheet data provided in the monthly bulletins of the ECB. However, from 1997M9 to 1998M12 the ECB was not yet responsible for the balance sheet in the euro area. Hence, the ECB balance sheet variable employed by us is a combined measure of the balance sheets of the individual member countries for this short period. However, there is no indication of a break in the time series when the ECB took over responsibility as shown, for instance, by Klose (2011a).

2008M8 is chosen to be the end date for the construction of the equilibrium balance sheet because from 2008M9 on we find ample evidence of quantitative easing of the Fed and the ECB, so the balance sheet expands from its equilibrium value from this time onwards. The expansion of the balance sheet was more pronounced for the Fed since her balance sheet more than doubled immediately after quantitative easing was employed. This stronger response might be due to the fact that the Fed had at this point less room to cut rates any further since interest rates had already approached values of about two percent when quantitative easing started while the ECB interest rate still was at four percent. We estimate a linear trend for the period up to 2008M8 and treat it as the natural level of the balance sheet in our estimations. In order to calculate the balance sheet gap we subtract this measure from the true values for the whole sample period (thus also including data from 2008M9 onwards) using the following formula:

$$(1)\ b_t = 100(\log(balance_t) - \log(balance^T_{08\,08_t})),$$

[4] Since the end of month size of the balance sheet might be influenced by the minimum reserve requirements the financial institutions have to fulfill, we also checked whether there is a bias by comparing this measure to the average size of the balance sheet for each month. However, the results are not altered by this exercise, so we can conclude that there is no bias in taking the end-of-month values.

with b_t being the balance sheet gap, $balance_t$ representing the size of the balance sheet and ${balance^T_{08\,08}}_t$ as the respective trend value up to 2008M8.

We use the balance sheet gap to estimate inflation expectations which are formed as a weighted average of the current inflation rate and the rate of the preceding eleven months plus the balance sheet gap. So inflation expectations are defined as:

$$(2)\ \pi_t^e = \frac{1}{12}\sum_{i=0}^{11}\pi_{t-i} + c_b b_t,$$

with π_t^e as inflation expectations and π_t as the inflation rate. The coefficient c_b shows the impact of the balance sheet gap in the formation of inflation expectations. Our prior is that the coefficient has a positive sign, since an expanding (positive) balance sheet gap results in higher inflation expectations. The intuition behind this relationship is straightforward: central banks try to influence the real interest rate as the nominal rate is (close to) zero. This can only be achieved by changing inflation expectations, i.e. by increasing the latter in order to lower the real rate.

One way of influencing inflation expectations is to credibly commit to keeping nominal interest rates low, even when the crisis is over (Krugman et al. 1998, Eggertsson and Woodford 2003, Jung et al. 2005).[5] However, the Fed and the ECB need to "prove" that interest rates will remain low for a long time because the simple announcement of doing so would be subject to a time inconsistency problem. If market participants anticipate the latter, inflation expectations are not altered. Expanding the size of the balance sheet is one way to credibly commit to low interest rates because the balance sheet cannot be brought back to its equilibrium level immediately after the crisis. Hence, in the spirit of Friedman (1963), the additional funds issued by the Fed and the ECB during the crisis tend to trigger higher future inflation rates. What is more, it is a way of signaling that interest rates will remain low even when the crisis will be over, since the additional funds need to be withdrawn from markets before interest rates can be raised.[6]

[5] Other approaches to monetary policy at the zero lower bound suggest that taxing money holdings can be used to set the nominal rate below zero. See, for instance, Goodfriend (2000) or Ilgmann and Menner (2011). However, taxing money holdings cannot actually be observed in the recent crisis, so we feel legitimized to stick to our approach when it comes to analyzing the financial turmoil of 2007-2010.

[6] This argument is also advanced by Bernanke et al. (2004), p. 18.

One comment on the timing of events in equation (2) seems to be adequate at this stage of analysis. We assume that the market participants form their inflation expectations knowing the current inflation rate. Thus π_t is included in the equation. However, it might be possible that inflation expectations need to be formed before the current inflation rate becomes available. This is due to a real time problem in data collection (Orphanides 2001). Therefore, we also checked whether the exclusion of the current inflation rate significantly alters our results. But this is not the case.

We implement this type of inflation expectations formation into the model of Laubach and Williams (2003) instead of their assumption of rational expectations. So the state-space-model we estimate consists of the following signal and state equations:

$$(3)\ y_t - \bar{y}_t = b_{y_1}(y_{t-1} - \bar{y}_{t-1}) + b_{y_2}(y_{t-2} - \bar{y}_{t-2})$$
$$+\frac{b_{y_3}}{3}[(y_{t-3} - \bar{y}_{t-3}) + (y_{t-4} - \bar{y}_{t-4}) + (y_{t-5} - \bar{y}_{t-5})]$$
$$+\frac{b_{y_4}}{3}[(y_{t-6} - \bar{y}_{t-6}) + (y_{t-7} - \bar{y}_{t-7}) + (y_{t-8} - \bar{y}_{t-8})]$$
$$+\frac{b_{y_5}}{3}[(y_{t-9} - \bar{y}_{t-9}) + (y_{t-10} - \bar{y}_{t-10}) + (y_{t-11} - \bar{y}_{t-11})]$$
$$+\frac{b_r}{2}[(r_{t-1} - \bar{r}_{t-1}) + (r_{t-2} - \bar{r}_{t-2})] + \varepsilon_{1t}$$

$$(4)\ \pi_t = c_{\pi_1}\pi_{t-1} + c_{\pi_2}\pi_{t-2} + \frac{c_{\pi_3}}{3}(\pi_{t-3} + \pi_{t-4} + \pi_{t-5})$$
$$+\frac{1-c_{\pi_1}-c_{\pi_2}-c_{\pi_3}}{6}(\pi_{t-6} + \pi_{t-7} + \pi_{t-8} + \pi_{t-9} + \pi_{t-10} + \pi_{t-11}) + c_{\pi^i}(\pi_t^i - \pi_t)$$
$$+ c_{\pi^o}(\pi_{t-1}^o - \pi_{t-1}) + c_y(y_{t-1} - \bar{y}_{t-1}) + \varepsilon_{2t}$$

$$(5)\ \bar{y}_t = \bar{y}_{t-1} + \frac{g_{t-1}}{12} + \varepsilon_{3t}$$

$$(6)\ g_t = g_{t-1} + \varepsilon_{4t}$$

$$(7)\ z_t = z_{t-1} + \varepsilon_{5t}$$

$$(8)\ r_t = i_t - \pi_t^e$$

$$(9)\ \bar{r}_t = g_t + z_t,$$

where $y_t/\bar{y}_t$ stands for the output and its potential, $r_t/\bar{r}_t$ is the real interest rate and its equilibrium value, π_t^i represents the import price inflation while π_t^O displays oil price inflation, g_t is the annualized growth rate of potential output and z_t corresponds to additional factors that influence r_t such as the time preference of the consumers or the population growth rate. In this model, equations (3) and (4) represent the measurement or signal equations while (5) to (7) are the state equations. Equation (8) shows the Fisher equation in which we will insert our measure of inflation expectations as described in (2).

Equation (9) finally describes the construction of the equilibrium real interest rate which is essentially derived from the two random walk variables g_t and z_t in line with Laubach and Williams (2003).

In contrast to Laubach and Williams (2003), however, we rely on monthly data because monetary policy is conducted at least at a monthly frequency if not even more frequently as the current financial crisis shows.[7] Therefore, we strictly adopt the lag structure imposed by Klose (2011a) who throughout uses eleven lags of the output gap in the IS-equation (3) and of the inflation rate in the Phillips curve (4). Moreover, the first two lags of the real interest rate gap enter equation (3), assuming that they have equal weights. These lags are constructed in the fashion of Laubach and Williams (2003) with the additional feature that the real interest rate is estimated specifically by equation (8). In equation (4) we add the import and oil price inflation gap to absorb possible price shocks in these sectors.

Since the standard deviations of the trend growth rate g_t and z_t might be biased towards zero due to the so called *pile-up-problem*[8] (Stock 1994), we cannot estimate the above model in a straightforward fashion. Hence, we correct for this potential bias by using the median unbiased estimator as discussed by Stock and Watson (1998). What is more, we proceed in four steps, strictly in line with the suggestions of Laubach and Williams (2003). First, we estimate the signal equations separately by OLS using the Hodrick-Prescott-filter (Hodrick and Prescott 1997) to generate a series of potential output. In the IS-equation, we omit the real interest rate gap. As a second step, we use the Kalman-filter to estimate these signal equations, assuming that the trend growth rate is constant. Taking this as a starting point, we are able to compute the median unbiased estimate λ_g which is equal to $\frac{\sigma_4}{\sigma_3}$. We use this relationship in a third step and add the real interest rate gap to equation (3). We also relax our assumption of a constant trend growth rate.

With this, we can estimate equations (3) to (7), assuming that z_t is constant. g_t and z_t enter the IS-equation by inserting (9) in (3). Moreover, the real interest rate is represented by equations (2) and (8). With this specification we deviate from other studies which assume rational expectations of market participants which is an assumption hard to justify in times

[7] Since monthly data of real GDP are not available, this measure is proxied by industrial production which is commonly used to represent production in a monthly frequency.

[8] In our context, the pile-up-problem occurs since in Maximum Likelihood estimations the standard deviations of g_t and z_t are likely to be biased towards zero. The median unbiased estimator corrects for this.

of financial turmoil. Having estimated these equations, we compute the median unbiased estimator as $\lambda_z = \frac{\sigma_5}{\sigma_1} \cdot \frac{b_r}{\sqrt{2}}$. As a final step, we include this relationship in equation (7) and estimate the whole system by means of the Maximum Likelihood estimation method.

Table 1: *Estimates of the state-space-model*

	USA	euro-area
b_{y_1}	0.93 (0.29)	0.96 (0.15)
b_{y_2}	0.22 (0.62)	0.65 (0.32)
b_{y_3}	0.10 (0.49)	-0.91 (0.38)
b_{y_4}	-0.33 (0.21)	0.28 (0.26)
b_{y_5}	0.07 (0.10)	-0.07 (0.12)
b_r	-0.01 (0.02)	0.04 (0.05)
c_b	0.02 (0.10)	0.01 (0.06)
c_{π_1}	0.40 (0.04)	0.22 (0.11)
c_{π_2}	0.23 (0.05)	0.02 (0.10)
c_{π_3}	0.17 (0.04)	-0.04 (0.08)
$c_{\pi_4} = 1 - c_{\pi_1} - c_{\pi_2} - c_{\pi_3}$	0.20	0.80
c_{π^N}	-1.22 (0.04)	-0.11 (0.03)
c_{π^O}	0.00 (0.00)	0.01 (0.00)
c_y	0.11 (0.03)	0.24 (0.04)
λ_g	0.018	0.050
λ_z	0.013	0.013
σ_1	0.290	0.353
σ_2	0.117	0.147
σ_3	0.676	0.894
σ_4	0.012	0.045
σ_5	0.340	0.125
$log - likelihood$	-78.67	-173.63

Standard errors in parentheses.

The results for the US and the euro area are presented in Table 1. They show that there is indeed a positive influence of the balance sheet gap on inflation expectations.[9] With this we generate our time series of inflation expectations which are shown in Figure 1. All time series for the US start in mid-1997 because the lag structure of one year generates the first reliable estimates only after this lag. The same holds for the euro area but in this case the time series starts in 1998M9 due to the shorter sample period. Nevertheless, for both areas we dispose of a sufficiently long pre-crisis period.

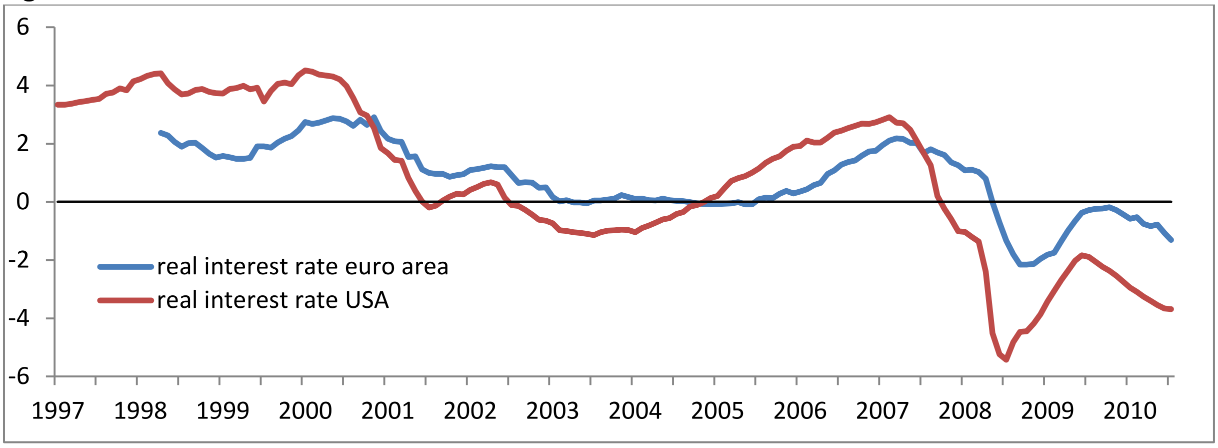
Figure 1: *Inflation expectations*

Notes: The inflation expectations are calculated using equation (2)

Figure 1 shows that inflation expectations remain firmly anchored at about two percent on both sides of the Atlantic until the end of 2007. Thereafter, they grew steadily until the end of 2008 where we observe a turning point in both time series. Inflation expectations then decreased until the beginning of 2010. But since actual rates have been rising almost continuously since 2010 and quantitative easing has not been reduced significantly, also inflation expectations started to increase again. So both time series exhibit the same trend within the financial crisis. However, as a stylized fact we observe that inflation expectations are always higher in the US than in the euro area in the crisis period. This might simply be due to the larger amount of additional funds issued by the Fed via quantitative easing compared to the ECB. But also the ECB has - according to its mandate - to monitor closely whether inflation expectations remain in a corridor that is acceptable, especially if we observe an ongoing increase in inflation rates. Moreover, the inflation expectations do deviate substantially from the realized inflation rates. Therefore, there is no endogeneity bias when adding these inflation expectations into Taylor reaction functions.

[9] However, we found a quite large standard errors in this coefficient. But this does not alter our analysis because we are only interested to find the most likely coefficient value which is given for the positive numbers in Table 1.

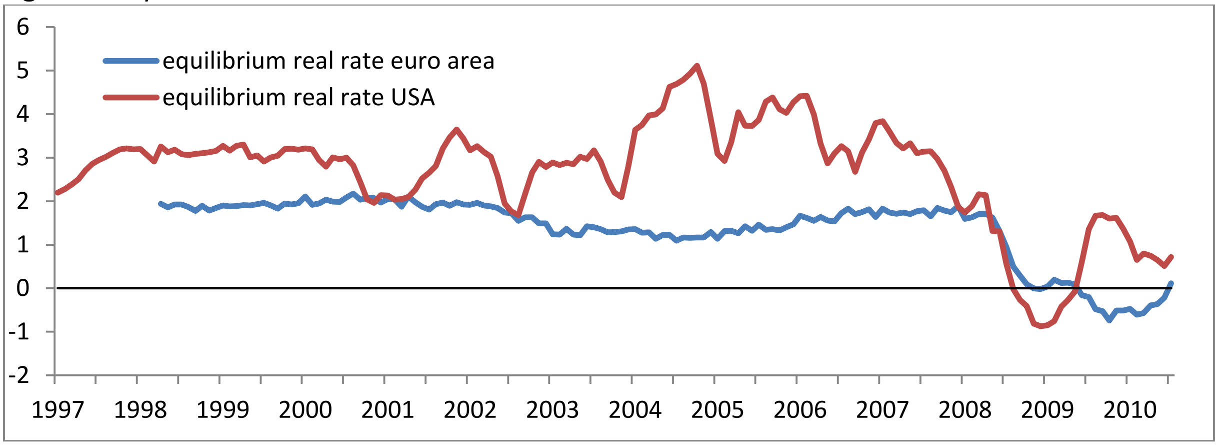
Figure 2: *Real interest rates*



Notes: The real interest rates are calculated using equation (8).

Inserting the inflation expectations into equation (2) yields the real interest rate whose empirical realizations are displayed in Figure 2. It reveals that the real interest rates in the US and the euro area moved almost in tandem with the US rate being more volatile than the euro area rate.

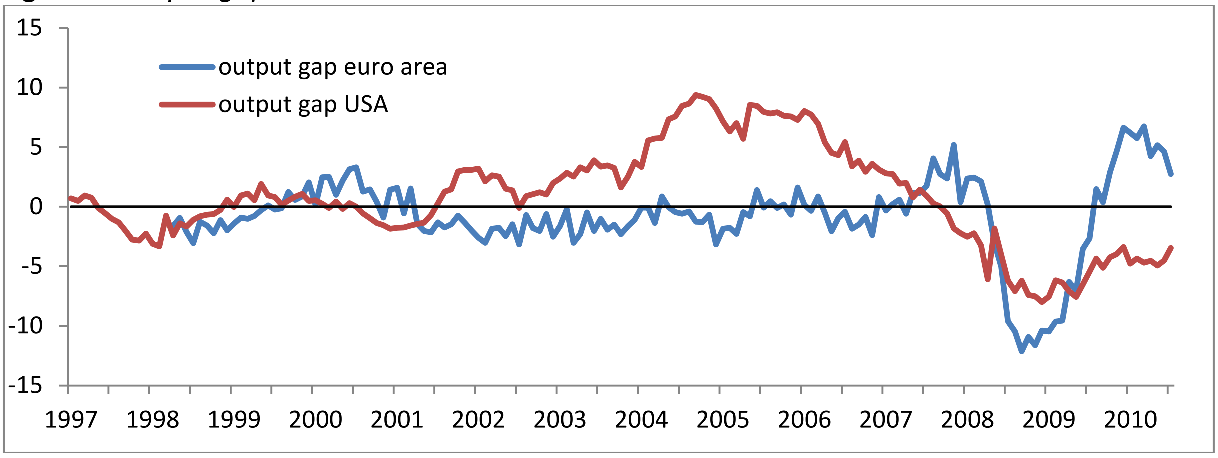
Figure 3: *Equilibrium real interest rates*



Notes: The equilibrium real interest rates are calculated using equation (9).

Nearly the same pattern turns out if we take a look at the equilibrium real rates as shown in Figure 3. The equilibrium rate in the euro area is firmly anchored at about two percent while the US equilibrium rate moves between two and five percent before the crisis started. During the crisis, a drop in the equilibrium real rate in the US and the euro area becomes visible. Indeed both equilibrium rates turn negative at least on some occasions within the crisis period. We interpret this as evidence that we can no longer employ the equilibrium real rate as a constant, but have to incorporate this measure explicitly as an additional variable in our Taylor reaction function estimations.

Figure 4: *Output gaps*



Finally, we also display the empirical realizations of the output gaps estimated by us according to our model in Figure 4. The figure reveals that the slowdown in the European economy in the wake of the financial crisis was even more pronounced than in the US but also that European output recovered much faster than US output.

3. Adjustment of Taylor reaction functions in the financial crisis

There are two general ways of adjusting Taylor reaction functions in order to fit them to the crisis period. First, we can adjust the Taylor rule itself, thus giving it another functional form but still sticking to the standard Taylor rule variables inflation and the output gap. We will do so to adjust for the zero lower bound of nominal interest rates which became binding in the crisis. Second, there might be other additional variables that describe much of the interest rate setting behavior of both central banks within the crisis. In order to avoid any omitted variable bias, these variables need to be added in one way or the other.

3.1. Adjusting the functional form of the Taylor Rule

A simple rule like the one proposed by Taylor (1993) is not applicable if nominal interest rates approach the zero- lower-bound, since the dependent variable can no longer be chosen freely. Therefore, the classical Taylor reaction function has to be modified for our purposes. This is done by focusing at the equilibrium nominal interest rate $\bar{\imath}_t$. This variable can be divided into the equilibrium real interest rate $\bar{r}_t$ and inflation expectations π_t^e. Quite surprisingly, the inflation expectations have played a minor role in Taylor rule estimates up to date. In principle, there are two ways of dealing with this issue. The first one (assumed in the classical Taylor rule) is introducing static expectations so that $\pi_t^e = \pi_t$.[10] This leads us directly to the Taylor principle which requires a reaction coefficient for inflation larger than unity in order to raise the nominal interest rate by more than the inflation rate if it is increasing, a so-called "leaning against the wind policy" of central banks. In the second specification π_t^e is set equal to the inflation target π^* (Clarida et al. 1999). The rationale for this choice is the assumption that the central bank is always able to bring expectations in line with its inflation target. However, this seems to be unlikely in a crisis period because credible announcements of central banks have to be "proven" in crisis times more than ever by complementary actions. Our approach does not make use of the assumptions pointed out above but uses the explicit measure of inflation expectations estimated with the state-space-model in section 2.

$$(10) \qquad i_t = \bar{r}_t + \pi_t^e + a_\pi(\pi_t - \pi^*) + a_y(y_t - \bar{y}_t)$$

By simply re-arranging the Taylor rule using the Fisher equation (8) the dependent variable is no longer the nominal but the real interest rate which is not bound to zero and which was in fact negative in some crisis months:

$$(11) \qquad r_t = \bar{r}_t + a_\pi(\pi_t - \pi^*) + a_y(y_t - \bar{y}_t)$$

Some comments on this modified Taylor rule seem to be indicated. First, the Taylor principle is now no longer fulfilled for an inflation coefficient of above unity because central banks now explicitly influence the real and not the nominal rate which is effectively zero within the crisis. So, just in order to fulfill the Taylor principle, the coefficient of the inflation gap has to be positive, meaning that the real rate rises if inflation increases.

Second, the Fed has not announced an explicit inflation target π^* as other central banks have done. This might be a problem in our estimations if the inflation target is supposed to be time varying as Leigh (2008) suggests. We do not account for adjustments in the inflation target of the Fed but argue instead that the long-run inflation target is fixed but short-run deviations from this target, for instance to influence inflation expectations, are accepted by the Fed. Moreover, fixing the inflation target makes results comparable to those of the ECB since the ECB has announced an explicit inflation target of close to but still below two

[10] We abstract here from forward-looking Taylor rules (Clarida et al. 2000) which in fact use mainly rational expectations forecasts (Gerdesmeier and Roffia 2004, Sauer and Sturm 2007).

percent in the medium term.[11] So for both central banks we will assume an inflation target of two percent in line with the announcement of the ECB and the suggestion of Taylor (1993). Concerning the other variable that was originally set constant, i.e. the equilibrium real interest rate, we have shown in section 2 that this does no longer correspond with the facts in the recent crisis. So we use the time series generated by us in the same section as our time-varying measure. Using a time-varying equilibrium real interest rate is rather novel in the context of Taylor reaction function estimates. However, this comes quite as a surprise since there is a large strand of literature available which is explicitly dealing with variations of this variable over time.[12]

Third, as in the case of the classical Taylor rule, the policy rate of the central banks might be subject to a substantial degree of interest rate smoothing. In the classical Taylor reaction function this is applied by adding the lagged nominal interest rate to the equation (10). However, we need to add the real instead of the nominal interest rate to equation (11) because the dependent variable has changed. So the modified Taylor reaction function including interest rate smoothing turns to:

$$(12) \qquad r_t = \rho \cdot r_{t-1} + (1-\rho) \cdot \left[\bar{r}_t + a_\pi(\pi_t - \pi^*) + a_y(y_t - \bar{y}_t)\right].$$

Using an interest-smoothing term we are able to show whether the central banks react only to the fundamentals of the Taylor rule (ρ equal to 0) or do not target those variables at all (ρ equal to 1). However, reasonable results should lie somewhere in between 0 and 1. Using a smoothing parameter we can test the “Mishkin principle”, i.e. that central banks react less inertially during a crisis (Mishkin 2008 and 2009). Evidence of the latter is given if the smoothing parameter drops significantly as soon as the financial crisis is included in the sample period.

3.2. Extending the Taylor rule

So far we have adjusted the functional form of the Taylor rule in a way that the zero lower bound of nominal interest rates is no longer binding. However, we have not yet adjusted the variables influencing the interest rate setting behavior of both central banks. But especially

[11] Blanchard et al. (2010) propose to increase the inflation target to dampen shocks. But up to date there is no announcement of central banks that they have adjusted their target rates according to this recommendation.
[12] See Bomfin (2001), Cuaresma et al. (2004), Arestis and Chortareas (2007) and Horváth (2009) for other models of a time varying equilibrium real interest rate.

within the current crisis there seems to be evidence that the ECB and the Fed do not only adjust their policies as a reaction to changes in the inflation rate and output gap but do also take other variables into account. We identify four groups of variables which might be of higher or lower interest in this period.[13][14]

The first one corresponds to the monetarist view that inflation is always and everywhere a monetary phenomenon (Friedman, 1963). Therefore, money growth is an indicator for future inflationary pressure. Therefore, we expand the reaction function by adding the growth of a target monetary aggregate which is M2 in case of the US and M3 in case of the ECB. In case we find these leading indicator properties the sign of the corresponding coefficients should be positive. Due to the fact that we expect the role of inflation to have diminished in the financial, this holds also for money growth. This is because high rates of money growth are no problem as long as inflationary pressures are not picking up.

As a second extension we add variables of credit growth, because we want to test for the hypothesis that a credit crunch or credit rationing occurred during the financial crisis.[15] A credit crunch/rationing is a scenario in which commercial banks cut the amount lent to individuals. We suspect that in the value of collateral decrease and the equity of the banks diminished with the decline in asset prices. Since the capital markets are linked with the real economy via the amount of credit offered, central banks try to overcome this shortage by endowing the banks with more liquidity so that they could again increase the amount of credit and, by this, promote investment and consumption. This implies lowering policy rates or expanding the central bank’s balance sheet, thus pouring additional money into the market to make credit lending work again.

Therefore, the estimated coefficient should increase in the crisis era. In order to check whether this fits with US and euro area data, we estimate Taylor reaction functions using

[13] Due to the choice of a contemporaneous Taylor rule specification there is no endogeneity bias in our estimates since the additional variables as also the inflation rate and output gap are influenced by the interest rate with a lag of more than one month. The endogeneity problem is only present when taking a forward looking Taylor reaction function with rational expectations because here the exogeneous variables are clearly influenced by the current setting of the interest rates.

[14] The list draws on the results found by Belke and Klose (2010).

[15] See Borio and Lowe (2004) for a discussion on the role of credit before the subprime crisis. Christiano et al. (2008) and Curdia and Woodford (2009) show that adding an aggregate credit variable tends to improve the goodness-of-fit of Taylor rule estimates.

two different credit measures. First, the overall credit supplied by banks. Second, we insert real estate credit because the financial crisis had its roots in the housing sector.

Increased risk in capital markets and the associated change in the equilibrium interest rate are accounted for by the third group of variables, the interest rate spreads.[16] During the current crisis the focus in this context switched towards the Libor/overnight indexed swap (OIS) spread.[17] Unfortunately this spread displayed only little variation before the financial crisis so that the coefficients are estimated imprecisely. So we have to use another measure.

This interest rate spread is found in the long-term/short-term spread because it exhibits sufficient variation before and after the crisis started. As a proxy of the short-term rate we prefer to use the 3-month rate. The long-run rate is the interest rate on ten-year treasury/governmental securities. Rising spreads signal rising risk within the capital market for long-term credits which are more important for investment decisions than short term rates. Central banks are expected to lower interest rates in response to a rise in the interest rate spread, the estimated coefficient should be negative (Tucker 2008). In addition, we should expect an even stronger monetary policy reaction throughout the ongoing crisis, since reducing the risk in the markets have explicitly been addressed by the authorities as a main goal of both the Fed and the ECB policy.[18]

The fourth and last group takes asset price inflation into account.[19] We focus on the two main asset classes, i.e. housing and stocks. Housing prices are included because the crisis had its roots in the US housing sector. Possible explanations for the influence of house prices on the central bank decision are twofold. First, there should be wealth effects associated with the house owners. Second, and surely more pronounced in the financial crisis, the value of the collateral is decreasing as house prices fall. Therefore, higher rates have to be paid to get a mortgage and credit falls. However, central banks should react to both channels by

[16] See Martin and Milas (2010) for a survey of the usefulness of applying interest rate spreads for an assessment of optimal monetary policy in the UK during the subprime crisis.
[17] See, for instance, Taylor (2008), Armatier et al. (2008) and Michaud and Upper (2008).
[18] See, for instance, Bernanke (2008) and Mishkin (2009) for the US and Trichet (2009) referring to the ECB.
[19] The debate about whether a central bank should respond to asset price changes is all but new. See, for instance, Bordo and Jeanne (2002), Cecchetti (2003), Detken and Smets (2004), Gruen et al. (2005), de Grauwe et al. (2008), Ahrend et al. (2008) or Botzen and Marey (2010). For a judgment of ECB representatives concerning the role of asset prices see Stark (2009). Cuaresma and Gnan (2008) apply stock price indices as measures of financial instability within Taylor rule estimations for the Fed and the ECB and a “pre-crisis” sample period.

decreasing the policy rate or increasing inflation expectations, so the sign of these coefficients should be positive and should have increased in the crisis period.

For stock prices there are also a wealth and collateral effects as in the case of house prices. Additionally, there is an effect on the companies issuing stock according to Tobin's q (Tobin 1969) which relates the market capitalization of a firm to its replacement costs. If the market capitalization expressed by the cumulative value of stock falls in response to a drop in stock prices, q falls and a firm would thus cut investment. But central banks should respond to this in the same vein as for the other two effects, by lowering the interest rate or increasing the inflation expectations. So we again expect a positive coefficient of this variable in estimates of the Taylor reaction function. Additionally, we expect the influence of this parameter to have increased in the crisis because it is more likely that the Fed and the ECB react more aggressively to a sharp downturn in stock prices than to a steady increase. However, in the case of the ECB, the effects should be less pronounced since financing of the firms in mainly done by receiving credit and much less via the capital market (Stark 2009).

4. Empirical evidence on modified Taylor reaction functions

In this section we present the results of our estimations of the Taylor reaction functions for the ECB and the Fed. Our aim is to verify whether there are significant differences in the reaction coefficients before and after the crisis started. Therefore, we need to find a specification that enables us to do so.

4.1. Estimation issues

In order to assess empirically whether there are significant differences in the pre- and crisis era we use a heaviside indicator as it is commonly done when estimating asymmetric Taylor reaction functions (see e.g. Bec et al. 2002, Bunzel and Enders 2010 or Klose 2011b). Accordingly, we divide the sample by this indicator. As a starting point of the crisis and thus the expected change in central bank policy, we have chosen August 2007.[20] So the equation to be estimated runs as follows:

[20] See, for instance, Cecchetti (2008) pp. 12-17 and Taylor and Williams (2009) p. 60. For a detailed schedule of what happened around that time and the decisions made by the most important central banks as a reaction to these events see Bank for International Settlements (2008) pp. 56-74. While this breakpoint is chosen exogenously it proofed that relying on endogenously determined breakpoints generates a problem because those differ considerably depending on the chosen variable.

$$(13) \qquad r_t = \begin{Bmatrix} \rho_B \cdot r_{t-1} + (1-\rho_B) \cdot \left[\bar{r}_t + a_{\pi_B}(\pi_t - \pi^*) + a_{y_B}(y_t - \bar{y}_t)\right]^{if\ t<2007M8} \\ \rho_A \cdot r_{t-1} + (1-\rho_A) \cdot \left[\bar{r}_t + a_{\pi_A}(\pi_t - \pi^*) + a_{y_A}(y_t - \bar{y}_t)\right]^{if\ t\geq 2007m8} \end{Bmatrix} + \varepsilon_t$$

Here the indices B and A stand for data "Before" and "After" the crisis started. Note that we do not add a constant to the modified Taylor reaction function (13) since all parameters influencing the constant, i.e. the equilibrium real interest rate and the inflation target, are explicitly modeled in our equation.

Equation (13) is estimated using GMM for the ECB and the Fed. This procedure appears highly adequate for our purposes because at the time of its interest rate setting decision, the central banks cannot observe the ex-post realized right hand side variables. That is why the central banks have to base their decisions on lagged values only (Belke and Polleit 2007). We decided to use the first twelve lags of inflation and the output gap and - whenever it is added to the regression equation - the first twelve lags of the "additional" variable as instruments. Moreover, we perform a J-test to test for the validity of over-identifying restrictions to check for the appropriateness of our selected set of instruments. As the relevant weighting matrix we choose, as usual, the heteroskedasticity and autocorrelation consistent HAC matrix by Newey and West (1987).

As a consistent procedure to incorporate the additional variables we decided to add those one-by-one to equation (13). These additional variables are: Money growth of M2 or M3 (M), year-on-year overall credit growth (CR) or real estate credit growth (CR HOUSE), the interest rate gap (I), house price inflation (HP) and stock price inflation (S). If the differences in the additional variables are found to be significant,[21] this measure is used in a second step with all other significantly different estimated additional variables in order to exclude possible interactions between the additional variables. We checked whether there are problems concerning multicollinearity when we apply such a procedure with the help of the variance inflation factor. However, except for the use of both credit growth measures in one estimation equation, there is no multicollinearity problem in our estimates. Therefore, we always include only one credit growth measure in the estimation of the significant additional variables.

[21] Significant differences between "Before" and "After" lagged interest rates, inflation rates, output gaps and additional variables are identified using Wald-tests.

4.2. Estimation results

In this section we derive the results of our analysis for the ECB and the Fed. We will look separately at both central banks to clearly reveal possible different reactions to the variables.

4.2.1. The ECB Taylor reaction function

Starting with the ECB, we present the results of the modified Taylor reaction function and its extensions in Table 2. Comparing the reaction coefficients before and after the crisis started leads in the modified version (column 2.1) to the result that the interest rate smoothing of the ECB decreases within the crisis. This is consistent with the Mishkin principle that central banks react more actively during a financial turmoil. The finding of a lower interest rate smoothing term in the period after 2007M7 is almost consistently found across all specifications. The only exception emerges when adding credit growth in the housing sector as an additional variable (column 2.4), where the reverse is true. However, this is the only case where we find no significant difference in the smoothing coefficients before and after the crisis started, as Table 2a reveals.

Turning to the reaction to inflation or more precisely the inflation gap when no additional variables are added (column 2.1), we find that the reaction seems to be decreasing. Moreover, within the crisis the ECB reacts even significantly negatively towards the inflation gap which means that the Taylor-principle is no longer fulfilled. However, this finding makes sense since the inflation rate might be less for the ECB in the crisis period because stabilizing the economy was the main goal, which is also supported by the studies of Gorter et al. (2009) or Klose (2011a). But we are unable to find a significant decrease in the inflation coefficient of the modified Taylor reaction function as Table 2a column 2.1 shows. A significantly lower coefficient can only be found when adding additional variables where we find a significant decrease in the inflation response in all but one case (column 2.7) for which the difference is again insignificant.

With respect to the output gap response we find in all cases a more moderate reaction which in contrast to the inflation reaction remains positive within the crisis. The differences between the pre- and crisis reaction are with one exception (column 2.5) found to be significant. Even though this result is also found by Gorter et al. (2009) and Klose (2011a) it is not what we would have expected. This is because stabilizing the economy and, expressed equivalently, the output gap was surely in the focus of the ECB. However, because of the substantial lag of the impact of monetary policy on the business cycle, the ECB does not seem to make use of this measure actively but relies on other determinants of possible future output growth. The estimated ECB's reaction to changes in these additional variables will be interpreted in the following.

Table 2: *Taylor reaction function estimates - The ECB case*

	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8
ρ_B	0.82***	0.86***	0.86***	0.59***	0.68***	0.69***	0.93***	0.66***
	(0.12)	(0.03)	(0.03)	(0.05)	(0.05)	(0.03)	(0.03)	(0.01)
a_{π_B}	3.21	4.76***	2.06***	1.21***	2.06***	0.50**	-0.77	0.52***
	(2.52)	(1.35)	(0.77)	(0.20)	(0.39)	(0.20)	(0.64)	(0.00)
a_{Y_B}	2.00*	0.80***	1.17***	0.21***	0.23***	0.30***	4.15***	0.25***
	(1.09)	(0.21)	(0.30)	(0.04)	(0.07)	(0.08)	(1.56)	(0.01)
a_{M_B}		-0.48***						0.00
		(0.11)						(0.01)
a_{CR_B}			-0.38***					0.11***
			(0.07)					(0.01)
$a_{CR\ House_B}$				-0.17***				
				(0.01)				
a_{I_B}					-1.16***			0.05***
					(0.14)			(0.02)
a_{HP_B}						-0.23***		-0.28***
						(0.02)		(0.01)
a_{S_B}							-0.08***	-0.01***
							(0.02)	(0.00)
ρ_A	0.57***	0.67***	0.62***	0.64***	0.09	0.50***	0.28***	0.56***
	(0.03)	(0.02)	(0.01)	(0.02)	(0.06)	(0.01)	(0.01)	(0.01)
a_{π_A}	-0.57***	-1.05***	-1.03***	-0.97***	-0.56***	-0.22***	0.00	-0.15***
	(0.08)	(0.15)	(0.14)	(0.08)	(0.03)	(0.05)	(0.02)	(0.01)
a_{Y_A}	0.11***	0.19***	0.20***	0.11***	0.14***	-0.04	0.04***	0.07***
	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.02)	(0.00)	(0.00)
a_{M_A}		0.19***						-0.08***
		(0.03)						(0.01)
a_{CR_A}			0.14***					0.14***
			(0.02)					(0.01)
$a_{CR\ House_A}$				0.14***				
				(0.03)				
a_{I_A}					-0.51***			0.32***
					(0.04)			(0.01)
a_{HP_A}						0.17***		-0.15***
						(0.04)		(0.01)
a_{S_A}							0.02***	0.03***
							(0.00)	(0.00)
$adj.R^2$	0.86	0.86	0.84	0.87	0.86	0.86	0.93	0.95
$J-Stat$	0.17	0.18	0.18	0.18	0.19	0.19	0.19	0.20
	(0.89)	(1.00)	(1.00)	(1.00)	(1.00)	(1.00)	(1.00)	(1.00)

Notes: GMM estimates, */**/*** denotes significance at the 10%/5%/1% level, standard errors in parentheses, for the J-statistic we put the p-value in parentheses, sample period: 2000M9-2010M12.

Column 2.2 adds as an additional variable the growth rate of the monetary aggregate M3. We do not find a leading indicator function of money growth to future inflation in the pre-crisis era as the coefficient is significantly negative. So we find a significant increase in the reaction to money growth in the crisis period. However, if we add all significantly different estimated additional variables in column 2.8, we find indeed a significant decrease in the reaction to money growth. So money growth seems to be influenced by other additional variables and the reaction changes if these are also explicitly taken into account.

The credit growth measures in columns 2.3 and 2.4 show a significantly negative reaction before the crisis started which turns significantly positive within the crisis. So we identify in both cases a significant increase in the reaction coefficient, an empirical pattern which is also supported when adding all significantly different variables in column 2.8.[22] From these results we can derive that the ECB classifies the reduced credit growth within the crisis as a credit crunch rather than credit rationing. In the former case a decrease in the (real) interest rate is consistent with a decline in credit growth, while in the latter the reverse is true. This finding is also supported by the quotation of ECB-president Trichet (2009) that “results do not point to a severe rationing of credit, although […] surveys of banks indicate that credit standards have been tightened”. The negative coefficients in the pre-crisis era indicate that the ECB even triggered credit growth by lowering the interest rate when credit growth is expanding which in the end has lead to the crisis.

Table 2a: *Wald-tests of significant differences in pre- and post-crisis coefficients – The ECB case*

	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8
$\rho_B = \rho_A$	3.73* (0.06)	21.66*** (0.00)	58.51*** (0.00)	0.68 (0.42)	54.38*** (0.00)	29.06*** (0.00)	521.41*** (0.00)	196.85*** (0.00)
$a_{\pi_B} = a_{\pi_A}$	2.27 (0.13)	18.00*** (0.00)	15.75*** (0.00)	93.13*** (0.00)	44.03*** (0.00)	12.81*** (0.00)	1.45 (0.23)	241.09*** (0.00)
$a_{Y_B} = a_{Y_A}$	2.98* (0.09)	8.30*** (0.00)	10.63*** (0.00)	5.33** (0.02)	1.54 (0.22)	14.53*** (0.00)	6.93*** (0.01)	750.69*** (0.00)
$a_{M_B} = a_{M_A}$		35.69*** (0.00)						67.20*** (0.00)
$a_{CR_B} = a_{CR_A}$			56.26*** (0.00)					12.52*** (0.00)
$a_{CR\ House_B} = a_{CR\ House_A}$				130.18*** (0.00)				
$a_{I_B} = a_{I_A}$					19.16*** (0.00)			188.53*** (0.00)
$a_{HP_B} = a_{HP_A}$						103.13*** (0.00)		144.66*** (0.00)
$a_{S_B} = a_{S_A}$							20.53*** (0.00)	7621.8*** (0.00)

Notes: Wald-tests based on the results of Table 2, */**/*** denotes significance at the 10%/5%/1% level, p-value in parentheses.

[22] Here we only include overall credit growth, even though both differences of the credit measures are found to be significant. But adding both measures would lead to a multicollinearity problem in our setting.

Concerning the interest rate gap reaction (column 2.5) we find a negative coefficient, which means that the ECB in fact reacts to increased risk spreads by reducing the interest rate. This reaction turns out to be significantly lower during the crisis period, i.e. the ECB does not react as strong as before to this measure. The same pattern emerges when adding all significantly different additional variables. However, in that case, the estimated reaction coefficients are positive.

The two asset price classes, house and stock prices (columns 2.6 and 2.7), exhibit the same tendencies. The ECB reacted negative to both measures before the crisis started, which means that further increases of asset price inflation were even fuelled by the ECB. In contrast to that in the downturn of asset prices as observed in the recent crisis, asset price inflation is tackled actively, thus the reaction coefficients are positive. So we again find significant differences in the coefficients of the additional variables in the pre- and post-crisis era.

4.2.2. The Fed Taylor reaction function

After having estimated the reaction coefficients for the ECB and having come up with substantial differences between the pre- and crisis era, we follow the same procedure for the Fed in order to check for differences in its reaction before and after the crisis started (Tables 3 and 3a) and possible diverging policies of the two central banks.

As in the case of the ECB we find for the Fed a reduced interest rate smoothing coefficient during the crisis. Here in fact all specifications point to a significantly lower degree of monetary policy inertia which also supports the Mishkin principle.

The response to the inflation gap is also decreasing during the crisis period. Except for the columns 3.3 and 3.4 we find for all specifications a significant lower response after 2007M7. As in the case of the ECB, the reaction coefficients to the inflation gap turn even negative. Thus, there is no evidence that the Fed does fight inflation actively during the crisis. This is no problem as long as inflation rates remain firmly anchored at about two percent. However, the Fed as also the ECB should put at least positive weight on the inflation gap as soon as the inflation rate starts to diverge from the inflation target. There are clear hints that the latter might happen, first because of the huge amount of quantitative easing and second because of rising commodity prices.

We find a consistently negative reaction of the Fed to the output gap. This result is somehow puzzling since the mandate of the Fed explicitly states that the Fed should promote maximum employment. But it becomes understandable when following the argumentation of Taylor (2010) concerning the great deviation. He argues that the Fed funds rate was too low from 2002-2005 according to the Taylor rule, thus triggering further output expansions. This is exactly what we observe in figure 4 where the output gap is consistently positive, thus, output is held above its potential. An output gap that relies on some kind of trend to estimate potential output, as it is frequently done in Taylor rule estimations, can by construction not lead to long periods of over- or undershooting of the potential. But our explicitly estimated output gap can and it does. Thus, we support with our finding of a significantly negative output coefficient Taylors great deviation hypothesis.

However, within the crisis there is a clear tendency that the Fed increases its response to the output gap. This is reasonable since the output gap turns negative within the crisis, thus sustainable growth is at risk. In the four specifications where we observe significant differences between the pre- and crisis reaction coefficients (columns 3.1, 3.3, 3.5, 3.8), we find a consistently higher response to the output gap. Moreover, in columns 3.1 and 3.5 the coefficients turn significantly positive. Therefore, we conclude that response coefficients increase within the crisis in contrast to the ECB.

The estimated reaction coefficient to money growth (column 3.2) before the crisis turns out to be positive and becomes significantly negative within the crisis. This drop in the response coefficient is exactly what we have expected, namely that money growth as a leading indicator of future inflation is less important during times of financial turmoil. However, if we add all significantly different additional variables then the estimated pre-crisis coefficient also turns out to be negative.

Table 3: *Taylor reaction function estimates - The Fed case*

	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8
ρ_B	0.92*** (0.04)	0.82*** (0.03)	0.95*** (0.03)	0.92*** (0.04)	0.71*** (0.05)	0.89*** (0.03)	0.92*** (0.03)	0.73*** (0.02)
a_{π_B}	2.47 (1.90)	1.57** (0.78)	3.38 (2.74)	0.44 (1.41)	-0.38* (0.22)	0.81 (0.54)	5.98*** (1.95)	0.06 (0.09)
a_{Y_B}	-0.44** (0.18)	-0.67*** (0.12)	-2.60* (1.56)	-0.91** (0.39)	-0.24*** (0.03)	-0.27** (0.12)	-0.31 (0.19)	-0.48*** (0.01)
a_{M_B}		0.29*** (0.10)						-0.60*** (0.05)
a_{CR_B}			1.33 (0.95)					
$a_{CR\ House_B}$				0.33 (0.22)				0.42*** (0.03)
a_{I_B}					-0.65*** (0.10)			-0.41*** (0.06)
a_{HP_B}						-0.08** (0.04)		-0.09*** (0.01)
a_{S_B}							-0.10* (0.06)	-0.03*** (0.00)
ρ_A	0.55*** (0.04)	0.63*** (0.02)	0.53*** (0.02)	0.67*** (0.04)	0.49*** (0.03)	0.59*** (0.02)	0.69*** (0.02)	0.68*** (0.01)
a_{π_A}	-1.66*** (0.16)	-0.77*** (0.17)	-0.76*** (0.12)	0.69* (0.39)	-1.14*** (0.09)	-0.62*** (0.10)	-2.31*** (0.14)	-1.78*** (0.09)
a_{Y_A}	0.12*** (0.11)	-0.97*** (0.17)	0.01 (0.08)	-0.48 (0.30)	0.15** (0.06)	-0.22** (0.09)	-0.43*** (0.14)	-0.10 (0.07)
a_{M_A}		-0.59*** (0.06)						-0.43*** (0.06)
a_{CR_A}			-0.22*** (0.02)					
$a_{CR\ House_A}$				-0.58*** (0.09)				0.09*** (0.03)
a_{I_A}					-0.29*** (0.09)			1.33*** (0.21)
a_{HP_A}						0.17*** (0.01)		0.01 (0.02)
a_{S_A}							0.11*** (0.01)	0.05*** (0.00)
$adj.R^2$	0.94	0.91	0.93	0.87	0.94	0.94	0.95	0.95
$J - Stat$	0.14 (0.92)	0.14 (1.00)	0.13 (1.00)	0.13 (1.00)	0.17 (1.00)	0.17 (1.00)	0.16 (0.99)	0.19 (1.00)

Notes: GMM estimates, */**/*** denotes significance at the 10%/5%/1% level, standard errors in parentheses, for the J-statistic we put the p-value in parentheses, Sample 1999M6-2010M12.

According to our results, the Fed has not responded to credit measures (columns 3.3 and 3.4) before the crisis started. This can be explained by the minor importance of credit markets in the US compared to the euro area especially in refinancing activities of companies. However, within the crisis the estimated response coefficients turn significantly negative, which at least in the case of the housing credit growth ends up in a significantly lower reaction after the crisis began. The same tendency can be observed when adding all significantly different additional variables. But here even the crisis coefficient remains positive. The decreased (and negative) coefficient after 2007M7 leads us to the conclusion that the Fed judges the downturn in credit growth as credit rationing rather than a credit crunch as the ECB does. Whereas under a credit crunch the market mechanism still works in the sense that interest rate adjustments bring supply of and demand for loans to equilibrium, credit rationing implies an equilibrium in which there is an excess demand for loans over credit supply (Green and Oh 1991). If there is credit rationing, the interest rate has to increase in order to reduce credit demand and expand credit supply to a new market equilibrium.

Table 3a: *Wald-tests of significant differences in pre- and post-crisis coefficients – The Fed case*

	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8
$\rho_B = \rho_A$	36.99*** (0.00)	21.12*** (0.00)	91.63*** (0.00)	16.59*** (0.00)	26.89*** (0.00)	63.91*** (0.00)	49.53*** (0.00)	5.65** (0.02)
$a_{\pi_B} = a_{\pi_A}$	4.58** (0.03)	7.92*** (0.01)	2.27 (0.13)	0.03 (0.87)	8.04*** (0.01)	7.84*** (0.01)	17.77*** (0.00)	150.10*** (0.00)
$a_{Y_B} = a_{Y_A}$	5.20** (0.02)	1.88 (0.17)	2.78* (0.10)	0.75 (0.39)	35.18*** (0.00)	0.09 (0.77)	0.21 (0.65)	27.03*** (0.00)
$a_{M_B} = a_{M_A}$		66.26*** (0.00)						4.44** (0.04)
$a_{CR_B} = a_{CR_A}$			2.67 (0.10)					
$a_{CR\ House_B} = a_{CR\ House_A}$				17.26*** (0.00)				51.47*** (0.00)
$a_{I_B} = a_{I_A}$					8.26*** (0.00)			60.87*** (0.00)
$a_{HP_B} = a_{HP_A}$						38.29*** (0.00)		13.96*** (0.00)
$a_{S_B} = a_{S_A}$							11.39*** (0.00)	112.74*** (0.00)

Notes: Wald-tests based on the results of Table 3, */**/*** denotes significance at the 10%/5%/1% level, p-value in parentheses.

With respect to the change in the reaction coefficients of the remaining additional variables, namely the interest rate spread and asset price inflation (columns 3.5 to 3.7), we can draw the same conclusions as for the ECB. So the estimated response coefficient to the risk spread increases within the crisis and asset price deflation is tackled actively in the crisis era, while before the crisis started the Fed even accommodated asset price inflation.

So all in all it can be concluded that monetary policy of both central banks can still be modeled with the (modified) Taylor reaction function. But the response coefficients need to be adjusted to account for the crisis period. This pattern is also stressed by Gerlach (2011) and Klose (2011a). Comparing the adjustment of the coefficients between both central banks, they tend to be the same in many cases. Both central banks act less inertially, put a smaller weight on the inflation gap, money growth and the risk spread, while the response to asset price inflation increases. However, the central banks diverge in their response to the output gap and credit growth.

5. Conclusions

In this paper we propose an alternative way of estimating Taylor reaction functions in the presence of the zero-lower-bound on nominal interest rates, as it was the case during the recent financial crisis. Our approach relies on a state-space-model that separately estimates the time series of the inflation expectations, the equilibrium real interest rate and the potential output needed to calculate the output gap. With these three variables at hand we are able to modify the functional form of the classical Taylor rule in a way that no longer the nominal but the real interest rate is targeted by the central bank. Because of our definition of the inflation expectations which incorporates the size of the balance sheet of the central bank, the monetary authority is able to influence the real rate even if nominal rates are (close to) zero via quantitative easing. So we allow for a second way of stimulating the economy for central banks besides the traditional interest rate setting policy.

However, this “second way” leads to a possible coordination problem between the “traditional” interest rate policy and quantitative easing. If the latter is in place, the central banks have two options at hand to conduct monetary policy. Especially if signs of a recovery are foreseeable, both central banks should clearly communicate their exit strategy which can be achieved either by increasing the nominal interest rate or reducing funds issued via quantitative easing.

According to our results, bringing quantitative easing to a halt has ceteris paribus several advantages. First, the goal of cooling down the economy and, thus, reducing future inflation can also be achieved this way because lowering funds will tend to reduce inflation expectations and increase the real interest rate. Second, not increasing the nominal rate builds up credibility in case of any similar crisis in the future. Third, running monetary policy with only one instrument is easier to communicate and especially in times of a recovery a clear communication to the public is urgently needed.

Besides the functional form of the Taylor rule we also suggest possible other indicators that might have changed within the crisis. Indeed, we find substantial differences between the

ECB and the Fed concerning their estimated reaction to credit growth and asset price inflation. While the ECB even triggered further expansions in the credit sector, the Fed did not react to these measures at all before the crisis started. Adding these measures to the reaction function with a significant positive weight might have stopped a too accommodative policy and would, thus, have avoided the recent crisis. The same applies for asset prices. According to our estimates, both central banks appear to have actively accommodated rising asset prices, modeled as stock and house prices. However, during the crisis with asset price inflation falling, both central banks clearly tried to avoid further reductions in stock and house prices. We recommend getting rid of this asymmetry between rising and falling asset price inflation but, instead, argue in favor of tackling it actively independent of whether asset prices are in- or decreasing. This would possibly put an end to or at least reduce boom-bust-cycles in asset markets.

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Data Appendix

United States

Variable	Measure	Source
interest rate	federal funds rate	OECD
inflation	year-on-year change in consumer price index	OECD
output-gap	industrial production subtracted by its potential calculated via the state-space estimate	Bureau of Economic Analysis
import price inflation (nonpetroleum)	year-on-year change of the price index for imports of nonpetroleum products	Bureau of Economic Analysis
import price inflation (petroleum)	year-on-year change in the price index for imports of petroleum and petroleum products	Bureau of Economic Analysis
money growth	year-on-year change in monetary aggregate M2	OECD
credit growth	year-on-year change in overall bank credit	Federal Reserve
house credit growth	year-on-year change in real estate loans	Federal Reserve
interest rate spread	difference 10 year treasury securities yields and 3-months yields	Federal Reserve
stock price growth	year-on-year change in an index of all common stock listed on the NYSE	OECD
house price growth	year-on-year growth of the S&P/Case-Shiller home price index	Standard and Poor’s

Euro area

Variable	Measure	Source
interest rate	Eonia	ECB
inflation	year-on-year change in the HICP	ECB
output gap	Industrial production subtracted by its potential calculated via the state-space estimate	ECB
import price inflation	year-on-year change in the import price deflator	ECB
oil price inflation	year-on-year change in oil prices	ECB
money growth	year-on-year change in monetary aggregate M3	ECB
credit growth	year-on-year change in overall bank credit	ECB
house credit growth	year-on-year change in real estate loans	ECB
interest rate spread	difference 10 year government bond yields and 3-month Euribor	ECB
stock price growth	year-on-year change in the Dow Jones EURO STOXX index	OECD
house price growth	year-on-year growth of the house price index	ECB