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# MONETARY POLICY WHEN THE ZERO LOWER BOUND IS WITHIN REACH: A SMOOTH TRANSITION REGRESSION APPROACH

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The period of low interest rates since the global financial crisis provides a unique opportunity to examine monetary policy reaction functions near the zero lower bound (ZLB). Using smooth transition regressions for the Euro area and a panel of industrialized countries we show that central banks anticipate the ZLB by less aggressive policies in its vicinity while we do not find a significant difference between both regimes for the US.

**Keywords:** Monetary Policy, Zero Lower Bound, Interest Rate Reaction Functions, Smooth Transition Regression Model

## 1. INTRODUCTION

The Taylor rule establishes a linear relationship between the policy interest rate, inflation, and the output gap. The zero lower bound (ZLB) on nominal interest rates, however, constrains central banks' interest rate reactions such that the Taylor rule is unable to describe monetary policy once this bound is reached. The current global financial crisis has shown that at low interest rates unconventional monetary policies like Quantitative Easing (QE) and forward guidance increasingly replace traditional interest rate policies.

This paper addresses the question whether central banks adjust their interest rate rule when they are operating close to the ZLB. Within the framework of a smooth transition regression (STR) model, we test whether nonlinearities are present in the vicinity of the ZLB. Our empirical results suggest that the European Central Bank (ECB) reacts less aggressively to inflation and output when the ZLB comes closer. This behavior can be confirmed for a panel data set including

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27 industrialized countries. For the US Fed, however, we do not find a change in behavior between low and high interest rate environments.

When their policy rate comes close to the ZLB, central banks have basically two options: Either they set interest rates according to their rule and switch to unconventional policies once the ZLB has been reached or they adjust their rule early enough and pursue policies intended not to hit the ZLB. In the literature two opposing strategies are conceivable: On the one hand, theoretical analyses show that central banks should try a "go-around" by cutting interest rates preemptively more than their regular reaction function suggests [see Orphanides and Wieland (2000), Reifschneider and Williams (2000), and Adam and Billi (2006)]. On the other, more policy-related views suggest that central banks should cut rates more cautiously near the ZLB in order not to "exhaust all its ammunition" [see Bini Smaghi (2008)].

Figuratively speaking, we ask how central banks prepare for landing: Do they just continue their approach and land on zero ground or do they disconnect the autopilot [see Alcidi et al. (2011)], adjust their course, and intend a go-around. Technically, we examine whether empirical Taylor reaction functions are nonlinear not only at the ZLB, but already when the ZLB is perceived to become binding in the near future.

The literature on Taylor rules has identified and examined nonlinearities before: First, the conduct of monetary policy might vary over time [see Judd and Rudebusch (1998), Boivin (2006), Kishor (2012), and Barnett and Duzhak (2019)]. Second, asymmetric central bank preferences could result in nonlinear responses to economic conditions [see Surico (2007)]. These different response regimes might be linked to the level of inflation [see Assenmacher-Wesche (2006), Chevapatrakul et al. (2009), and Castro (2011)] or the stance of the business cycle [see Brüggemann and Riedel (2011) and Beckmann et al. (2017)]. Third, parameter uncertainty might imply that central banks react in a nonlinear way to deviations of inflation from its target [Tillmann (2011)]. Finally, asymmetries arise because interest rates cannot fall below the ZLB [see Kim and Mizen (2010) and Kiesel and Wolters (2014)]. Gerlach (2011) and Gerlach and Lewis (2014) show in a smooth transition model following Mankiw et al. (1987) that the ECB cut interest rates more rapidly when being close to the ZLB. While these authors focus on the ECB policy during the financial crisis, our approach considers a longer time period and a set of industrialized countries. Chevapatrakul et al. (2009), in turn, do not find more aggressive behavior near the ZLB. Cao and Illing (2015) provide an argument why central banks seem to be reluctant to raise policy rates: Expected low interest rates induce banks to invest in excessive risky liquidity transformation, which forces the central bank to maintain a low policy rate for an extended period.

The remainder of this paper is structured as follows: Section 2 describes linear and nonlinear Taylor rules. Our empirical results are presented in Section 3. The final section concludes.

## 2. MONETARY POLICY REACTION FUNCTIONS

### 2.1. Traditional Linear Specification

Taylor (1993) proposes a monetary policy reaction function where the policy interest rate depends on the deviation of inflation from its target and on the output gap:

$$i_t^T = \alpha + \beta\pi_t + \gamma y_t^{gap}, \tag{1}$$

where $i^T$ is the target (or desired) nominal policy interest rate and $\pi$ the actual inflation rate. The index $t$ denotes the time period. The long-run real interest rate and the inflation target are subsumed into the constant $\alpha = r - (\beta - 1)\pi^*$, and the output gap $y_t^{gap} = y_t - y_t^*$ is defined as the difference between actual and potential output.[1]

After accounting for interest rate smoothing by a partial adjustment model [see Brüggemann and Riedel (2011) for the details], we get the following reduced-form model:

$$i_t = \alpha^* + \beta^*\pi_t + \gamma^* y_t^{gap} + \sum_{j=1}^{J} \rho_j i_{t-j} + u_t, \tag{2}$$

where $\rho$ governs the speed of adjustment and $u_t$ is an iid innovation, which can be characterized as an exogenous shock to the interest rate.

Given that the effects of monetary policy materialize with a delay, policy decisions are based on an assessment of current and future economic conditions.[2] Accordingly, Clarida et al. (1998) propose forward-looking policy rules, where current variables are replaced by their forecast:

$$i_t = \alpha^* + \beta^* E[\pi_{t+k}|\Omega_t] + \gamma^* E[y_{t+k}^{gap}|\Omega_t] + \sum_{j=1}^{J} \rho_j i_{t-j} + u_t, \tag{3}$$

where $E$ denotes the expectations operator and $\Omega_t$ is the information set available at time $t$.

### 2.2. Nonlinear Specification: Logistic Smooth Transition Model

To test whether central banks' interest rate reaction changes in the vicinity of the ZLB, we perform an LM-type linearity test in the spirit of Terasvirta (1994) and apply an STR model.[3,4] Computationally, we expand equation (3) by a nonlinear term:

$$\begin{aligned} i_t = {} & \alpha_1^* + \beta_1^* E[\pi_{t+k}|\Omega_t] + \gamma_1^* E[\, y_{t+k}^{gap}|\Omega_t] + \sum_{j=1}^{J} \rho_{j,1} i_{t-j} \\ & + \left[\alpha_2^* + \beta_2^* E[\pi_{t+k}|\Omega_t] + \gamma_2^* E[\, y_{t+k}^{gap}|\Omega_t] + \sum_{j=1}^{J} \rho_{j,2} i_{t-j}\right] G(s_t, \theta, c) + \epsilon_t. \end{aligned} \tag{4}$$

As functional form for the transition function $G$ we choose the logistic function[5] such that

$$G(s_t, \theta, c) = \left\{1 + exp\left[-\theta \prod_{k=1}^{K}(s_t - c_k)\right]\right\}^{-1}. \quad \textbf{(5)}$$

$G$ is a continuous function between 0 and 1. It depends on (i) the transition variable $s_t$, which splits the relationship in different regimes, (ii) the threshold $c_k$ that corresponds to the value of the transition variable where one regime moves into the other, and (iii) the speed parameter $\theta$ that determines how fast the transition between regimes takes place. After choosing initial values of $c$ and $\theta$ by a grid search, they are determined within the model using a form of the Newton–Raphson algorithm to maximize the conditional maximum-likelihood function. $s$ has to be set. $K$ is the number of thresholds. The model is estimated using the nonlinear least squares (NLS) technique.

In the case of one threshold variable, the coefficients change monotonically. The coefficient on inflation, for instance, may change from $\beta_1^*$ to $\beta_1^* + \beta_2^*$. We call this model LSTR1. For two thresholds, the model is called LSTR2 and the coefficients are constant between $c_1$ and $c_2$ and change otherwise.

## 3. EMPIRICAL ANALYSIS

### 3.1. Data

The empirical analysis is based on a quarterly panel data set of 27 industrialized countries listed in Appendix, which covers the period 1990–2014. Policy interest rates of central banks are taken from the International Financial Statistics (IFS) of the IMF and complemented with data from the Historical Financial Statistics of the Center for Financial Stability. Inflation is measured by the annualized change in the consumer price index. Forecasts are taken from two sources: The World Economic Survey (WES) of CESifo and the World Economic Outlook (WEO) of the IMF.

WES provides data on inflation expectations for the current year on a quarterly basis, while expected growth of real GDP for the current year is ascertained only once a year in its second quarter issue. We assume that this expectation is relevant for central bank policy in the quarter of its publication and the three following ones.

With respect to the WEO data, we assume that the forecast of the April issue is used in Q2 and Q3 and the forecast published in its October issue corresponds to the information available to central banks in Q4 and Q1 of the following year. Forecasts are available for the current and the following calendar year. We assume that for monetary policy the relevant forecast extends over a horizon of one year: It starts with the current quarter ($t$) and ends four quarters into the future ($t + 4$). To transform the calendar year data in these fixed-term forecasts we construct a weighted average of two calendar-year forecasts. Our quarterly forecast is defined as

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**TABLE 1.** Linearity tests

| | Specification | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| F | 0.000 | 0.000 | 0.210 | 0.000 | 0.000 | 0.011 | 0.000 | 0.000 | 0.348 |
| F4 | 0.452 | 0.679 | 0.958 | 0.211 | 0.321 | 0.768 | 0.585 | 0.121 | 0.320 |
| F3 | 0.036 | 0.080 | 0.667 | 0.309 | 0.264 | 0.104 | 0.818 | 0.276 | 0.106 |
| F2 | 0.000 | 0.000 | 0.006 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.950 |
| Model | LSTR1 | LSTR1 | linear | LSTR1 | LSTR1 | LSTR1 | LSTR1 | LSTR1 | linear |

*Note*: The testing procedure follows Terasvirta (2004). The numbers of specifications correspond to those of Table 2. The first row denoted by F provides the $p$-value of the joint significance test which allows to discriminate between linearity and nonlinearity. If a nonlinear model is warranted, we consider three other hypotheses to make a decision on the number of regimes $K$: F4 corresponds to the $p$-value of $H_{04} : \rho_3 = 0$. F3 gives the $p$-value of $H_{03} : \rho_2 = 0|\rho_3 = 0$. Finally, the row F2 shows the $p$-value of $H_{02} : \rho_1 = 0|\rho_2 = \rho_3 = 0$. If the smallest $p$-values are found in either $H_{02}$ or $H_{04}$ the LSTR1 model is indicated; otherwise the appropriate choice is the LSTR2 model.

$$E[x_{t+4}|\Omega_t] = \frac{4-q}{4}E[x_{year}|\Omega_t] + \frac{q}{4}E[x_{year+1}|\Omega_t],$$

where $x = (\pi, y^{gap})$. $x_{t+4}$ indicates the value of $x$ four quarters ahead from $t$, $x_{year}$ is the value of $x$ for the current calendar year, and $q$ indicates the quarter of the year with $q = 1, 2, 3, 4$.

To account for international linkages, we add the world policy rate as a measure of the stance of monetary policy in major economies [see Beckmann et al. (2017)]. It equals the US policy rate except for the US where it is calculated as the average of the policy rates in the Euro area (Germany until 1998), Japan, and the UK.

We choose the lagged value of the policy interest rate as transition variable. When policy interest rates are falling, the central bank might move from a regime, where it is not concerned about the ZLB, to a second regime, where its reaction is affected by policymakers' knowledge that the ZLB might become binding in the near future.

Once the ZLB is reached, we cannot expect any further downward reaction in the interest rate even if our fundamentals (inflation, output growth, and/or world policy rate) would suggest this. Therefore, the inclusion of periods where the interest rate is constant at its lower bound would bias the results. Hence, in our empirical analysis we drop all observations starting with the second quarter once the ZLB was hit until the first rate increase. The ZLB is defined as a situation where the policy rate equals 0.5% or less and stays at this lower floor value at least for four quarters.

### 3.2. Results

We present results for both forward- and backward-looking Taylor rules. Forward-looking specifications are based on expected values derived from either WES (columns 1–3) or WEO (columns 4–6). Backward-looking rules are based on

**TABLE 2.** Nonlinear Taylor rules: US

| | Forward-looking | | | | | | Backward-looking | | |
|---|---|---|---|---|---|---|---|---|---|
| | WES expectations | | | WEO expectations | | | | | |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| **Linear part** | | | | | | | | | |
| Inflation | −0.323 | −0.373 | −0.037 | 0.584* | 0.386 | 0.691*** | −0.067 | −0.666 | −0.165 |
| | (−0.72) | (−0.73) | (−0.36) | (1.72) | (0.61) | (3.79) | (−0.01) | (−0.40) | (−1.17) |
| Growth | 0.422** | 0.445** | 0.107 | 0.198 | 0.206 | 0.202** | −0.872 | −0.270 | 0.026 |
| | (2.10) | (2.05) | (1.26) | (1.22) | (0.83) | (2.61) | (−0.02) | (−0.14) | (0.28) |
| World rate | | 0.055 | 0.017 | | 0.158 | −0.110** | | 0.311 | −0.014 |
| | | (0.23) | (0.39) | | (0.41) | (−2.02) | | (0.20) | (−0.14) |
| Policy rate (−1) | | | 1.563*** | | | 1.064*** | | | 0.950*** |
| | | | (12.64) | | | (7.67) | | | (12.41) |
| Policy rate (−2) | | | −0.617*** | | | −0.223* | | | |
| | | | (−5.02) | | | (−1.81) | | | |
| **Nonlinear part** | | | | | | | | | |
| Inflation | 0.604 | 0.740 | | −0.718 | 0.360 | −0.615** | −0.155 | 0.940 | |
| | (1.00) | (0.97) | | (−1.23) | (0.33) | (−2.33) | (−0.02) | (0.37) | |
| Growth | 0.021 | −0.048 | | 0.268 | 0.178 | −0.324 | 1.413 | 0.872 | |
| | (0.06) | (−0.12) | | (0.69) | (0.33) | (−1.65) | 0.03 | 0.27 | |
| World rate | | −0.117 | | | −0.652 | −0.005 | | −0.844 | |
| | | (−0.29) | | | (−0.88) | (−0.05) | | (−0.32) | |
| Policy rate (−1) | | | | | | 0.678** | | | |
| | | | | | | (2.24) | | | |
| Policy rate (−2) | | | | | | −0.782*** | | | |
| | | | | | | (−3.04) | | | |
| Model | LSTR1 | LSTR1 | linear | LSTR1 | LSTR1 | LSTR1 | LSTR1 | LSTR1 | linear |
| Threshold ($c_1$) | 3.24 | 3.30 | | 3.87 | 3.64 | 4.52 | −4.72 | −.0.34 | |
| Speed ($\theta$) | 1.08 | 1.05 | | 1.02 | 0.62 | 165.91 | 0.10 | 0.17 | |
| $R^2$ | 0.94 | 0.94 | 0.95 | 0.93 | 0.95 | 0.97 | 0.91 | 0.92 | 0.83 |

*Notes*: Regressions span over the period 1990:Q3–2008:Q4 and contain 71 observations. $t$-statistics are reported in parentheses. The symbols *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. In backward-looking specifications, growth is replaced by the rate of unemployment.

**TABLE 3.** Linearity tests: Euro area

| | Specification | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| F | 0.000 | 0.000 | 0.010 | 0.000 | 0.000 | 0.004 | 0.000 | 0.000 | 0.001 |
| F4 | 0.570 | 0.533 | 0.767 | 0.004 | 0.764 | 0.923 | 0.676 | 0.006 | 0.004 |
| F3 | 0.220 | 0.131 | 0.070 | 0.023 | 0.010 | 0.026 | 0.349 | 0.858 | 0.372 |
| F2 | 0.000 | 0.000 | 0.002 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.006 |
| Model | LSTR1 | LSTR1 | LSTR1 | LSTR1 | LSTR1 | LSTR1 | LSTR1 | LSTR1 | LSTR1 |

*Notes*: The testing procedure follows Terasvirta (2004). The numbers of specifications correspond to those of Table 4. The first row denoted by F provides the $p$-value of the joint significance test which allows to discriminate between linearity and nonlinearity. If a nonlinear model is warranted, we consider three other hypotheses to make a decision on the number of regimes $K$: F4 corresponds to the $p$-value of $H_{04} : \rho_3 = 0$. F3 gives the $p$-value of $H_{03} : \rho_2 = 0|\rho_3 = 0$. Finally, the row F2 shows the $p$-value of $H_{02} : \rho_1 = 0|\rho_2 = \rho_3 = 0$. If the smallest $p$-values are found in either $H_{02}$ or $H_{04}$ the LSTR1 model is indicated; otherwise the appropriate choice is the LSTR2 model.

variables lagged by one period (columns 7–9). All approaches have in common that the used information is available to the central bank when its interest rate decision is taken.

*3.2.1. Time-series analysis for the US and Euro area.* For the US, results of the linearity tests, which are presented in Table 1, show that nonlinearity is present with the LSTR1 model being the preferred choice in all except two specifications. Two lags of the interest rate seem to be sufficient to eliminate any serial correlation in the error term. Table 2 shows the regression results. The analysis is based on a shorter time period that ends in 2008:Q4, the quarter when the US policy rate reached the lower bound (0.125%) and did not leave it until the end of our period of consideration (2014:Q4). When forward-looking interest rate reaction functions based on WES forecasts are applied, the FED reacts below the threshold—which lies between 3.2% and 3.3% in these specifications—and increases policy rates when economic growth is strong. Due to the smooth transition the FED reacts less to growth for interest rates above the threshold. In the specification based on WEO expectations, the US interest rates are increased with inflation in the low interest rate environment; this effect, however, vanishes slowly as the interest rate increases. Moreover, there is evidence for interest rate smoothing indicated by the significance of the lagged policy rate. Finally, in the backward-looking specifications all explanatory variables besides the lagged policy rate turn out to be insignificant although the $R^2$ is quite large.

For the Euro area, linearity tests show that the LSTR1 model is the preferred choice independently of the specification (see Table 3). Estimation results are presented in Table 4. Except specification (5) where the effect of inflation on the interest rate becomes positive and significant beyond the threshold value, effects in regressions without interest rate smoothing are insignificant. If the lagged dependent variable is included, results for the forward-looking specifications

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**TABLE 4.** Nonlinear Taylor rules: Euro area

| | Forward-looking | | | | | | Backward-looking | | |
|---|---|---|---|---|---|---|---|---|---|
| | WES expectations | | | WEO expectations | | | | | |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| **Linear part** | | | | | | | | | |
| Inflation | −2.658 | −0.327 | 0.128 | −1.407 | −2.255 | 0.105 | −1.419 | −2.416 | 0.134*** |
| | (0.00) | (−0.41) | (1.34) | (−0.68) | (−1.39) | (0.98) | (−0.83) | (0.00) | (3.21) |
| Growth | −1.099 | −0.145 | 0.007 | −0.264 | 0.221 | 0.046 | 0.212 | −1.258 | −0.111*** |
| | (0.00) | (−0.66) | (0.19) | (−0.38) | (0.44) | (0.93) | (0.22) | (0.00) | (−4.39) |
| World rate | | 0.092 | 0.075*** | | −0.675 | 0.048* | | −0.627 | 0.148*** |
| | | (0.44) | (2.77) | | (−1.05) | (1.86) | | (0.00) | (6.26) |
| Policy rate (−1) | | | 0.860*** | | | 0.889*** | | | 0.664*** |
| | | | (15.19) | | | (18.14) | | | (11.32) |
| **Nonlinear part** | | | | | | | | | |
| Inflation | 4.423 | 1.359 | 0.111 | 2.498 | 3.549* | 0.278 | 1.799 | 4.025 | 0.266 |
| | (0.00) | (0.63) | (0.54) | (1.01) | (1.87) | (1.16) | (0.97) | (0.00) | (1.12) |
| Growth | 2.043 | 0.572 | −0.074 | 0.689 | −0.163 | −0.043 | −0.274 | 1.771 | 0.217*** |
| | (1.57) | (0.91) | (−1.04) | (0.77) | (−0.23) | (−0.40) | (−0.24) | (0.00) | (3.38) |
| World rate | | 0.062 | 0.353*** | | 1.079 | 0.337*** | | 1.225 | 0.232*** |
| | | (0.10) | (4.82) | | (1.30) | (4.58) | | (0.00) | (3.95) |
| Policy rate (−1) | | | 0.265*** | | | 0.110 | | | 0.192 |
| | | | (2.76) | | | (0.84) | | | (1.02) |
| Model | LSTR1 | LSTR1 | LSTR1 | LSTR1 | LSTR1 | LSTR1 | LSTR1 | LSTR1 | LSTR1 |
| Threshold ($c_1$) | −4.54 | 7.46 | 4.13 | −0.15 | −1.93 | 4.13 | −8.71 | −4.50 | 4.13 |
| Speed ($\theta$) | 0.11 | 0.30 | 989 | 0.40 | 0.36 | 756 | 0.22 | 0.14 | 1040 |
| $R^2$ | 0.97 | 0.98 | 0.98 | 0.97 | 0.98 | 0.98 | 0.95 | 0.97 | 0.98 |

*Notes*: Regressions span over the period 1991:Q2–2014:Q4 and contain 95 observations. $t$-statistics are reported in parentheses. The symbols *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. In backward-looking specifications, growth is replaced by the rate of unemployment.

**TABLE 5.** Nonlinear Taylor rules: Panel

| | Forward-looking | | | | | | Backward-looking | |
|---|---|---|---|---|---|---|---|---|
| | WES expectations | | | WEO expectations | | | | |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| **Linear part** | | | | | | | | |
| Inflation | −4.080*** | −1.064*** | −1.058*** | −1.991*** | −0.222* | −0.061 | −0.578*** | −0.788*** |
| | (−19.25) | (−6.81) | (−5.93) | (−8.14) | (−1.96) | (−0.46) | (−5.77) | (−5.89) |
| Growth | −0.530*** | −0.104 | −0.019 | −6.022*** | −1.147*** | −1.185*** | −0.422*** | −0.453*** |
| | (−3.75) | (−1.21) | (−0.17) | (−20.25) | (−7.01) | (−6.79) | (−7.55) | (−5.76) |
| World rate | | | −0.438*** | | | −0.264*** | | −0.743*** |
| | | | (−5.26) | | | (−3.45) | | (−5.45) |
| Policy rate (−1) | | 0.592*** | 0.514*** | | 0.592*** | 0.548*** | 0.572*** | 0.474*** |
| | | (23.20) | (19.04) | | (24.10) | (21.61) | (19.84) | (15.16) |
| **Nonlinear part** | | | | | | | | |
| Inflation | 5.145*** | 1.470*** | 1.407*** | 2.750*** | 0.647*** | 0.321* | 0.719*** | 0.986*** |
| | (24.83) | (8.76) | (7.34) | (9.88) | (4.62) | (1.89) | (6.14) | (6.21) |
| Growth | 0.993*** | 0.379*** | 0.154 | 7.244*** | 1.608*** | 1.588*** | 0.522*** | 0.544*** |
| | (5.42) | (3.16) | (0.97) | (24.27) | (9.03) | (8.36) | (7.97) | (5.70) |
| World rate | | | 0.798*** | | | 0.492*** | | 1.160*** |
| | | | (6.73) | | | (4.64) | | (6.46) |
| Threshold ($c$) | 1.29 | 2.62 | 1.81 | −1.11 | 2.25 | 1.81 | 1.57 | −0.48 |
| Speed ($\theta$) | 0.37 | 0.42 | 0.32 | 0.26 | 0.33 | 0.31 | 0.34 | 0.22 |
| Observations | 1142 | 1142 | 1142 | 1243 | 1243 | 1243 | 1031 | 1031 |
| $R^2$ | 0.69 | 0.79 | 0.80 | 0.75 | 0.83 | 0.83 | 0.72 | 0.74 |

*Notes*: Regressions are estimated by LSTR1 models. The sample contains 27 industrialized countries (see Appendix) over the period 1990:Q1–2014:4. $t$-statistics are reported in parentheses. The symbols *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

suggest that the ECB smooths its interest rate and follows the world rate. Both effects are stronger above the threshold. The fully specified backward-looking model shows that the ECB smooths its interest rate setting and increases its rate when inflation is high. Above the threshold of 4.13% the ECB follows more closely the world policy rate. At the same time, high unemployment is associated with a lower policy interest rate. This effect, however, vanishes and switches signs as the interest rate increases.

*3.2.2. Panel data analysis.* Table 5 replicates the specifications of Tables 2 and 4 for a sample of 27 industrialized countries. A general pattern emerges: Responses to inflation and growth are negative at low levels of the policy interest rate, increase when interest rates become larger, and ultimately turn positive and significant. While the negative coefficients might be evidence for the central banks attempt not to touch the ZLB even at low inflation and growth, the standard Taylor rule with positive coefficients can be confirmed for policy interest rates far above the ZLB. Results suggest that the threshold lies somewhere between 1% and 3%. In some cases the threshold value of the policy rate is negative and outside economically relevant values indicating that the relationship is linear.

## 4. CONCLUSIONS

While it is well known that monetary policy reaction functions are nonlinear at the ZLB, this paper emphasizes that central banks adjust their response to economic fundamentals already at the vicinity of the ZLB. In particular, when the policy interest rate falls below a threshold of about 1%–3%, reaction coefficients decrease in a panel of industrialized countries. The ECB, in turn, reacts less aggressively to the world policy rate and its own lagged rate in the vicinity of the ZLB. For the US Fed we do not find a significantly different behavior for low and high policy rate environments. As an additional result, we find that the Fed rather follows a forward-looking Taylor rule than a backward-looking one.

*NOTES*

1. Christensen and Nielsen (2009) find that the FED rather responds to the bond rate than to inflation.
2. Hubert (2015) presents evidence for forward-looking behavior of the FED.
3. For the details of the STR model, please refer to the works of Terasvirta (1994) and van Dijk et al. (2002).
4. Central bank reaction functions close to the ZLB might be asymmetric: The reaction to fundamentals might depend on whether interest rates are lowered and the ZLB approached from above or whether interest rates are increased leaving the ZLB. In our data set, however, the number of lift-off episodes is too small to be able to distinguish econometrically between these two cases. By implication our econometric results describe how central banks approach the ZLB from above.
5. Alternatively, the econometric literature proposes an exponential function where the value of coefficients is a symmetric function of the distance from the threshold. In our application, however, the logistic function is warranted because we want to model the transition between two different regimes.

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## APPENDIX: SAMPLE OF COUNTRIES

| | | | | | |
|---|---|---|---|---|---|
| Australia | Euro area | Iceland | Malta | Portugal | Sweden |
| Austria | Finland | Ireland | Netherlands | San Marino | Switzerland |
| Belgium | France | Italy | New Zealand | South Africa | United Kingdom |
| Canada | Germany | Japan | Norway | Spain | United States |
| Denmark | Greece | Luxembourg | | | |

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