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Conventional and Unconventional Monetary Policy Reaction to Uncertainty in Advanced Economies: Evidence from Quantile Regressions

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Abstract:

This paper offers new insight on how the Federal Reserve (Fed) and other monetary policy makers (Bank of England, Bank of Japan and the European Central Bank), reacted in the aftermath of the financial crisis. To this end, the paper makes use of a quantile-based approach that estimates the response of interest rates to inflation and the output gap at various points of the conditional distribution of interest rates. Furthermore to gauge the importance of monetary policy making at the zero lower bound, and to test the propositions that policy shows greater aggression in expansionary measures as interest rates reach low levels, and increasing aggression as the lower bound is approached, we make use of the shadow short rate of interest and a measure of uncertainty to capture this fact. While the results show no detectable evidence of increasing aggression to inflation as the zero lower bound is approached, yet the decreased reaction of the Fed and other monetary policy makers towards uncertainty particularly at lower quantiles of interest rates lends support to expansionary mechanism in place during this time.

Keywords: Interest rate rule, zero lower bound, shadow rate of interest, uncertainty, advanced economies.
JEL Codes: C22, E52.

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1. Introduction

There has been considerable work on empirical estimates of monetary policy reaction functions, predominantly Taylor (1993)-type rule models, and these have been conducted not only at the central mean of interest rate but more recently, in the context of quantile regression, whereby the response of interest rate to inflation and output (and exchange rate) has been investigated at various quantiles on the conditional distribution of interest rates (see, Christou et al., (forthcoming) for a detailed discussion in this regard). Moreover nonlinear policy rules in the vein of smooth transition autoregressive models (STAR) have looked at interest rate responses at various levels of inflation or output gap and semi-parametric and nonparametric specification have provided some further insight in the sense that they do not impose any distributional condition in modelling the interest rate and is therefore able to reveal structure in data that might be missed by classical parametric linear/nonlinear models.

The most common form of monetary policy reaction functions typically assume that interest rates relate linearly to the gap between actual and desired values of inflation and output (see e.g. Taylor, 1993, Clarida et al., 2000, and Swamy et al., 2005). Nonlinear policy rules emerge from either asymmetric central bank preferences (e.g. Nobay and Peel, 2003, and Cukierman and Muscatelli, 2008) or a nonlinear (convex) aggregate supply or Phillips curve (e.g. Dolado et al., 2005), or still when central banks follow the opportunistic approach to disinflation (Aksoy et al., 2006). Dolado et al. (2004) discuss a model, which comprises both asymmetric central bank preferences and a nonlinear Phillips curve. Another strand of the monetary policy literature, dynamic stochastic general equilibrium models (see e.g. Smets and Wouters, 2003) make use of linear policy reaction function.

Empirical work on the analysis of monetary policy is dominated by studies that use the linear Taylor rule with prominent studies that have estimated asymmetric monetary policy reaction functions. Cukierman and Gerlach (2003), Ruge-Murcia (2003), Dolado et al. (2004, 2005), and Surico (2007) have shown evidence supporting asymmetries by adopting a monetary policy reaction function that feature asymmetries in either inflation or the output gap for the US, UK, EU and OECD countries. More recently, Ma et al. (2018) estimate nonlinear Taylor rules over the 1986–2008 sample time period and augment the traditional Taylor rule by including principal components together with uncertainty measures to better model Federal Reserve policy. These authors found strong evidence indicating that the Fed responded to increases in macroeconomic uncertainty by cutting the Federal Funds rate over the sample period, besides the fact that the Fed was also found to respond aggressively to increases in capacity utilization, especially when the inflation rate was above 2%. The fact that the Fed did respond to macroeconomic uncertainty in the pre- zero lower bound (ZLB) period has also been earlier confirmed by Evans et al., (2015), when estimating modified Taylor-type monetary policy rules.[1] However most of these studies have focussed on estimates only at the central mean of the policy rate with recent few exceptions that offer quantile regression method to generate estimates of the response to inflation and output gap at each of the points (quantiles) of the interest rate distribution. For instance, Chevapatrukul et al. (2009) employed quantile regression to Taylor rules for Japan and the USA. They found that inflation has a larger effect on higher quantiles of interest rates (where inflation is presumably higher than desired) than at lower quantiles of interest rates (where inflation is likely relatively low) contrary to the greater aggression to inflation that they expected to find as interest rates reach low levels as the lower bound is approached. Wolters (2012), when estimating a quantiles-based Taylor rule for the US, found significant and systematic variations of parameters over the conditional interest rate distribution. Wolters (2012) further indicated that asymmetric interest rate responses can be related to expansions and recessions

[1] Note that the negative response of interest rate to uncertainty (shocks) is also consistently detected in the vector autoregressive model-based analysis of uncertainty, where by uncertainty shocks are identified as negative demand shocks (see for example, Bloom (2009), Colombo (2013), Jones and Olson (2015), Jurado et al., (2015), Gupta et al., (2018), and references cited there in)..

(but not to preference shifts of the Fed.) and are consistent with a recession avoidance preference of the Fed during the Volcker–Greenspan era. More recently, unlike the above two studies, Chen and Kashiwagi (2017), estimated quantiles-based monetary policy rules in Japan using a sample that includes recent periods of zero interest rates. Taking into account censoring and endogeneity, these authors computed censored quantile instrumental variable estimators and compared them with estimates from uncensored quantile regressions. Their results indicated that not accounting for censoring of interest rates tends to result in downwardly biased estimates. More importantly, Chen and Kashiwagi (2017) showed that censored quantile regressions lead to relatively flat coefficients of inflation and insignificant coefficients of the output gap over the conditional interest rate distribution, suggesting that monetary policy in Japan may be well described by a linear rule. Finally, Liu (2018), using a Markov-switching quantile Taylor-rule model, estimated the conditional interest-rate distribution of the response of the Fed for endogenously identified monetary regimes. Liu found that the Taylor principle upholds only for the upper tails of the interest-rate distribution in Hawkish regimes, but not in interim and Dovish regimes. Moreover, the results showed that the Fed responded more aggressively to inflation at upper tails than at lower tails in both monetary Dovish and Hawkish regimes, with it responding to inflation more aggressively during the latter regimes than the former across quantiles.[2]

Moreover, the impact of uncertainty on the Fed's monetary reaction function has received ample scrutiny both theoretically and empirically, we however want to pursue this aspect in the aftermath of the recent financial crisis where such concern might most probably have been the highest. Uncertainty is generally accepted to be a fundamental and an integral part of monetary policy decision making. The concept of uncertainty in monetary policy practice was coined by Brainard (1967) and hence the Brainard's attenuation principle. The former

[2] Quantiles-based estimation of Taylor rules for emerging and developing Asian and Latin American countries can be found in Miles and Schreyer (2012, 2014), and Christou et al.,(forthcoming).

Federal Reserve Chairman, Greenspan (2003), contends that “Uncertainty is not just an important feature of the monetary policy landscape, it is the defining characteristic of that landscape”. Mishkin (2010) laments the unfortunate reality that most existing studies on optimal monetary policy have abstracted from considerations of macroeconomic risk in the context of financial disruptions. Thus empirical and theoretical formulations of monetary policy must take into account the quantitative relevance of uncertainty because it is a constant feature of monetary policy practice.

There is currently a large body of literature on the quantitative significance of imperfect knowledge of the state of the economy and forward looking indicators, noisy and uncertain data and the measurement issues for monetary policy. This literature includes Svensson (1999), Peersman and Smets (1999), Estrella and Mishkin (2000), Orphanides et al. (2000), Rudebusch (2001), Ehrmann and Smets (2003), Martin and Milas (2009) and Naraidoo and Raputsoane (2014) who present evidence in support of the seminal Brainard (1967) attenuation principle. This principle hypothesizes that uncertainty dampens the monetary authorities’ response to the target variables of monetary policy compared to when monetary policy decisions are made under complete certainty or certainty equivalence. On the contrary, Giannoni (2002) and Sonderstrom (2002), among others, have presented evidence that supports an aggressive reaction of monetary policy under uncertainty.

A point of departure from previous studies on these economies is that the empirical estimates are conducted not only at the central mean of interest rate, but we also take into account the response of interest rate to inflation, output and a measure of uncertainty at various points on the conditional distribution of interest rates. This allows us to test predictions of nonlinearity in terms of the response of the central banks at different bounds of interest rate. What the quantile estimation offers is the possibility to test predictions of greater or lesser aggression at different bounds of low or high quantile of interest rates. In so doing, we try to shed light on whether monetary policy in the US reacts symmetrically over the data sample. While the main focus of the analysis is on the Fed, we also analyse the behaviour of the Bank of England, Bank of Japan and the European Central Bank. Also our study offers a new perspective on the results derived from new Keynesian models that explore the policy reaction function in the presence of a lower bound in the context of unconventional monetary policy which has dominated all the forefronts of policy making and research in the recent past. There are a number of studies, viz., Kohn (1996), Kuttner and Posen (2001) and Bernanke and Reinhart (2004) among others that have pointed to a more aggressive reaction of the central bank when interest rates approach the ZLB in order to guard against the possibility of deflation and negative demand shocks. To this end, we make use of the shadow interest rates, which is the nominal interest rate that would prevail in the absence of its effective lower bound, with it derived by modelling the term structure of the yield curve. Thus, we are also able to study the monetary policy behaviour across conventional and unconventional monetary regimes without worrying about explicitly modelling the ZLB, as the shadow short rates (SSR) offer an excellent description of the historic interest rate behaviour (Wu and Xia, 2016). Understandably, by using the SSR and the quantiles based approach, with lower quantiles of the estimated monetary policy function econometrically capturing the reaction of central banks corresponding to the abnormal ZLB period (Liu, 2018), we do not need to pursue any kind of censoring as in Chen and Kashiwagi (2017). Furthermore, we contribute to this debate by assessing how the Fed, and other monetary authorities of advanced economies, have reacted to a (news-based) measure of uncertainty in the aftermath of the recent financial crisis. In the process, we, for the very first-time, contribute to the existing literature on quantile-based estimation of Taylor rules by analysing the behaviour of major central banks to not only inflation and output gap, but also to uncertainty, across the periods of conventional and unconventional monetary policy decisions. In sum, while studies like Evans et al., (2015) and Ma et al., (2018) have included uncertainty in the Taylor-rules, there sample have been restricted to the pre-ZLB era only and results derived based on a conditional-mean model, we use a quantiles-based approach that allows us to study the entire conditional distribution of the interest rate response. In the process, we also add to the literature on quantiles-based Taylor rule of Chevapatrukul et al., (2009), Wolters (2012), Chen and Kashiwagi (2017), and Liu (2018) by incorporating the role of uncertainty in the model, which has been shown to be important in interest rate setting behaviour by Evans et al., (2015), and Ma et al., (2018) in conditional-mean based monetary policy rules. The remainder of the paper is organized as follows: Section 2 discusses the methodology, while Section 3 presents the data and results, and finally Section 4 concludes.

2. Methodology: The Interest Rate Rule Estimation using Quantile Regression

For the purpose of this study, we extend Taylor's original rule in order to capture the reaction of monetary policy to economic policy uncertainty movement:

$$i_t = \alpha_0 + \alpha_\pi \pi_{t+k|t} + \alpha_y y_t + \alpha_{epu} epu_t + \varepsilon_t, \tag{1}$$

where ε_t is a policy shock, y_t is the output gap, $\pi_{t+k|t}$ is a k-period-ahead inflation forecast and epu_t is the economic policy uncertainty index. The standard approach of estimating a forward-looking Taylor rule, is to estimate the model parameters at the mean by GMM due to endogeneity, with a limited number of lagged variables included in the instrument set. However, parameter estimation at the mean of the interest rate distribution conditional on inflation and output gap is an incomplete description of monetary policy reactions. In this paper we adopt the quantile regression methodology suggested by Lee (2007) to estimate monetary policy rules defined in Eq. 1 over the whole conditional distribution of interest rates:

$$i_t = \alpha_0(\tau) + \alpha_\pi(\tau)\pi_{t+k|t} + \alpha_y(\tau) y_t + \alpha_{epu}(\tau) epu_t + u_t, \tag{2}$$

Quantile Regression Analysis: The control function approach of Lee (2007)

We estimate the forward-type interest rate rule using the quantile regression methodology suggested by Lee (2007): IVQ. The methodology adjusts for endogeneity by adopting a control function approach. The model has the form:

$$i_t = x_t \alpha_x(\tau) + z_{1t}' \alpha_z(\tau) + u_t, \tag{3}$$

$$x_t = m(\tau^*) + z_t{}' \vartheta(\tau^*) + v_t, \tag{4}$$

$$Q_{u_t|x_t,z_t}(\tau|x_t, z_t) = Q_{u_t|v_t,z_t}(\tau|v_t, z_t) = Q_{u_t|v_t}(\tau|v_t) \equiv \lambda(v_t), \tag{5}$$

$$Q_{v_t|z_t}(\tau^*|z_t) = 0, \tag{6}$$

where i_t is the dependent variable, x_t is the endogenous explanatory variable, $z_t = (z_{1t}, z_{2t})'$ is the vector of exogenous explanatory variables, and u_t and v_t are unobserved random variables. Parameters $m(\tau^*)$ and $\vartheta(\tau^*)$ are unknown parameters, and $\alpha_x(\tau)$ and $\alpha_z(\tau)$ are unknown parameters of interest at for some $\tau \in (0,1)$, $\tau^* \in (0,1)$, while $\lambda(\cdot)$ is a real-valued function of v_t. Let us denote the τth quantile of A conditional on $C = c$ is denoted by $Q_{A|C}(\tau|c)$. According to (3) and (4), we get

$$Q_{i_t|x_t,z_t}(\tau|x_t, z_t) = x_t \alpha_x(\tau) + z_{1t}' \alpha_z(\tau) + \lambda(v_t), \tag{7}$$

$$Q_{x_t|z_t}(\tau^*|z_t) = m(\tau^*) + z_t{}' \vartheta(\tau^*). \tag{8}$$

This suggests that the parameters of interest can be estimated in two steps. In the first step, we estimate v_t by the residuals of a linear $\tau^* th$ linear quantile regression of x_t on $(1, z_t)$. Specifically, $\hat{v}_t = x_t - \widehat{m}(\tau^*) + z_t' \hat{\vartheta}(\tau^*)$, $t = 1,2, \ldots, T$, and $(\widehat{m}(\tau^*), \hat{\vartheta}(\tau^*))$ is the solution to:

$$\min_{m,\vartheta} T^{-1} \sum_{t=1}^{T} \xi_{\tau^*}\big(x_t - m(\tau^*) + z_t' \vartheta(\tau^*)\big), \tag{9}$$

where $\xi_{\tau^*}(\kappa) = |\kappa| + (2\tau^* - 1)\kappa$, $\kappa \in (0,1)$, the check function. In the second step, we estimate the parameters of interest in a quantile regression of i_t on x_t, z_{1t}, and the residuals $\hat{v}_t$ extracted in step 1. Lee (2007) carries out this step via series estimation. Specifically, $\lambda(v)$ can be approximated by a linear combination of smooth functions $\{f_i : i = 1,2, \ldots\}$. Let $\widehat{w} = (x, z_1, \hat{v})$ and $F_n(\widehat{w}) = (x_t, z_{1t}, f_1(\hat{v}_t), f_2(\hat{v}_t), \ldots., f_n(\hat{v}_t))$ for any positive integer n. Then, we calculate $\hat{\Delta} = (\hat{\alpha}_x(\tau), \hat{\alpha}_z{}'(\tau), \hat{\delta}'(\tau))'$ by solving the following minimisation problem:

$$\min_{\Delta} \; T^{-1} \sum_{t=1}^{T} \hbar(\widehat{w}_t) \xi_\tau [y_t - F_n{}'(\widehat{w}_t)\Delta], \tag{10}$$

where $\hbar(\widehat{w}_t) = \mathbb{1}(\widehat{w}_t \in \mathcal{W})$ is a trimming function useful for avoiding extreme values and $\xi_\tau(\cdot)$ is the check function defined earlier. As discussed in Lee (2007), the minimisation problem in (10) can be easily solved by computation methods developed for quantile regression models since it has a linear programming representation. The two-step quantile estimator $(\hat{\alpha}_x(\tau), \hat{\alpha}_z{}'(\tau))$ is asymptotically normal:

$\sqrt{T}\begin{pmatrix} \hat{\alpha}_x(\tau) - \alpha_x(\tau) \\ \hat{\alpha}_z(\tau) - \alpha_z(\tau) \end{pmatrix} \xrightarrow{d} N(0, \Sigma)$, where the variance-covariance matrix can be consistently estimated through kernel methods that lead to valid asymptotic inferences.

In our case, the dependent variable i_t , is the interest rate. We set $x_t \equiv epu_t$ and $z_{1t} \equiv (\pi_{t+12}, y_t)'$, where epu_t is the economic policy uncertainty, π_{t+12} is the forward looking inflation and y_t denotes the output gap.

3. Data and Empirical Analysis

3.1. Data

Our analysis uses monthly data on four countries (regions) namely the European Union (EU), Japan, the United Kingdom (UK) and the United States (US), with the period of coverage being: 1995:01 to 2017:05. While the start date is driven by the common starting- point of data across the four countries (regions) for the measure of interest rate, the end-point is purely driven by availability of data at the time the paper was being written. The estimation of the Taylor-rule involves four variables, namely a measure of output, inflation, interest rate and uncertainty. In our case, output is captured by the (seasonally-adjusted) industrial production, while month-on-month inflation is computed based on the (seasonally-adjusted) Consumer Price Index (CPI). Data on both these variables for all the four economies under consideration is derived from the main economic indicators (MEIs) database of the Organisation for Economic Co-operation and Development (OECD).

Besides using a quantiles-based estimation approach, an unique feature of our study is that our data sample covers both the conventional and unconventional monetary policy periods, with the latter ensuing in the wake of the zero lower bound (ZLB)-situation of the monetary policy instrument in these economies, following the global financial crisis of 2008. The myriad unconventional monetary policies (such as large scale asset purchases, a maturity extension program and efforts of forward guidance in order to manage expectations of a prolonged period of low policy rates) were all directed towards improving financial conditions for firms and thereby eventually supporting an expedited recovery from the financial crisis. Given the ZLB, and the fact that a range of unconventional monetary policies were pursued, for estimation of policy rules across the conventional and unconventional regimes of central banking, we would need a uniform and coherent measure of the monetary policy stance. For our purpose, we use the shadow short rate (SSR). The SSR is the nominal interest rate that would prevail in the absence of its effective lower bound. The SSR used in this paper is developed by Krippner (2013), based on (two-factor) models of term-structure, at a daily frequency for the four economies of our concern, and is available for download from the website of the Reserve Bank of New Zealand.[3] The yield curve-based framework developed by Krippner (2013) essentially removes the effect that the option to invest in physical currency (at an interest rate of zero) has on yield curves, resulting in a hypothetical "shadow yield curve" that would exist if physical currency were not available. The process allows one to answer the question: "what policy rate would generate the observed yield curve if the policy rate could be taken negative?" The "shadow policy rate" generated in this manner, therefore, provides a measure of the monetary policy stance after the actual policy rate reaches zero. The main advantage of the SSR is that it is not constrained by the ZLB and thus allows us to combine the data from the ZLB period with the data from the non-ZLB era, and use it as the common metric of monetary policy stance across the conventional and unconventional monetary policy episodes. Note that, to match the monthly frequency of our other variables, the end of the month value of the daily SSR is used for our analysis.[4]

Our final variable that goes in the estimation of the monetary policy rules is uncertainty. But, uncertainty is a latent variable, and in order to quantify the impact of uncertainty on the interest rate (SSR) decisions, one requires ways to measure the former. In this regard, besides the various alternative measures of uncertainty associated with financial markets (such as the implied-volatility indices (popularly called the VIX), realized volatility, idiosyncratic volatility of equity returns, corporate spread associated), primarily three broad approaches to quantify uncertainty exists (Gupta et al., 2018, forthcoming): (1) A news-based approach,

[3] The data can be downloaded from the following link: https://www.rbnz.govt.nz/research-and-publications/research-programme/additional-research/measures-of-the-stance-of-united-states-monetary-policy/comparison-of-international-monetary-policy-measures.

[4] For comparability, all of the estimates are obtained using the Krippner (2013) shadow/lower bound framework with two factors, i.e. the K-ANSM(2), a fixed 12.5 basis point lower bound, and yield curve data with maturities from 0.25 to 30 years with the sample beginning in 1995. SSR estimates can be very sensitive to the model specification, data, and estimation method. Krippner's (2013) approach is designed to be as comparable as possible by holding each of the above aspects consistent between the four economies. In addition, SSR results from different K-ANSM(2) applications are shown by Krippner (2013) to be robust in profile and magnitude, and correspond well with unconventional monetary policy events. These properties do not generally hold for SSR estimates from three-factor models, which includes K-ANSM(3) model of Wu and Xia (2016). Hence our decision to use this database, besides the fact that Wu and Xia (2016) does not report SSR estimates for Japan.

with the main idea behind this method being to perform searches of major newspapers for terms related to economic and policy uncertainty (EPU) and to use the results of this search to construct measures of uncertainty; (2) Measures of uncertainty from estimates of various types of small and large-scale structural models related to macroeconomics and finance. Specifically speaking, the uncertainty measure is the average time-varying variance in the unpredictable component of a large set of real and financial time-series, i.e., it attempts to capture the average volatility in the shocks to the factors that summarize real and financial conditions, and; (3) Uncertainty derived from dispersion of professional forecaster disagreement. As far as the metric of uncertainty is concerned, we use the first approach, i.e., news-based measure of Baker et al., (2016), primarily due to the act that the measure does not require any complicated estimation of a large-scale model to generate it in the first place, and hence, is not model-specific.[5] In addition, the data is available publicly for download.[6]

3.2. Estimates at the Conditional Mean

To fix ideas, Table 1 reports GMM estimates of the Taylor rule equation (1). Inflation, output gap and uncertainty measure are instrumented using appropriately chosen lags of these variables. The set of instruments are determined by choosing lags that are sufficiently long to avoid correlation with the error term. We use the *J*-test (Hansen; 1982) for the validity of overidentifying restrictions for each set of chosen instruments.

The specification for equation (3) allows for a forward-looking rate of inflation 12 months ahead, k=12 for inflation, a contemporary output gap (the dependence of these countries monetary policy on current rather than expected output gaps agrees with general consensus as

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[5] For the US, to measure policy-related economic uncertainty, Baker et al., (2016) construct an index from three types of underlying components. The first component quantifies newspaper coverage of policy-related economic uncertainty; the second component reflects the number of federal tax code provisions set to expire in future years, and; the third component uses disagreement among economic forecasters as a proxy for uncertainty. For the EU, Japan and the UK, the index is based on only the first component.

[6] The data can be downloaded by following the appropriate country (region)-specific links at: http://www.policyuncertainty.com/.

for example in Chevapatrakul et al. (2009)), and a contemporaneous uncertainty measure. We have tried various lags of uncertainty measure and we report the contemporaneous effect since it is of most importance. *, **, *** denote statistical significance at 10%, 5% and 1%, respectively. Our results show that the set of instruments includes a constant, 1-3 lagged values of inflation, output gap and uncertainty measure. The inflation effect is statistically significant satisfying the "Taylor principle" that inflation increases trigger an increase in the real interest rate and the response to uncertainty is significantly negative, confirming the Brainard attenuation principle. This result echoes Chevapatrakul et al. (2009) results for the US. The inflation coefficient estimate for the EU is above one while the estimate for Japan is significant with the wrong sign, with the UK having an insignificant reaction. The response to output gap is significant for the EU and the UK and the response to uncertainty confirms a particularly high negative response while we detect no significant reaction for Japan.

[INSERT TABLE 1 HERE]

3.3. The Taylor Rule at Various Quantiles

Table 2 reports the estimated coefficients at each quantile using Lee's (2007) IVQ. We use an equation with the same set of instruments and the same forward-looking horizon as reported above in Section 3.2.

3.3.1. The Case of the US

The coefficient on the inflation rate is significantly different from zero from the 10th to the 95th quantile. The response is greater than unity above the 50th quantile, supporting the Taylor principle. The responsiveness of the interest rate toward inflation at the upper end of the distribution of interest rate, i.e., at the relatively higher levels of interest rates (and possibly inflation as well) suggests that the Fed responded more aggressively to inflation and hence shows evidence of a deflation bias to monetary policy. In fact, the response to inflation is greater than 1.50 above the 70th quantile distribution of the interest rate and generally increases across quantiles. In contrast, we do not observe evidence of aggressive response as the ZLB is approached in the US.

The response to output gaps is significant from the 20th quantile onwards, with a rather strong response to the output gap when inflation and interest rate are high with the output response being insignificant at low inflation and interest rates. One could possibly argue that the Fed places high importance on inflationary pressures of output during periods of rising inflation.

With respect to the impact of uncertainty on policy, the results indicate that the Fed has been concerned about volatility throughout much of the sample period with a however higher negative response at the zero lower bound when the uncertainty about the conditions in financial markets was important to the interest rate setting behavior from 2008 for a prolonged period of time. So what might not have been an evidence of aggressive response to inflation as the ZLB is approached in the US might well have been translated instead into the decreased reaction to uncertainty as financial markets predicament unfolded. To this end, our results go to complement the findings of Chevapatrakul et al. (2009) who found no detectable evidence of increasing aggression to inflation as the zero lower bound is approached in the US and Japan together with the fact that monetary authorities decrease its reaction to volatility, which are largely consistent with the Brainard's (1967) attenuation principle. This decreased reaction to uncertainty as we approach the zero lower bound translated into a higher cut in the interest rate to expand the economy.[7]

[INSERT TABLE 2 HERE]

[7] We conducted additional robustness analyses to assess the sensitivity of our findings. First, we used a different inflation horizon (i.e., one-month ahead); second, we utilized the average over the month (instead of the end-of-month) measure of shadow short rate; third, we repeated the analysis using the narrower news-based measure of uncertainty, and; finally; we also investigated the quantile interest rate rule estimation using the new method suggested by Lee (2016) which also takes into account the persistence of the regressors. In general, our results were qualitatively similar to those reported in the paper, and are available upon request from the authors.

3.3.2. International Evidence

To highlight the importance of the uncertainty measure and how it contributed to monetary policy instance, we conduct the estimation for the EU, Japan and the UK, and report the results in Table 2 as well, along with that of the US. First, we find a general consensus that uncertainty decreases the monetary authorities' reaction which are largely consistent with the Brainard's (1967) attenuation principle, and the proposition of cautious policy under uncertainty by Blinder (1999), suggesting that the monetary policy maker becomes less aggressive to a particular variable when it becomes more uncertain. Second, we also notice an across the board lesser aggressiveness at lower quantiles of interest rate, meaning that as one approaches the zero lower bound, the central bankers have an incentive to cut the interest rate even more to ensure proper expansionary mechanism in the economy. While the magnitude of the EPU estimates of the EU are roughly in line with the US, we note a particularly high response of this parameter for the UK, most probably highlighting the fact of a small open economy undertaking quantitative easing in the face of increased risk to its highly exposed financial markets. The Bank of Japan reaction to uncertainty is also in line with higher negative response at lower interest rate quantiles. Hence the prevalence of nonlinearity in the reaction to uncertainty by virtually all the central banks lend support to the added information obtained from quantile estimates over estimates at the conditional mean.

4. Conclusion

This paper provides some new results to the conduct of conventional and unconventional monetary policy for advanced economies. Importantly, the paper bridges the gap between existing empirical studies such as Chevapatrakul et al. (2009) that found no detectable evidence of increasing aggression as the zero lower bound is approached in economies such as the US and Japan and the strong theoretical prediction that central banks should guard against the possibility of deflation if they operate near lower bounds by being willing to act especially forcefully, which were done in practice with Quantitative Easing for instance. To tackle this issue, the empirical analysis conducted in this paper makes use of the shadow interest rates, i.e., the nominal interest rate that would prevail in the absence of its effective lower bound and a news-based measure of uncertainty in the aftermath of the recent financial crisis. The results show an increased negative reaction of the Fed and other central banks towards uncertainty particularly at lower quantiles of interest rates, hence lending support to increased aggressiveness as the ZLB is approached.

Other results emerge for the US such as adherence to the Taylor principle not just at the mean of interest rate and inflation but also across the different quantiles of interest rate. The prevalence of nonlinearity is present with the Fed reacting more aggressively at higher levels of interest rate. These results clearly show that relying on linear models to investigate monetary policy reaction functions might be misleading and furthermore measures of uncertainty is of particular importance to gauge monetary policy reaction especially in dire situations such as crisis times.

An issue that we ignore in this paper is possible regime shifts in future monetary policy. As part of future research, it would be interesting to estimate regime-switching quantiles-based Taylor rules as in Liu (2018). In addition, we could also pursue a full-fledged quantile-on-quantile regression estimate of the Taylor rule, based on the development of this methodology by Ma and Koenker (2006), and Sim and Zhou (2015), so that we could accommodate for the asymmetric response of interest rate over its entire conditional distribution corresponding to the various sizes (quantiles) of the output gap, inflation rate and uncertainty.

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Table 1: Conditional mean GMM results

	α_{π}	α_{y}	α_{epu}
EU	1.1578	0.2591***	-6.1573***
Japan	-1.1888**	0.0376	-0.0806
UK	-2.3181	0.3387**	-6.4593***
US	1.4321**	-0.0078	-1.0167***

Notes: Instruments: 3 lags of inflation, output gap and interest rate. Taylor rule: $i_t = \alpha_0 + \alpha_{\pi}\pi_{t+12} + \alpha_y y_t + \alpha_{epu} epu_t$ *,where* i_t *is the end of month shadow interest rate,* π_{t+12} *the forward looking inflation,* y_t *the output gap, and* epu_t *is economic policy uncertainty index.*

Table 2: IVQ (Lee; 2007) results

	τ										
	0.05	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	0.95
Panel A: **Inflation coefficients α_{π}**											
EU	1.1137**	0.1782**	0.2634*	0.2096**	0.1184**	0.3404**	0.2882**	0.2488***	0.2252**	0.3968***	0.0078**
Japan	0.1838	-0.7823	-1.0112	-0.9113**	-0.7776**	-0.9328	-0.3662	0.2545	0.0866	0.1024	0.1083
UK	1.1083	0.4742**	0.1664**	0.2092***	0.2994**	0.2040	0.1246	0.2449	0.4153	0.5465	0.6688***
US	1.1323	1.4597***	0.8343***	0.1478***	0.7185***	1.2776***	1.4844***	1.8906***	2.1985***	2.4423***	2.6881***
Panel B: **Gap coefficients α_{y}**											
EU	0.2667***	0.2944***	0.2675***	0.2805***	0.2681***	0.2318***	0.1909***	0.1611***	0.1601***	0.1572***	0.1388***
Japan	0.1666	0.2160	0.0471***	0.0578***	0.0552**	0.0281***	0.0508***	0.0324***	0.0254**	0.0200**	0.0120***
UK	0.3635***	0.3141***	0.3113**	0.3219***	0.2907***	0.2674***	0.2676***	0.1835***	0.1883***	0.2454***	0.2692***
US	-0.4042	-0.2878	0.0074***	0.0185***	0.0495***	0.0597***	0.2080***	0.3070***	0.3638***	0.5211***	0.5512***
Panel C: **EPU coefficients α_{epu}**											
EU	-0.0935***	-0.0878***	-0.0831***	-0.0791***	-0.0782***	-0.0760***	-0.0727***	-0.0686***	-0.0591***	-0.0570***	-0.0522***
Japan	-0.0153***	-0.0306***	-0.0341***	-0.0341***	-0.0310***	-0.0385***	-0.0145***	0.0011***	-0.0005***	0.0001***	-0.0001***
UK	-7.3442***	-6.9726***	-6.5009***	-6.4039***	-6.3889***	-6.3196***	-6.1370***	-6.0838***	-5.9039***	-5.2520***	-5.0515***
US	-0.1171***	-0.0946***	-0.0958***	-0.1128***	-0.1070***	-0.0955***	-0.0791***	-0.0564***	-0.0384***	-0.0271***	-0.0078***

Notes: Instruments: 3 lags of inflation, output gap and interest rate. Taylor rule: $i_t = \alpha_0(\tau) + \alpha_{\pi}(\tau)\pi_{t+12} + \alpha_y(\tau)y_t + \alpha_{epu}(\tau)epu_t$ *, where* i_t *is the end of month shadow interest rate,* π_{t+12} *the forward looking inflation,* y_t *the output gap, and* epu_t *is the economic policy uncertainty index*