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Neville R. Francis
Laura E. Jackson
and
Michael T. Owyang

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How Has Empirical Monetary Policy Analysis Changed After the Financial Crisis?*

Neville R. Francis  
*Department of Economics  
University of North Carolina, Chapel Hill

Laura E. Jackson†  
*Department of Economics  
Bentley University

Michael T. Owyang  
Research Division  
Federal Reserve Bank of St. Louis

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Abstract

In the wake of the Great Recession, the Federal Reserve lowered the federal funds rate (FFR) target essentially to zero and resorted to unconventional monetary policy. With the nominal FFR constrained by the zero lower bound (ZLB), empirical monetary models cannot be estimated as usual. We investigate whether alternative policy instruments (e.g., long-term rates or the shadow rates proposed by Krippner [2015a] and Wu and Xia [2016]) can be considered substitutes for the FFR over the ZLB period in a standard monetary VAR or whether we must impose breaks. We find that, when using a dataset that spans both the pre-ZLB and ZLB periods, shadow rates act as a fairly good proxy for monetary policy by producing impulse responses of macro indicators similar to what we would expect based on the post-WWII, non-ZLB benchmark and by displaying stable parameter estimates when compared to this benchmark. [JEL codes: E43, E44, E52]

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†175 Forest Street, Waltham, MA 02452 (ljackson@bentley.edu)
1 Introduction

Since the onset of the Financial Crisis, monetary policy in the U.S. has taken unprecedented measures in an effort to stimulate the economy. The Federal Reserve lowered its primary policy instrument—the target for the federal funds rate—essentially to zero.\footnote{Friedman [2010] describes a detailed timeline of the steps taken by the Fed along with significant market events. Williams [2011] reviews the unconventional monetary policies employed during the financial crisis.} At that point, this instrument became ineffective due to the nominal bound at zero and the Fed was forced to resort to unconventional monetary policy.\footnote{Unconventional monetary policy used in the U.S. included quantitative easing (QE), large scale asset purchases (LSAPs), and forward guidance. Walsh [2010] discusses the channels through which QE could stabilize the economy. Wright [2011] analyzes how long-term interest rates respond to LSAP’s in a ZLB environment. Gagnon et al. [2011] present the mechanisms through which these purchases affect the overall macroeconomy. Campbell et al. [2012] discuss the effects of forward guidance.}

From the standpoint of academics, this period presents an important problem for assessing the effects of monetary policy. Many monetary models use the effective nominal federal funds rate (FFR) to represent the stance of policy. Nominal interest rates, however, cannot take on negative values in a world in which cash is a viable alternative to standard short-term assets. Because the nominal FFR has been constrained by the zero lower bound (ZLB) for an extended period, empirical monetary models cannot be estimated as usual. Even in models for which determining the effects of monetary policy is not the primary objective (e.g., measuring the effects of fiscal policy), a proper measure of the stance of monetary policy is often necessary.

The empirical literature offers a number of potential remedies. First, we could treat the ZLB period as special, using either breaks or dummies to represent changes in economic relationships.\footnote{This option could be considered the most extreme as it suggests that the effect of monetary policy is potentially time-varying [see, for example, Aastveit et al. [2014]]. If the effectiveness of policy varies, the Fed must reconsider at each moment the conduct of policy and the appropriate instruments.} Second, we could include alternative policy instruments, such as the size of the balance sheet or dummies representing the implementation of unconventional policies. These two alternatives have the disadvantage of increasing the number of estimated parameters for a period that, presumably, represents a short sample. Third, we could replace the FFR as the conventional stance of monetary policy with a proxy that is allowed to violate the ZLB and that captures the effects of both conventional and unconventional policy.

Since the financial crisis, academics have proposed such proxies of the accommodative stance of monetary policy when the short rate is at the ZLB. Recently, Krippner [2015a] and Wu and Xia...
[2016] have used the shadow rate methodology to construct alternative measures of the stance of policy. Krippner [2015a] builds on Black [1995] and Gorovoi and Linetsky [2004], modeling interest rates as options by calculating the value of a call option to hold cash.\(^4\) Krippner [2015a] derives a continuous-time version of the option-pricing framework and integrates the implied expression for the forward rate to apply the model directly to observed data on interest rates. Alternatively, Wu and Xia [2016] utilizes the discrete-time version of this model to construct an analytical approximation of forward rates, thus producing closed-form expressions used to approximate the shadow forward rates. Both models calculate a shadow short-term interest rate which would be seen in financial markets if the cash option did not exist. In principle, the Fed may have dropped the FFR further if not for the nominal bound at zero. The shadow rate has been considered a proxy for the stance of monetary policy in an environment in which the zero lower bound is binding.\(^5\) From this foundation one can develop a full model of the shadow term structure based upon the shadow short rate depicting the fundamental policy objectives.

In this paper, we compare these approaches to modeling monetary policy at the ZLB in commonly-used, benchmark linear or piecewise-linear models. Many of the papers analyzing monetary policy after the Great Recession either (1) fix the dataset and innovate along the model dimension;\(^6\) (2) fix the model dimension and propose a new measure for the stance of monetary policy;\(^7\) or (3) vary both the policy instrument and the model.\(^8\) We fix the model to be the linear VAR (consistent with the pre-ZLB literature) and consider the use of a variety of different policy instruments.\(^9\)

Our results show that, using the various monetary policy measures, our VARs fail to find any discernible differences in the macroeconomic effects of monetary policy. That is, the impulse

\(^4\)Black [1995] modified the Gaussian affine term structure model (GATSM) to relax the nominal ZLB by introducing a hypothetical instantaneous shadow (zero maturity) interest rate that can take on negative values. When the nominal rate is above the ZLB, the shadow rate takes on the nominal value.

\(^5\)Damjanović and Masten [2016] used shadow short rates in the Euro area and found the results to be sensitive to the probability of sovereign default. Because our focus is on the U.S., we do not face that issue here.

\(^6\)For example, Aastveit et al (2016); Baumeister and Benati (2013); and Feldkircher and Huber (2016) advocate the use of time-varying parameter VARs.

\(^7\)Krippner [2015a] and Wu and Xia [2016] utilize models of the term structure to compute hypothetical shadow short rates meant to replace the funds rate in a zero-lower-bound environment.

\(^8\)For example, Gambacorta, Hoffman and Peersman (2014) consider a model of only the ZLB period—essentially a model with breaks—using the size of the Fed’s balance sheet as a policy instrument.

\(^9\)The main difference between our approach and (1) and (3) is that we ask “can we retain the linear VAR?” rather than “how much does the VAR need to change?” This implicitly assumes the VAR as the reference model and is similar to thinking about switching the null and alternative hypotheses. Unlike the approach of (2), we test multiple alternative policy instruments, including multiple SSRs, long rates, and the balance sheet.
responses using the shadow rate measures (that accounts for the ZLB period) are all contained within the confidence bands of similar impulse responses when we naïvely apply the FFR as policy instrument without accounting for the ZLB period. We also find that the method proposed by Krippner [2015a] delivers stable parameter estimates when the ZLB period is included in the sample. Under the assumption of no structural shift in the conduct of monetary policy, we view the stability of the parameters in favor of using the Krippner shadow rate to represent policy during the unique environment at the ZLB.\textsuperscript{10} However, using either shadow rate is preferable to using the bounded FFR.

The balance of the paper is organized as follows: Section 2 establishes the benchmark VAR that describes monetary policy in the pre-ZLB environment and for the full sample through the end of 2015. In this section, we also test for parameter stability just prior to the onset of the ZLB period. Section 3 examines how we can model some of the actions taken by the Fed at the zero lower bound in these standard models. Section 4 presents some robustness checks. Finally, Section 5 concludes.

2 Establishing a Benchmark

The short rate—often, an overnight rate—is one of the primary instruments for conducting monetary policy. When adverse shocks are large, monetary accommodation can drive the short rate close to zero. In practice, no-arbitrage conditions prevent nominal rates from falling below zero since agents can substitute out of bonds into cash. This feature of nominal interest rates can prevent a proper evaluation of the stance of monetary policy when the short rate is at or near zero and other instruments must be relied upon to conduct policy. In this section, we estimate a standard monetary VAR for the pre-crisis period (1960:I-2007:IV) and then naïvely extend the analysis with data for the financial crisis period.

2.1 The Pre-ZLB VAR

Before we can determine whether empirical models of monetary policy have changed, we must first establish a pre-ZLB benchmark, covering the period from 1960:I to 2007:IV, which starts after

\textsuperscript{10}We make this claim taking the shadow rates as given, without regard to whether the respective methods generate series that can be deemed "appropriate" from an occular metric or justified from a financial model of the term structure.
the Korean War price control period and ends prior to the financial crisis and generally resembles the standard VAR used for monetary analysis prior to the FFR hitting the ZLB. We estimate a quarterly four-variable VAR(4) in output, inflation, commodity prices, and a policy instrument. Our measure of output is the annualized quarterly difference in the log of GDP taken from the BEA. Inflation is measured as the difference in the log of the GDP deflator, obtained from the FRED database maintained by the Federal Reserve Bank of St. Louis. Commodity prices are the log differences in the Producer Price Index: All Commodities. For the benchmark model, we include the effective FFR as the policy instrument.\footnote{We also estimated the VAR in log levels of the macro variables and find no significant changes in the results.} All data are seasonally adjusted.

To fix notation, we write the structural VAR as

$$B_0Y_t = B_1(L)Y_{t-1} + u_t, \quad (1)$$

where $B_1(L)$ is a polynomial in the lag operator, $u_t$ are the iid standard normal and uncorrelated structural shocks. We suppress the constant and any trends for notational simplicity. The corresponding reduced-form VAR is

$$Y_t = A(L)Y_{t-1} + \varepsilon_t,$$

where $A(L) = B_0^{-1}B_1(L)$, $\varepsilon_t \sim N(0, \Sigma)$, and $\Sigma = B_0^{-1}B_0^{-1}$. We estimate the VAR in the reduced form and recover the structural form by imposing restrictions on the contemporaneous effects. In particular, the monetary shock is identified by assuming that FFR can react to macro variables but the macro variables cannot contemporaneously react to shocks to the FFR. Our identification, then, amounts to a recursive ordering; we explore alternative identifications in a later section.

Partitioning $A(L)$ into blocks will facilitate exposition in future sections: Let $X_t$ represent the macro variables of interest and $R_t$ represent the FFR. Then, we can rewrite the VAR as:

$$\begin{bmatrix} X_t \\ R_t \end{bmatrix} = \begin{bmatrix} A^X(L) & A^{RX}(L) \\ A^{XR}(L) & A^R(L) \end{bmatrix} \begin{bmatrix} X_{t-1} \\ R_{t-1} \end{bmatrix} + \begin{bmatrix} \varepsilon^x_t \\ \varepsilon^r_t \end{bmatrix},$$

where $A^X(L)$ represents the effects of the lagged macro variables on each other, $A^{RX}(L)$ represents the effects of policy on the macro variables, $A^{XR}(L)$ represents the feedback from macro variables...
to policy, and $A^R(L)$ represents the possible persistence in FFR. To preserve consistency with results in later sections, the VAR presented here is estimated with Bayesian methods. The prior is a zero-mean Normal-inverse Wishart distribution. The posterior distributions are simulated using the Gibbs sampler.

The left column of Figure 1 shows the impulse responses for the VAR(4) outlined above using the effective nominal FFR as the policy instrument and data for the period ending in 2007:IV. The responses shown are to a 25-basis-point (increase) shock to the effective nominal FFR ordered last in the VAR and identified using the Cholesky decomposition. The responses are computed for each draw of the sampler, generating the posterior coverage. The plots show the median response (blue line) as well as the 90-percent posterior coverage intervals (blue shaded regions). The impulse responses are as expected: Increasing the policy rate causes output to fall and inflation to fall after some time.

2.2 A Naïve Approach to the ZLB Period

A challenge posed by the ZLB period is how to model the use of new monetary instruments that may be omitted from the VAR. One approach would be to ignore the change in the monetary environment and naïvely extend the sample through the ZLB period without accounting for the use of alternative policy instruments. Thus, we reestimate the VAR using data from 1960:I-2015:II to determine how the impulse responses would change if one naïvely extended the sample into the ZLB period.

The right column of Figure 1 shows the impulse responses for the VAR(4) outlined above using the effective nominal FFR as the policy instrument through the ZLB period. The plots show the median responses (dark green line) as well their associated 90-percent posterior coverage intervals (green shaded region) for the naïve full-sample VAR extending the data through 2015:II. The thick dark blue lines and blue shaded regions give the impulse response median point estimates and their 90-percent posterior coverage for the benchmark specification in which the data end in 2007:IV. The responses resemble those of the benchmark in both quantitative and qualitative terms—a contractionary policy shock results in a decrease in output, a (somewhat delayed) eventual decline in inflation, and falling commodity prices.\textsuperscript{12}

\textsuperscript{12}In Section 3.4, we more formally measure the distance between the posterior distributions of the benchmark
The result is not surprising given the preponderance of data in the pre-crisis period. Even though the nominal FFR does not change for a number of years, adding the ZLB period does not qualitatively change the resulting impulse responses to a monetary shock. There are slight quantitative differences from the benchmark, but the impulse responses do not change all that much. Consequently, very little bias results from computing the impulse responses naïvely by including data from both non-ZLB and ZLB periods. However, this exercise does not tell us much about the ZLB period itself since the conventional policy instrument effectively does nothing during this period. While the estimates are slightly different, we can still effectively describe what happens in normal times but we do not know what happens in the ZLB period.

2.3 Testing for Parameter Instability

If one believed that the policy environment changed dramatically at the ZLB, a first reaction might be to impose a break at, say, 2007:IV, just before the nominal funds rate hit the bound. Let $M_0$ and $M_1$ represent the no-break and break models, respectively. To determine whether the data prefer the break model to the no-break model, we compute twice the log of the Bayes Factor to obtain a statistic $B$ that has scale comparable to that of the likelihood ratio test statistic:

$$B = 2 \ln \left( \frac{\pi (Y|M_1)}{\pi (Y|M_0)} \right),$$

where $\pi (Y|M_i)$ is the marginal likelihood of the data, given model $M_i$.\(^\text{13}\)

We construct a dummy variable to indicate data from the ZLB period during the crisis and post-crisis recovery, taking on a value of 0 for dates prior to and including 2007:IV and a value of 1 after 2007:IV. We test for parameter instability in five subsets of the model parameters: (1) a break in the variance/covariance matrix ($\Sigma$) only; (2) a break in the response of macro variables to the policy instrument, $A^{RX} (L)$; (3) a combination of (1) and (2) - breaks in $\Sigma$ and $A^{RX} (L)$; (4) a break the full set of VAR coefficients, $A (L)$; and (5) a combination of (1) and (4) - breaks in $\Sigma$ and $A (L)$. To impose the breaks in (2) and (3), we include an interaction between the ZLB dummy parameters and those estimated with the ZLB data included.

\(^\text{13}\)We compute the marginal likelihood using the output of the Gibbs sampler with the method described in Chib [1995]. We use the scale suggested in Jeffreys [1961] to interpret the strength of evidence against model $M_0$ and in favor of model $M_1$, where values of $B > 6$ are considered strong evidence in favor of the break model. Negative values of $B$ indicate that the no-break model is preferred.
variable and all lags of the policy rate in each of the first three VAR equations. Therefore, the break model allows for a change in the VAR coefficients on the policy rate in each of the equations describing the behavior of the fundamental macroeconomic variables. To impose the breaks in (4) and (5), we include an interaction between the ZLB dummy variable and all lags of the \( Y_t \) vector in all four equations of the VAR.\(^ {14} \)

The first line of Table 1 show the values of \( B \) comparing models for a VAR(4) using the effective FFR as the monetary instrument for the entire post-war sample (1960:I-2015:II).\(^ {15} \) We find strong evidence in favor of breaks in the parameters relating macro variables to monetary policy.\(^ {16} \) The model with parameter instability is favored over the baseline model when allowing for variation in the response of macro variables to the FFR, \( A^{RX}(L) \), and variation in \( \Sigma \). The break in \( A^{RX}(L) \) results from the fact that the fed funds rate exhibits no variation in the post break period, perhaps biasing the coefficients in the no break model. Likewise, the variance of the FFR innovation (and the associated covariances) change in the ZLB period. However, a (simultaneous) break in the full set of model parameters (cases (4) and (5) described above) is not favored. These cases introduce instability in the parameters describing the dynamics among the macro variables or shocks to these variables. It is not clear that these relationships should differ once the economy reaches the ZLB. Furthermore, allowing for parameter instability in the VAR(4) models introduces an excessive number of new parameters to estimate with limited data over the ZLB period; thus, we do not find definitive evidence supporting the models with breaks.\(^ {17} \)

3 Monetary Policy at the ZLB

We want to be able to account for the effects of the Fed’s unconventional monetary policy during the times in which the FFR is at the ZLB. Using the FFR alone to represent policy would erroneously

\(^{14}\)To evaluate the power of our break tests, we use the method described in Chib [1995] to compute the numerical standard errors of the marginal likelihoods used to build the Bayes Factors. Based on the Gibbs draws used in constructing the marginal likelihoods, the numerical standard errors are very small—all less than 0.01 percent of the estimate of the marginal likelihood itself. This would suggest the marginal likelihoods are estimated precisely.

\(^{15}\)Because the number of breaking parameters is potentially large and the sample for the post-break period is short, we estimated a VAR(1) to verify robustness. Results were similar and are available from the authors upon request.

\(^{16}\)We repeat this exercise using only data from the the post-Great Moderation sample (1984:I-2015:II) and find similar results. These are available from the authors upon request.

\(^{17}\)In the VAR(1), this result is overturned. This suggests that breaking a small set of parameters might produce more desirable results than imposing constant parameters. However, breaking the sizable number of parameters in a VAR(4) is not supported.
suggest that the Fed was inactive during the depths of the financial crisis and did little to stimulate the recovery. We need to incorporate the policy accommodation associated with the balance sheet and liquidity programs and the use of forward guidance that were employed by the Fed during the crisis. However, we want to do this in the simplest and most straightforward way possible. In particular, we pose the following question: *Is there a policy instrument that summarizes the stance of monetary policy during the ZLB period that retains the linearity of the VAR?*

Ideally, the new instrument would map back into some observable indicators, allowing one to address policy questions that can be answered in the same linear framework without requiring breaks. Other authors have proposed various alternative policy instruments—e.g., long rates or balance sheet.\(^{18}\)

We first augment the VAR with a long-term interest rate to incorporate how the Fed’s unconventional policies effectively flattened the yield curve by influencing rates at the longer horizon and compare the responses to those of the benchmark VAR model. Finally, we will use the two shadow rate measures that explicitly account for the ZLB period (one adopted from Krippner [2015a] and the other from Wu and Xia [2016]) as proxies for the policy instrument and again compare the impulse responses associated with these measures to the benchmark responses.

### 3.1 Adding Alternative Monetary Instruments

As we mentioned above, during the ZLB period, the Fed began to utilize alternative policy measures intended to provide temporary injections of liquidity and often targeted yields for longer maturity assets. These policies also represented a substantial increase in the Fed’s balance sheet. We consider whether adding a long-term interest rate or the size of the Fed’s balance sheet to the VAR is sufficient to capture the effect of large scale asset purchase programs. In each case, we add the new policy instrument, ordered last, to the baseline VAR and identify shocks to the alternative policy instrument via the Cholesky decomposition.

During the ZLB period, the responses of the macro variables to a shock to the long-term interest rate or to the size of the balance sheet, accounting for the fact that the FFR is already at zero and does not fluctuate after these shocks, are computed using generalized impulse responses (GIRFs),

\(^{18}\) *Meaning and Zhu [2012] measure the response of long rates to changes in the size and composition of the Fed’s balance sheet to evaluate the effects of unconventional policy during the ZLB period. Gambacorta et al. [2014] suggested adding the level of the balance sheet to a VAR for the ZLB period only.*
first proposed by Koop et al. [1996].\textsuperscript{19} We construct GIRFs for all variables in the VAR, restricting the FFR to remain at its initial value at the time of the shock. In this way, we capture aggregate fluctuations as measures of unconventional policy—such as changes in long-term interest rates or the balance sheet—vary, while imposing that the short-term policy instrument is constrained.

Figure 2 compares (1) the GIRF to a 25-basis-point increase in the 10-year Treasury Bond rate in the ZLB with a traditional 25-basis-point increase in the FFR in normal times, and (2) the GIRF of the 10-year T-Bond shock in the ZLB period with a similar T-Bond shock in normal times, allowing the FFR to respond without restriction. The response of GDP growth to the 10-year T-Bond shock in the ZLB resembles the response to the benchmark FFR shock. This suggests that the channel through which policy affects real activity through long rates is similar to the effect via short rates under normal conditions. However, in the ZLB period, the responses of nominal variables, inflation and commodity prices, look more similar to those in response to benchmark long-rate shocks, with no restrictions, rather than conventional FFR shocks. As depicted in Figure 2, the ZLB responses of the FFR are restricted to be zero at all horizons, compared with the richer dynamics in the benchmark when the policy rate is left unconstrained. Finally, the persistence of a shock to the 10-year T-Bond rate under normal or ZLB conditions is almost identical, thus unaffected by the constraints imposed on the short end of the term structure.

We also want to determine whether the addition resolves the need to incorporate breaks. The second lines of each panel in Table 1 compare the break statistic for the VARs that includes the 10-year Treasury Bond rate after the FFR. We find evidence favoring a break in $A^{RX} (L)$ and $\Sigma$ for the full-sample model. The explanatory value of long-term interest rates increases during the early stages of the financial crisis and during the period in which the FFR is lowered towards the ZLB. Incorporating these additional dynamics emphasizes the variation underlying the structural form of the model and amplifies the importance of allowing for parameter instability. This very strong evidence favoring changing coefficients over constant coefficients on lagged values of the policy instrument in the equations for the macro variables suggests that accounting for the unconventional policy via long-term interest rates is not sufficient to maintain VAR linearity.\textsuperscript{20}

\textsuperscript{19}GIRFs use Monte Carlo methods to compute the difference in two indirect forecasts—one conditional on the shock and one conditional on no shock.

\textsuperscript{20}We find some evidence supporting a break in the $\Sigma$ matrix in both the full-sample and post-Great Moderation VAR(1) model. This further supports the need to allow for variation in the volatility of reduced-form shocks at the ZLB.
We also consider adding the size of the Fed’s balance sheet to the VAR to more directly capture the effects of unconventional policy. We estimate the VAR(1) from Section 2.1 with data from 2008:I through 2015:II, including the macroeconomic data in log levels and the FFR in levels.\footnote{The VAR in levels appears to be sensitive to the number of lags included for estimation. Thus, we opt to use one lag for comparison with the results using the shortened dataset with only the ZLB period. This sensitivity stresses the importance of finding a policy measure to replace the FFR rather than adding variables to the VAR.} We obtain comparable results to those found in Gambacorta et al. [2014]: increasing the size of the Fed’s balance sheet has expansionary effects. The naïve approach would then be to simply add the balance sheet to the full-sample VAR. However, shocks to the balance sheet would presumably only represent countercyclical policy action during the ZLB period when the FFR is constrained. Thus, we construct GIRFs to a one-standard-deviation increase in the balance sheet during the ZLB period, again restricting the FFR to remain at its initial level. Figure 3 depicts the expected expansionary effects of such a policy. We evaluate the need for breaks in the VAR coefficients using the balance sheet and compute $B$ for this specification. However, we find no evidence favoring a break under these circumstances. The balance sheet data exhibit considerable volatility during the ZLB period and thus estimates of $\Sigma$ in the post-break sample are too imprecise to suggest a break provides any improvement in model fit. Therefore, we do not report those results in Table 1.

Accounting for shocks to the long-term interest rate or the size of the balance sheet produces a sufficient representation of policy for the full post-war period, including a majority of non-ZLB data. However, augmenting the model in this way may not diminish the need for parameter breaks to model the ZLB period and also might prove to be an inefficient approach for future empirical work once we return to a normal, non-ZLB environment and these supplementary instruments may no longer be important for measuring conventional policy effects. The Fed has a variety of alternative policy programs in its arsenal but does not need to use them when it can adjust the FFR effectively. Including alternative measures of policy in addition to the FFR introduces more parameters to estimate. Furthermore, adding variables specific to the ZLB period is an extreme treatment that mimics a break in the linear VAR. If there do exist breaks in the coefficients during times of crisis, it is very difficult for policymakers to construct meaningful forecasts and obtain a clear guide to the appropriate policy action. In response to this, we pose the question: Can we find a proxy measurement of $R_t$ that captures the stance of policy across all periods? We attempt to answer this question with the use of shadow interest rates.
3.2 Shadow Short Rates

As an alternative to including long rates in the VAR, one could examine the term structure of interest rates to uncover a potential alternative policy instrument.\textsuperscript{22} Black [1995] proposed a model with a hypothetical shadow bond with the same maturity as the policy instrument and an unconstrained shadow interest rate. The nominal short rate, $R_t$, can then be expressed as the maximum of the shadow short rate (SSR), $r_t$, and a (potentially non-zero) lower bound for $r_t$, $\underline{r}$:

$$
R_t = \max\{r_t, \underline{r}\}.
$$

When the nominal rate hits the bound, the SSR is still unconstrained and can fall below $\underline{r}$.\textsuperscript{23} To compare with the Wu and Xia [2016] 3-factor shadow rate, we use the 2-factor model from Krippner [2015a] with a fixed $\underline{r} = 0.25$, which is consistent across both approaches. Krippner [2015b] argues in favor of 2-factor over 3-factor models.\textsuperscript{24}

Krippner [2015a] and Wu and Xia [2016] argue that SSRs can be used to measure the stance of monetary policy when nominal rates hit the ZLB. SSRs, however, are purely financial constructs that do not explicitly take into account their effect on macro variables.\textsuperscript{25} If we are to use SSRs in empirical models of monetary policy, we need to know whether standard VAR models can be extended through the ZLB period by replacing the effective FFR with the exogenously constructed SSR or if the ZLB period, in and of itself, requires a different model.

Figure 4 plots the policy instruments for subsample from 2008:I-2015:II. By construction, the SSR takes the value of the nominal short rate when the nominal short rate is positive. The figure also highlights some of the dates in which the Fed announced unconventional policy actions.

Reading from left to right, the solid vertical lines indicate the announcements of: QE1, QE2, ...

\textsuperscript{22}Bauer and Rudebusch [2016] include macroeconomic factors in the shadow rate model but do not propose using the shadow rate itself to describe the stance of monetary policy. They argue that when the markets anticipate a lift-off might reflect the stance of policy. Krippner [2014] also proposed a number of alternative measures of the stance of policy but suggested that they may not be useful for evaluating the effects of policy in a linear framework.

\textsuperscript{23}Krippner [2015a], Wu and Xia [2016], and Christensen and Rudebusch [2015] each estimate different SSRs and find that they can differ depending on the number of factors and the choice of $\underline{r}$. Krippner [2015a] both experiments with fixed (0 or 25 basis points) or estimated levels of $\underline{r}$. Wu and Xia [2016] fixes $\underline{r}$ at 25 basis points.

\textsuperscript{24}We repeated the exercises of Sections 3.2 and 3.4 for the Krippner [2015a] 2-factor model with $\underline{r} = 0$ and the 3-factor model with $\underline{r} = 0$ and $\underline{r} = 0.25$ and found no qualitative differences. These results are available upon request.

\textsuperscript{25}The SSR developed by Krippner [2012], and discussed subsequently in Krippner [2013a], Krippner [2013b], and Krippner [2015a], is publicly available on the Reserve Bank of New Zealand website. The SSR developed by Wu and Xia [2016] is publicly available on Federal Reserve Bank of Atlanta website. Both SSRs are available at a monthly frequency. The quarterly SSR data is obtained by averaging the monthly values.
Operation Twist, QE3, and the “Taper Tantrum”, the first time the Fed mentioned the possibility of tapering the QE programs. The dashed vertical lines indicate the first usage of the "extended period" language, date-based forward guidance, and threshold-based forward guidance. Following the announcement of QE1 and the use of "extended period" language, both SSRs fall until the announcement of QE2 in 2010:IV. The Krippner SSR rises slightly but then falls again until the Fed’s forward guidance is adjusted to incorporate specific thresholds for the unemployment and inflation rates in 2012:IV. Alternatively, the Wu-Xia SSR stays consistently low and stable until the “Taper Tantrum”.  

To assess the viability of SSRs as a policy instrument, we estimate the same VAR(4) as above, replacing the fed funds rate with a SSR. Figure 5 shows the impulse responses of the VAR using the shadow rates substituted for the effective funds rate at the ZLB. The left column estimates the VAR with the Krippner [2015a] SSR as the policy instrument from 2009:I-2015:II and the right column estimates the VAR with the Wu and Xia [2016] SSR as the policy instrument. We again include the responses to shocks to the FFR from the benchmark specification in blue for comparison. Using either SSR to represent policy generates posterior coverages for the responses of all macro variables similar to the benchmark. The median benchmark responses fall within the posterior coverage for the full-sample analyses in all cases except for medium- and longer-horizon responses of commodity prices.

We consider whether replacing the FFR with the SSRs can eliminate the need for including parameter breaks for the ZLB period. Lines 3 and 4 of Table 1 show B comparing models using the Krippner [2015a] and Wu and Xia [2016] SSRs as the policy instrument, respectively. There is very slight evidence suggesting the need for a shift in the macro responses to the Wu and Xia [2016] SSR in the VAR(4) model over the entire post-war sample. Conversely, when using the Krippner [2015a] SSR, the VAR(4) results always favor the constant-parameter model. This shadow rate takes on greater negative values, suggesting a more accommodative policy stance, which may help recreate the responses to the pre-ZLB FFR shocks.

26For a more detailed discussion, see Krippner [2012] and Wu and Xia [2016].

27Evidence supporting a break in $A^{RX}(L)$ is dimished for the post-Great Moderation subsample.

28Hännikäinen [2016] compares the marginal predictive power of the Krippner [2015a] and Wu and Xia [2016] SSRs for U.S. real activity and inflation using a large dataset including both economic and financial market data and finds that, while both SSRs have out-of-sample predictive power for inflation, the Wu and Xia [2016] shadow rate produces more accurate forecasts. Alternatively, neither SSR has predictive power for real activity.
3.3 Policy Effects During the ZLB Period

These results suggest that replacing the FFR with a SSR is one method to maintaining a consistent linear VAR when estimating a model with data that includes the ZLB period. But are the effects of a SSR shock different if we only use data from the ZLB period? The SSR experiences a substantial downward movement in the early stages of the Great Recession and, thereafter, becomes increasingly negative while the FFR remains near zero. Do these downward movements in the SSRs represent significant policy stimulus associated with unconventional policies when the FFR does not deviate from the ZLB?

Wu and Xia [2016] treat the recessionary period differently than the subsequent period when the economy is no longer in recession but the FFR is still at the ZLB and unconventional policies are still in use. They argue for using the shadow rate to model policy action only after the recessionary conditions subside. We desire a comprehensive measure of policy even during the recessionary period. The large negative shocks that pushed the economy into recession and drove the FFR towards zero are important for determining the validity of the SSR approach to modeling policy in these abnormal environments.

We re-estimate the VAR and include only the period after the onset of the ZLB to look specifically at economic conditions when the SSR should provide more information than the FFR alone. Due to the limited amount of data for this period, we shorten the number of lags in the VAR to include only one lag of the vector of dependent variables. Figure 6 shows both the impulse responses of the benchmark VAR(1) and a VAR(1) where the SSR replaces the FFR over the period from 2008:I through 2015:II. During this time, the nominal FFR remained near zero and, thus, provides little explanatory value regarding the effectiveness of countercyclical monetary policy. The SSR incorporates both the influence of unconventional policy measures on current economic conditions as well as market expectations of future policy. Thus, the responses of macro aggregates to shocks to this alternative policy measurement capture more comprehensive policy action during the severe economic contraction.

The impulse responses are estimated with much less precision and the posterior coverage is considerably wider using only ZLB data; however, the median benchmark responses do tend to fall

\[\text{29} \text{Of course, given the data limitations for this period, error bands are expected to be large and results will be only suggestive.}\]
within the considerably wide posterior coverage. For the ZLB period, the Wu-Xia SSR produces a larger decline in output than the Krippner SSR, which still produces a larger decline than the FFR in the pre-ZLB period.\textsuperscript{30} Not surprisingly, the median responses of inflation and commodity prices fluctuate substantially from the benchmark. During the ZLB period, inflation did not fluctuate much, which appears to amplify the price puzzle. Caution must be taken when interpreting these results as the response of inflation implies a price puzzle in the benchmark VAR(1) but neither of the SSRs replicate this type of response during the ZLB period. Contractionary policy shocks are associated with falling inflation and commodity prices using the Krippner SSR but falling inflation and rising commodity prices with the Wu-Xia SSR. As we previously discussed, the SSR may incorporate future expectations as it extracts data from interest rates and investment decisions.\textsuperscript{31}

### 3.4 Quantifying Distance from the Benchmark Model

Next, we test whether there are appreciable differences in the impulse responses to a shock to the SSR estimated over the full sample versus the responses to a shock to the FFR in our benchmark pre-ZLB sample. To do this, we construct the Kullback-Leibler Divergence (KLD) between the posterior distribution of the benchmark VAR parameters and the posterior distribution of the VAR parameters estimated using the alternative policy instruments.\textsuperscript{32} We can think of the KLD as a type of loss function that measures deviations between distributions.\textsuperscript{33} We take the benchmark, pre-ZLB posterior parameter distributions as the truth and measure the extent to which the posterior distributions differ from this when using the shadow rate proxies.

We also computed the percentage of the posterior of impulse responses with the alternative measurements of policy that overlap with the posterior of impulse responses of the benchmark. We implement this by computing the 90-percent coverage interval of each posterior and then computing

\begin{itemize}
\item \textsuperscript{30}Lombardi and Zhu [2014] construct an alternative version of the shadow rate using a dynamic factor model and treating the federal funds rate as unobserved during the ZLB period. Structural shocks to their shadow funds rate produced by a standard monetary VAR suggest greater stimulus than shocks to the actual federal funds rate.
\item \textsuperscript{31}For robustness, we repeat these impulse response comparisons after adjusting the benchmark to begin after the end of the Great Moderation (1984:I-2007:IV) rather than using the entire post-war sample. We reach the same qualitative conclusions regarding the deviation from the benchmark for full-sample and ZLB sub-sample responses using the FFR and the shadow rates.
\item \textsuperscript{32}While it would be ideal to consider the difference in the distributions of the impulse responses themselves, there is a one-to-one mapping between the impulse responses functions and the VAR coefficient and covariance matrices. Thus, we can use the output of the Gibbs sampler to analyze the posterior distribution of the parameter estimates directly.
\item \textsuperscript{33}The Kullback-Leibler Distance is a metric to assess the deviation of one distribution from another. See Kullback and Leibler [1951] for more details regarding how to construct this distance.
\end{itemize}
the percentage of draws from the posterior of alternative impulse responses that lie *entirely* within the benchmark posterior. Table 2 gives the values of the KLD between the post-war, pre-ZLB benchmark (1960:I-2007:IV) and the full-sample (1960:I-2015:II) when using the FFR and each of the two SSRs. Table 3 shows the percentage of overlap between the posterior distributions of each set of impulse responses.

When including both the pre-ZLB and ZLB periods in the sample, the model with the FFR as the sole policy instrument produces the smallest KLD relative to the benchmark.34 Additionally, the distribution of impulse responses to the FFR overlap the most with the benchmark for three of the four variables in the VAR, ranging from 54% to 82%. The Krippner SSR produces a larger overlap for the response of GDP (80% versus 77%) but the two measurements are comparable, consistent with our previous results using the full-sample. When looking specifically at the ZLB period, the Krippner [2015a] SSR has the smallest KLD and exhibits less variation than the FFR or the Wu and Xia [2016] SSR. Furthermore, the impulse responses to the Krippner SSR overlap the most with the benchmark for three of the four variables in the VAR, ranging from 19% to 43%, substantially more than the other policy measures for these responses. Interestingly, the response of inflation to the Wu-Xia SSR demonstrates the most consistency across subsamples.35

Examining data from the ZLB period in isolation reveals the benefit of exploiting variation in the SSRs to produce a comprehensive representation of policy. We cannot compute the impulse responses of macroeconomic variables to the FFR at the ZLB as it did not exhibit meaningful variation over this time. Alternatively, shocks to the SSRs maintain some of the pre-ZLB structural dynamics of the macro variables. However, there is little consistency in terms of which policy rate produces the most cohesive measurement of policy when merging together non-ZLB and ZLB subsamples. The SSRs provide the greatest consistency if we employ a dataset encompassing the entire post-war period, including the years at the ZLB. Thus, when we sufficiently lift off from zero, the inclusion of a number of years at the ZLB between extended episodes of the more conventional

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34 Using the 3-factor model from Krippner [2015a] with $\varphi = 0$, the KLD is slightly smaller over the full-sample and post-Great Moderation subsamples than that produced using the FFR. This SSR stays closer to zero than the 2-factor and Wu and Xia [2016] versions, taking on values closer to those of the observed FFR.

35 The results are generally invariant to considering only data from the Great Moderation, 1984:I-2007:IV. For the full post-Great Moderation (1984:I-2015:II) sample, the KLD for the FFR model is smaller than those of the two SSR models. The responses of commodity prices and the policy rate to a shock to the FFR overlap the most with the benchmark; however, responses to the Krippner SSR more closely resemble the post-Great Moderation benchmark for GDP and inflation. The Wu-Xia SSR produces the response of inflation most similar to the benchmark.
environment does not seem to prohibit the use of standard, linear VARs to analyze the effects of monetary policy.

4 Robustness

In this section, we test whether the results presented in the previous sections are robust to variation in the data, the method of identification, and the timing of the break.

4.1 Alternative Data Series

We consider a few common variations in the monetary VAR dataset that one might see in the literature. In particular, we explore alternative definitions of inflation, adding the unemployment rate, and adding measures of financial conditions. Table 4 outlines the alternative specifications that we consider.

First, we consider two alternative measures of the inflation rate. We substitute CPI inflation or PCE inflation for the GDP deflator. The results for the full-sample dataset are similar to those produced under the baseline specification. Additionally, the only slight change in the results is for the response of the inflation rate to policy shocks at the ZLB. In the baseline, the response of GDP deflator inflation to the Wu-Xia SSR most closely resembled the benchmark response to the FFR.

Second, we add the unemployment rate to our baseline VAR. The first row of Figure 7 displays the response of the unemployment rate to the FFR in the benchmark, the FFR in the full-sample, and to the two SSRs. The magnitude of the response to the FFR and the Wu-Xia SSR over the full sample is slightly larger than the response to the FFR in the benchmark. The response to the Krippner SSR more closely resembles the benchmark, a result supported by the overlap of the distribution of impulse responses being substantially higher with this policy measure. The other responses are qualitatively unchanged and are available from the authors upon request.

Third, we add two different measures of financial conditions separately to the VAR: the Federal Reserve Bank of Chicago National Financial Conditions Index and the spread between rates on Baa-rated corporate debt and 10-year Treasury bonds. The second and third rows of Figure 7 show the response of these variables to each policy measure in the benchmark or full-sample period. When adding the NFCI to the VAR, the FFR produces the largest percentage of overlap in the
distribution of impulse responses for all variables using the full-sample dataset. With only data at the ZLB, the Krippner SSR now produces the most consistent responses. Qualitatively, the behavior of our macroeconomic variables is unchanged from the simple, four-variable VAR in the baseline. All three policy measures produce similar responses of the credit spread over the full-sample period. The overlap of the distribution of impulse responses is comparable across policy rates. It is difficult for any policy rate to produce consistent responses of the credit spread and commodity prices with only data at the ZLB.

4.2 Alternative Identification

In the previous section, we identified the monetary shock recursively by taking the Cholesky decomposition of the covariance matrix and assuming that the monetary instrument is ordered last. The literature on identifying monetary shocks using VARs, however, utilizes a variety of different identification schemes. Some of these schemes are not easily implemented for unconventional policy. For example, one popular identification scheme uses high frequency fed funds futures data. Because the FFR is at the ZLB, the futures market will not pick up changes in many of the forms of unconventional policy. Instead, we focus on two other methods of identifying monetary shocks: sign restrictions and alternative exclusion restrictions.\textsuperscript{36} For ease of exposition, we provide a qualitative discussion of our findings here but do not include additional figures or quantitative results in the tables. These are available from the authors upon request.

We adopt the common assumption that a contractionary monetary policy shock would cause a decline in output, inflation, and commodity prices. Thus, we implement sign restrictions consistent with this assumption: a contractionary monetary policy shock increases the policy rate and decreases GDP growth, inflation, and PCOM for at least three quarters. To impose these sign restrictions, we follow the methodology of Fry and Pagan [2011].\textsuperscript{37}

The responses of GDP growth and inflation to a contractionary monetary policy shock are comparable across the alternative policy measures. The impulse responses for the pre-ZLB period

\textsuperscript{36}Fry and Pagan [2005] was the first to explore using sign restrictions to identify monetary shocks. Fry and Pagan [2011] have a fairly recent survey. Leeper and Zha [2003] used exclusion restrictions to identify monetary shocks.

\textsuperscript{37}The Fry and Pagan [2011] method first requires estimation of the reduced-form VAR to obtain the $\Sigma$ variance-covariance matrix. Then, we construct a Givens matrix to rotate $\text{chol}(\Sigma)'$ and test whether the impulse responses suggested by this new contemporaneous-impact matrix satisfy the sign restrictions. We retain only those draws which satisfy our conditions. See Fry and Pagan [2011] for a more thorough discussion.
and the full sample, including the ZLB period, generally overlap. The only exception is for the response of PCOM. Thus, there may be alternative sign restrictions one could impose for this variable. When examining the ZLB period in isolation, the responses of GDP and inflation to shocks to the Krippner shadow rate more consistently fall within the posterior coverage from the pre-ZLB subsample.

Secondly, the alternative exclusion restrictions we consider follow the approach of Leeper and Zha [2003]. We separate the variables into three blocks: the macroeconomic block (real GDP, prices, and the unemployment rate); the monetary block (the M2 money stock and the policy instrument); and the financial block (commodity prices). Variables within the macroeconomic block respond to one another contemporaneously but only with a lag to the monetary and financial variables. Monetary variables respond contemporaneously to each other and to output and prices in one dimension, but only with a lag to the financial variables. Financial variables respond contemporaneously to all shocks.

Section 2.1 describes the reduced-form representation of the VAR. To implement this identification scheme, we estimate the structural form, equation (1), where \( Y_t = [PCOM, M2, SSR, GDP, DEF, UR] \) and impose zero restrictions on \( B_0 \). The unrestricted elements of \( B_0 \) can be described by the x’s:

\[
B_0 = \begin{bmatrix}
    x & x & x & x & x \\
    x & x & x \\
    x & x & x \\
    x & x \\
    x & x \\
    x & x \\
\end{bmatrix},
\]

where all other elements are restricted to be zero.

Like the previous results using sign restrictions, the responses of most variables to a contractionary monetary policy shock are qualitatively comparable across policy measures. The full-sample impulse responses tend to overlap with the pre-ZLB responses. Alternatively, when examining the ZLB period in isolation, the impulse responses of M2, the policy rate, and inflation to SSR shocks are contained within the posterior coverage of the responses from the pre-ZLB period more often
than are responses to FFR shocks. The unemployment rate responds similarly to the FFR and the Wu-Xia SSR but the responses of GDP and commodity prices rarely fall within the pre-ZLB posterior coverage for any policy measure. In summary, we obtain similar conclusions from identification via exclusion or sign restrictions to those from the simple Cholesky decomposition in our original specification.

4.3 Varying the Break Dates

We imposed the break in the model when the nominal FFR reached the ZLB. One could make credible arguments that the macroeconomic dynamics—and the effectiveness of monetary policy, in particular—changed either before or after the date at which the policy rate crossed the ZLB. Here, we explore whether the results are robust to altering the break date. We consider potential break dates at each quarter from 2007:IV through 2008:IV by constructing Bayes Factors using the method described in Section 2.3.

For every quarter within this range, we find significant evidence with the FFR of a break in the coefficients in the equations for the macro variables in the VAR and a break in the covariance matrix \( A^{RX}(L) \) and \( \Sigma \). This is consistent with our original results and provides further evidence that linearity of the VAR is violated when using the FFR across pre-ZLB and ZLB periods. We initially found only weak evidence of a break in \( A^{RX}(L) \) in 2007:IV when using the Wu-Xia SSR. This is the only date for which we find any evidence of a break. Furthermore, we find zero evidence suggesting a break is necessary at any of these dates with the Krippner SSR. Both SSRs are much more successful than the FFR at preserving linearity in the model.

5 Conclusions

Researchers attempting to measure the effects of monetary policy during the financial crisis and subsequent recession beginning in 2008 have encountered difficulties when trying to use the FFR which essentially flatlines at zero for much of the period under consideration. We have proposed using the shadow rate as a measure of policy which is able to fluctuate to negative values when the effective central bank policy rate faces a binding constraint at zero. Our results suggest that the shadow rates act as a good proxy for monetary policy throughout the ZLB environment only
if using a dataset that spans both the pre-ZLB and ZLB periods. Furthermore, when considering the ZLB period in isolation, the Krippner [2015a] shadow rate may be successful in characterizing the stance of monetary policy.

Examining the FFR alone may suggest that policy has become inactive or ineffective but the monetary authority has indeed been successful at implementing expansionary policy albeit through alternative mechanisms. An important point to note is that the economy has witnessed a break in the instrument used to enact policy but not a break in the effects of monetary policy on the macroeconomy. Economic researchers use the FFR as a measurement of the policy instrument for the post-WWII era even though the Fed targeted non-borrowed reserves from 1979-1982 and borrowed reserves from late 1982 through the mid-1980’s. It did not stop targeting M1 until 1987 and M2 until 1993 and began announcing formal targets for the FFR only in 1994. Similarly to that change in the behavior of central bankers, the ZLB period beginning in December 2008 has rendered the traditional policy tool impotent for stimulating economic activity. The Fed has successfully utilized balance sheet items as instruments and introduced a much more expansive period of alternative policy measures than the time spent targeting non-borrowed/borrowed reserves. In order to accurately represent monetary policy during this period, we need a surrogate measurement such as the shadow rate.
References


A Tables and Figures

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<td>Wu-Xia Shadow Rate</td>
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Table 1: Bayes Factor Comparison for Parameter Instability. Comparison of log marginal likelihoods of models allowing for parameter instability in the VAR coefficients and/or covariance matrix, using various measures of the policy rate: 1. the effective nominal FFR, 2. the FFR and a long-term interest rate (10-year Treasury Bond rate) in the VAR, 3. the shadow rate of Krippner (2015), and 4. the shadow rate of Wu and Xia (2016). We compare one model assuming constant parameters in the pre-ZLB and ZLB periods with another allowing for a break in some subset of the model parameters. We compute an adjusted Bayes Factor, as described in the text, to convert it to a scale similar to that used in the well-known Likelihood Ratio tests. Interpretation of the Bayes Factors is as follows: * indicates positive evidence in favor of the model with parameter instability, ** indicates strong evidence, and *** indicates very strong evidence.
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<td><strong>Alternative:</strong></td>
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<td>49.53</td>
<td>65.38</td>
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Table 2: Kullback-Leibler Divergence between the posterior distributions of the VAR parameters estimated with the benchmark data, using the FFR, and the posterior distributions when estimating the model using full-sample instrument combining the FFR and shadow rate policy measurements. We compare the distributions to either the full pre-ZLB benchmark (1960:I-2007:IV) or the post-Great Moderation benchmark (1984:I-2007:IV). When estimating the parameters using only ZLB data, we shorten the VAR to include only one lag of the vector of dependent variables and compare the results to VAR(1) results from the benchmark periods.
### Table 3: Percentage of Overlap Between the Posterior Distribution of Impulse Responses to the Benchmark and the Alternative Measurements of Policy - We compute the 90-percent coverage interval of each posterior and then computing the percentage of draws from the posterior of alternative impulse responses that lie entirely within the benchmark posterior.

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<tr>
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### Table 4: Alternative Specifications of Data in the VAR - The data enter into the VAR ordered from top to bottom in the table. We identify monetary policy shocks using a recursive ordering via the Cholesky decomposition.

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Figure 1: Impulse Responses with the FFR - Left Column: Benchmark IRF (1960:I-2007:IV): VAR(4) with GDP growth, GDP Deflator Inflation, Commodity Price Inflation, and the FFR as the policy instrument. The thick blue line and the blue shaded area show the median point estimate and the 90% posterior coverage, respectively, for the impulse responses to a 25 basis-point shock to the policy instrument. Right Column: IRF of full-sample VAR (1960:I-2015:II) using the FFR as the policy instrument through the ZLB period. The thick green line and the green shaded area give the median IRF point estimates and 90% posterior coverage, respectively, incorporating data through the ZLB period without accounting for any potential changing macroeconomic dynamics. The thick blue line and the blue shaded region replicate the plots from the benchmark model.
Figure 2: Generalized Impulse Responses in the ZLB Environment - Left panel: VAR(4) with GDP growth, GDP Deflator Inflation, Commodity Price Inflation, the FFR, and the 10-year Treasury Bond Rate. The thick blue line and the blue shaded area show the median point estimate and the 90% posterior coverage, respectively, for the impulse responses to a 25 basis point shock to the FFR in the non-ZLB environment (1960:I-2007:IV). The thick green line and the green shaded area give the median generalized IRF point estimates and 90% posterior coverage, respectively, of the responses to a 25 basis point increase in the 10-year Treasury Bond Rate during the ZLB environment, restricting the response of the FFR to be zero. Right panel: The blue areas now show the unrestricted responses to a 25 basis point shock to the 10-year T-Bond Rate in the non-ZLB period, compared with the green areas showing the restricted generalized IRF responses to a 25 basis point shock to the 10-year T-Bond Rate in the ZLB period.
Figure 3: Generalized Impulse Responses to Balance Sheet Shocks in the ZLB period - The VAR(1) is estimated with log GDP, log GDP Deflator, log Commodity Price Index, the level of the FFR, and log levels of the size of the Fed’s balance sheet. The thick lines and the shaded areas show the median point estimate and the 90% posterior coverage, respectively, for the impulse responses to a one-standard-deviation increase in the balance sheet during the ZLB environment, restricting the response of the FFR to be zero.
Figure 4: Policy Rates and Unconventional Policy Announcements - Plot of quarterly nominal FFR and shadow rates over the period from 2008:I - 2015:II. The solid vertical lines (left to right) indicate the announcements of: QE1, QE2, Operation Twist, QE3, and the first mentioning of tapering the quantitative easing programs in 2013. The dashed vertical lines indicate the first use of forward guidance associated with the following: "extended period" language, date-based forward guidance, and threshold-based forward guidance.
Figure 5: Impulse Responses Over the Full Sample with the Shadow Rates - Left Column: IRF of full-sample VAR (1960:I-2015:II) using the Krippner (2015) shadow rate as the policy instrument through the ZLB period. The thick green line and the green shaded area give the median IRF point estimates and 90% posterior coverage, respectively, incorporating data through the ZLB period without accounting for any potential changing macroeconomic dynamics. The thick blue line and the blue shaded region replicate the plots from the benchmark IRF (1960:I-2007:IV). Right Column: IRF of full-sample VAR using the Wu and Xia (2016) shadow rate as the policy instrument through the ZLB period.
Figure 6: Impulse Responses in the ZLB Environment with Shadow Rates—First panel: Benchmark IRF (1960:I–2007:IV): VAR(1) with GDP growth, GDP Deflator Inflation, Commodity Price Inflation, and the FFR as the policy instrument. The thick blue line and the blue shaded area show the median point estimate and the 90% posterior coverage, respectively, for the impulse responses to a 25 basis point shock to the policy instrument.

Second panel: IRF of VAR(1) using data from the ZLB period only, 2008:I–2015:II, and using the Krippner (2015) shadow rate as the policy instrument. The thick green line and the green shaded area give the median IRF point estimates and 90% posterior coverage, respectively, using only data from the ZLB period. The thick blue line and the blue shaded region replicate the plots from the benchmark model. Third panel: IRF of VAR(1) using data from the ZLB period only and using the Wu and Xia (2016) shadow rate as the policy instrument.
Figure 7: Impulse Responses of Alternative Data Series Over the Full Sample with the FFR and Shadow Rates - First column: Benchmark IRF (1960:1-2007:IV): VAR(4) with the FFR as the policy instrument. The thick blue line and the blue shaded area show the median point estimate and the 90% posterior coverage, respectively, for the impulse responses to a 25 basis-point shock to the policy instrument. Second panel: IRF of full-sample VAR (1960:1-2015:II) using the FFR as the policy instrument through the ZLB period. The thick green line and the green shaded area give the median IRF point estimates and 90% posterior coverage, respectively, incorporating data through the ZLB period without accounting for any potential changing macroeconomic dynamics. The thick blue line and the blue shaded region replicate the plots from the benchmark model. Third panel: IRF of full-sample VAR using the Krippner (2015) shadow rate as the policy instrument through the ZLB period. Fourth panel: IRF of full-sample VAR using the Wu and Xia (2016) shadow rate as the policy instrument through the ZLB period.