ECONOMIC RESEARCH
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WORKING PAPER SERIES

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Authors	Neville Francis, Laura E. Jackson, and Michael T. Owyang
Working Paper Number	2014-019H
Revision Date	October 2017
Citable Link	https://doi.org/10.20955/wp.2014.019
Suggested Citation	Francis, N., Jackson, L.E., Owyang, M.T., 2017; How Has Empirical Monetary Policy Analysis Changed After the Financial Crisis?, Federal Reserve Bank of St. Louis Working Paper 2014-019. URL https://doi.org/10.20955/wp.2014.019

Published In	Economic Modelling
Publisher Link	https://doi.org/10.1016/j.econmod.2019.04.022

How Has Empirical Monetary Policy Analysis in the U.S. Changed After the Financial Crisis?*

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March 19, 2019

Abstract

During the Great Recession, the Federal Reserve lowered the federal funds rate nearly to zero and began using unconventional monetary policy. A fed funds rate near zero is no longer a proper representation of policy. Thus, empirical models of monetary policy cannot be estimated as usual. We use a linear empirical model to investigate whether alternative instruments such as the balance sheet or shadow rates can replace the fed funds rate to capture unconventional policy. Our objective is to determine whether adding to or replacing the policy instrument can preserve linearity or whether one must allow structural breaks. We include data for both normal and unconventional periods and find that shadow rates preserve linearity better than using a bounded federal funds rate alone, adding the balance sheet, or adding long rates. When short rates are bounded, shadow rates produce similar responses to the unbounded period and alleviate the need for structural breaks.

[JEL codes: E43, E44, E52]

Keywords: zero lower bound, affine term structure

*The authors benefitted from conversations with Anusha Chari, Leo Krippner, Cynthia Wu, Sushanta Mallick, four anonymous referees, and conference participants at the SNDE, CEF, and Midwest Macro. Diana Cooke, Hannah G. Shell, and Kate Vermann provided research assistance. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sector. The views expressed here are the authors' alone and do not reflect the opinions of the Federal Reserve Bank of St. Louis or the Federal Reserve System.

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Highlights

1. Shadow short rates produce dynamics comparable to conventional monetary models
2. Macroeconomic responses vary slightly depending on which shadow rate is used
3. Long rates during the crisis have effects similar to short rates in normal times
4. Exogenous shocks to the Fed's balance sheet produce expansionary responses
5. Results are robust to different data and alternative identification of policy shocks

1 Introduction

The approach to U.S. monetary policy has become unprecedented since the onset of the Financial Crisis. To stimulate the economy, the Federal Reserve lowered its primary policy instrument—the federal funds rate (FFR) target—essentially to zero, where it became ineffective due to the nominal bound at zero. The Fed was then forced to resort to a variety of unconventional monetary policies.[1]

Many monetary models use the FFR to represent the stance of policy. Nominal interest rates, however, do not typically take on negative values in a world in which cash is a viable alternative to standard short-term assets.[2] Because the Fed held its policy instrument at the zero lower bound (ZLB) for an extended period, empirical monetary models cannot be estimated as usual. Thus, academics find it difficult to assess the effects of monetary policy when including the period during which short-term nominal interest rates were near zero.

The empirical literature offers a number of potential remedies. First, we could treat the ZLB period as special, using either breaks to represent changes in economic relationships.[3] Second, we could include alternative policy instruments, such as the size of the balance sheet, that represent the implementation of unconventional policies. Third, we could both treat the ZLB period as special and add alternative policy instruments.[4] These alternatives all have the disadvantage of increasing the number of estimated parameters to include a period that represents a short sample. Moreover, treating the ZLB period with breaks suggests that the effect of monetary policy is time-varying. If the effectiveness of policy varies, the Fed must reconsider at each moment the conduct of policy and the appropriate instruments. Finally, we could replace the FFR with a proxy that can cross the ZLB and that captures the effects of both conventional and unconventional policy.[5]

[1]These unconventional monetary policies include quantitiative easing (QE), large-scale asset purchases (LSAPs), and forward guidance. Walsh (2010) discusses the channels through which QE could stabilize the economy. Wright (2012) 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 could affect the overall macroeconomy. Campbell et al. (2012) discuss the effects of forward guidance. Williams (2011) reviews the unconventional monetary policies employed during the financial crisis. Friedman (2011) describes a detailed timeline of the steps taken by the Fed along with significant market events.

[2]A few countries, including Japan, Sweden, Switzerland, and the countries of the Euro Area, have negative nominal interest rates. Negative rates are possible if there is a carrying cost to cash. See Blinder et al. (2017) for a detailed discussion of central banks' experiences with unconventional policy around the world.

[3]Aastveit et al. (2017); Baumeister and Benati (2013); and Feldkircher and Huber (2018) estimate VARs with time-varying parameters. Other papers, such as Mallick et al. (2017), treat the pre- and post-Crisis subsamples differently.

[4]For example, Gambacorta et al. (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.

[5]Krippner (2015b) and Wu and Xia (2016) use term structure models to compute hypothetical shadow short rates.

In this paper, we compare various approaches to modeling monetary policy when at least a portion of the sample includes a ZLB experience in commonly used benchmark linear or piecewise-linear models.[6] We examine the appropriateness of each approach over the entire post-war sample period and over subsamples. We ask a series of questions: Are these methods accurately capturing the stance of monetary policy? Do these instruments allow for the continued investigation of the macroeconomic effects of monetary policy using linear VARs over various subsamples? Or have economic relationships changed, thus rendering the VAR unsuitable to the continued study of monetary policy and its macroeconomic effects?

We find few discernible differences in the macroeconomic effects of monetary policy. That is, the impulse responses to alternative policy measures are mostly contained within the confidence bands of impulse responses with the FFR as the policy instrument in the pre-ZLB benchmark. We also find that the method proposed by Krippner (2015b) delivers stable parameter estimates when the ZLB period is included in the sample. The stability of the VAR parameters lead us to favor the Krippner shadow rate to represent policy during the unique environment at the ZLB.[7] However, using either shadow rate is preferable to using the bounded FFR. Given the recent interest in monetary studies—and, in particular, the ZLB and unconventional monetary policies—researchers may desire a single, consistent instrument and guidance on the scenarios in which to use that instrument. Our work makes an important contribution in facilitating this selection process for measures of monetary policy.

The balance of the paper is organized as follows: Section 2 establishes the benchmark VAR that describes monetary policy in the pre-ZLB environment (through 2007:IV) and for the full sample (through 2018:III). We 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 ZLB in these VARs. Section 4 presents some robustness checks. Section 5 concludes.

During normal times, these shadow rates are approximately equal to the FFR but can become negative when the FFR reaches the ZLB.

[6] A similar issue arose in the 1980's when the Fed targeted reserves. This brief period, while acknowledged in the literature, has not discouraged the use of the FFR as the policy instrument in monetary models even when using data for that period.

[7] 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.

2 Establishing a Benchmark

The short rate—often an overnight rate—is one of the primary instruments for conducting monetary policy. Adverse shocks can drive the short rate close to zero. Typically, no-arbitrage conditions prevent negative nominal rates, as agents can substitute out of bonds into cash. In this case, other instruments must be relied upon to conduct (and evaluate) monetary policy. In this section, we estimate a standard monetary VAR for the pre-Crisis period and then naïvely extend the analysis with data for the Financial Crisis period.

2.1 The Pre-ZLB VAR

Before we determine whether or how empirical models of monetary policy have changed, we establish a pre-ZLB benchmark, starting after the Korean War price controls and ending prior to the Financial Crisis (1960:I-2007:IV). We estimate a four-lag, quarterly VAR with output, inflation, commodity prices, and a policy instrument. Our measure of output is the difference in the log of quarterly GDP taken from the BEA. Our measure of inflation is the difference in the log of the GDP deflator taken from the FRED database maintained by the Federal Reserve Bank of St. Louis. Our measure of commodity prices is the difference in the log of the KR-CRB Commodity Price Index: All Commodities. For the benchmark model, we include the FFR as the policy instrument.[8] All data are seasonally adjusted. 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.

To fix notation, the structural VAR has the form

$$B_0 Y_t = B_1 (L) Y_{t-1} + u_t, \tag{1}$$

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

[8] We also estimated the VAR in log levels of the macro variables and find no significant changes to our conclusions. The results are available from the authors upon request.

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

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

Partitioning $A(L)$ into blocks facilitates exposition in future sections. Let X_t represent the macro variables of interest and R_t represent the policy instrument; then, the VAR can be written as:

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

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 policy.

The left column of Figure 1 shows the impulse responses from the VAR using the effective nominal FFR as the policy instrument. The responses shown are to a 25-basis-point increase to the FFR. The responses are computed for each draw of the sampler, generating the posterior coverage. The plots show the median response (black line) as well as the 90-percent posterior coverage intervals (gray 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-2018:III to determine how the impulse responses would change if one naïvely extended the sample into the ZLB period.

The right column of Figure 1 plots show the median impulse responses (light gray line) as well their associated 90-percent posterior coverage intervals (light shaded region) for the VAR with the FFR as the policy instrument naïvely extending the data through 2018:III. The thick black lines and dark gray shaded regions show the impulse response median and 90-percent posterior coverage for the benchmark specification where the data end in 2007:IV. The two sets of responses are similar—a contractionary policy shock results in a decrease in output, a (somewhat delayed) decline in inflation, and falling commodity prices. The result is not surprising given the preponderance of data in the pre-crisis period: Although the FFR does not change for a few years, adding the ZLB period produces slight quantitative differences but does not qualitatively alter the responses to a monetary shock.

2.3 Testing for Parameter Instability

If one believed that the policy environment changed, a first reaction might be to impose a single break around the time the FFR hit the ZLB.[9] To determine whether a break is preferred, we compute a Bayesian statistic $\mathcal{B}$ that has scale comparable to a likelihood ratio test statistic:

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

where M_0 and M_1 represent the no-break and break models, respectively, and $\pi\left(Y|M_i\right)$ is the marginal likelihood of the data, given model M_i.[10] Because we do not know whether a structural change in the economy would result from the Financial Crisis or hitting the ZLB, we consider potential break dates at each quarter from 2007:IV through 2008:IV. Thus, the alternative dynamics would persist from the break date until the Fed first lifted its policy target away from the ZLB in

[9] A number of papers have conjectured that the Financial Crisis resulted in changes to how monetary policy transmits to the rest of the economy. At the very least, other papers have argued that alternative monetary policy instruments transmit through different channels. For example, Joyce et al. (2012) argue that unconventional policy is transmitted through shifting the maturity structure of assets in the economy. See also Gertler and Karadi (2011); Cúrdia and Woodford (2011); and von Borstel et al. (2016).

[10] We compute the marginal likelihood using the output of the Gibbs sampler as described in Chib (1995). The scale suggested in Jeffreys (1961) is used to interpret the evidence against model M_0 and in favor of model M_1. Values of $\mathcal{B} > 6$ are considered strong evidence in favor of the break model. Negative values of $\mathcal{B}$ indicate that the no-break model is preferred.

2015:IV. The economy would return to pre-crisis dynamics after this point for the remainder of the sample.

We test for parameter instability in five subsets of the model parameters: (1) the covariance matrix, Σ, only; (2) the response of macro variables to the policy instrument, $A^{RX}(L)$; (3) both Σ and $A^{RX}(L)$; (4) the full set of VAR coefficients, $A(L)$; and (5) both Σ and $A(L)$.[11]

The first row of each section in Table 1 shows the values of $\mathcal{B}$ comparing models for a four-lag VAR using the FFR as the policy instrument for the post-war sample (1960:I-2018:III).[12] We find strong evidence in favor of breaks either in $A^{RX}(L)$ or in Σ after 2008:II and 2008:III. The break in $A^{RX}(L)$ may result from the fact that the FFR does not vary in the post-break period, biasing the coefficients in the no-break model. Similarly, the variance of the innovation to the FFR changes in the ZLB period. However, a break in the full set of VAR coefficients (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, but it is not clear that these relationships would differ once the economy reaches the ZLB.

3 Incorporating Data from the ZLB

We now account for the effects of the Fed's unconventional monetary policy during the ZLB. Using the FFR alone might erroneously suggest the Fed was inactive during the Financial Crisis and did little to stimulate the recovery. We want to incorporate the effect of policies associated with the balance sheet, liquidity programs, and forward guidance but in the simplest and most straightforward way possible. In particular, we pose the following question: *Is there a (single) 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 relate to observable indicators, addressing policy questions that can be answered in the same linear framework but without requiring breaks. Other authors

[11]We evaluate the power of the tests by using the method described in Chib (1995) to compute the numerical standard errors of the marginal likelihoods. We find that the numerical standard errors are small—all less than 0.01 percent of the estimate of the marginal likelihood.

[12]Because the number of breaking parameters is large and the sample for the post-break period is short, we estimated a VAR(1) to verify robustness. We also repeated the exercise using data from the post-Great Moderation period (1984:I-2018:III). In both of these cases, results were similar and are available upon request.

have proposed various alternative policy instruments—e.g., long rates or balance sheet.[13]

3.1 Adding Alternative Monetary Instruments

During the ZLB period, the Fed began 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 either a long-term interest rate or the size of the Fed's balance sheet to the VAR is sufficient to capture the effect of unconventional policy.[14] 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.

We account for the fact that the FFR remains constant during the ZLB period by computing generalized impulse responses (GIRFs) to a shock to the alternative policy instrument.[15] We construct GIRFs for all variables in the VAR, keeping the FFR at its initial value at the time of the shock. We also estimate this five-variable VAR with data from 1960:I-2007:IV to compare the GIRFs to the effects of shocks when the FFR is unbounded.

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 rate shock in the ZLB period with a similar 10-year rate shock in normal times, allowing the FFR to respond without restriction. The response of GDP growth to the 10-year rate shock at the ZLB resembles the response to the benchmark FFR shock, suggesting that the channels through which long rates affect real activity are similar to those for short rates during normal times. On the other hand, the responses of inflation and commodity prices during the ZLB period are similar to those induced by long-rate shocks in the benchmark model. Finally, the persistence of a shock to the 10-year rate under normal or ZLB conditions is almost identical, unaffected by the constraints on short rates.

Next, we ask whether adding the new policy instrument alleviates the need to incorporate

[13] 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.

[14] Swanson (2017) finds that the Fed's large-scale asset purchases had significant and persistent effects on longer-term Treasury yields. Thus, changes in the long-term interest rate may capture some of the effects of the unconventional policy stimulus at the ZLB.

[15] GIRFs (Koop et al. (1996)) use Monte Carlo methods to compute the difference in two indirect forecasts—one conditional on the shock and one conditional on no shock.

breaks. The second lines of each panel in Table 1 show $\mathcal{B}$ for the VARs that include the 10-year rate after the FFR. We find evidence favoring a break in $A^{RX}(L)$ for the full-sample model after 2008:II and 2008:III, similar to the timing of the breaks with the FFR as the sole policy instrument. 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 toward the ZLB. The evidence is in favor of changing coefficients over constant coefficients within $A^{RX}(L)$. Moreover, this suggests that accounting for the unconventional policy via long-term interest rates is not sufficient to maintain VAR linearity.

We also consider adding the size of the Fed's balance sheet to the VAR. We estimate the VAR(1) from Section 2.1 with data from 2008:I through 2015:IV, including the macroeconomic data in the first difference of logs, the FFR in levels, and the size of the balance sheet scaled by GDP.[16] Our results are comparable to Gambacorta et al. (2014): Increasing the size of the Fed's balance sheet has expansionary effects. A naïve approach might add the balance sheet to the full-sample VAR. However, shocks to the balance sheet would represent policy actions only 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, restricting the FFR to its initial level. Figure 3 depicts the expected expansionary effects of such a policy. We then evaluate the need for breaks in the VAR coefficients using the balance sheet but find no evidence favoring a break. The balance sheet data exhibit considerable volatility during the ZLB period due to the Fed's rapid, unprecedented accumulation of assets. Thus, these data produce imprecise estimates of Σ in the post-break sample. As a result, pinning down parameter values within the subsample after the break is difficult, suggesting that a break would not provide any improvement in model fit. Therefore, we do not report those results in Table 1.

While these alternative policy instruments produce impulse responses for the ZLB-period similar to the benchmark, they may not eliminate the need for parameter breaks. Moreover, they also might prove to be inefficient in future empirical work once the economy returns to a non-ZLB environment as they require extra parameters in the VAR. Furthermore, adding variables specific to the ZLB period is an extreme treatment that mimics a break in the linear VAR. If the coefficients change

[16] The VAR with the balance sheet is sensitive to the number of lags. We use one lag to compare with the results using the ZLB-only dataset. This sensitivity stresses the importance of finding a policy measure to replace the FFR rather than adding variables to the VAR.

during times of crisis, it is very difficult for policymakers to construct meaningful forecasts and obtain a clear guide to the appropriate policy action. Thus, we next pose the question: *Can we find a proxy for R_t that captures the stance of policy across all periods?*

3.2 Shadow Short Rates

Academics have proposed replacing the FFR not with long rates or the balance sheet but with a proxy of the stance of monetary policy derived from the term structure of interest rates. Black (1995) and Gorovoi and Linetsky (2004) propose models with a hypothetical shadow bond with the same maturity as the policy instrument and an unconstrained shadow interest rate. Krippner (2015b) and Wu and Xia (2016) use a similar methodology to construct alternative measures of the stance of policy. Krippner (2015b) calculates the value of a call option to hold cash and derives a continuous-time approximation to the option-pricing framework. Wu and Xia (2016) use the discrete-time model to construct an analytical approximation of forward rates, producing closed-form expressions to obtain the shadow rates. Both models calculate a shadow short-term interest rate, which would be seen in financial markets if the cash option did not exist.[17]

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, $\underline{r}$:

$$R_t = \max\left\{r_t, \underline{r}\right\}. \tag{3}$$

When the nominal rate hits the bound, the SSR is still unconstrained and can fall below $\underline{r}$.[18] To compare with the Wu and Xia (2016) 3-factor shadow rate with a fixed $\underline{r} = 0.25$, we use the 2-factor model from Krippner (2015b) with a fixed $\underline{r} = 0.125$. Krippner (2015a) argues in favor of 2-factor over 3-factor models.[19]

Krippner (2015b) and Wu and Xia (2016) argue that SSRs can be used to measure the stance of

[17]The SSR developed by Krippner (2012) and discussed subsequently in Krippner (2013b), Krippner (2013a), and Krippner (2015b) 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.

[18]Krippner (2015b), Wu and Xia (2016), and Christensen and Rudebusch (2015) each estimate SSRs and find that they differ depending on the number of factors and the choice of $\underline{r}$. Krippner (2015b) 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.

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

monetary policy when nominal rates hit the ZLB.[20] SSRs, however, are purely financial constructs that do not explicitly take into account their effect on macro variables. 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.

Figure 4 plots the policy instruments for the subsample from 2008:I-2015:IV. By construction, the SSR takes the value of the nominal short rate when the nominal short rate is positive.[21] The figure also highlights some of the dates when the Fed announced unconventional policies. Reading from left to right, the solid vertical lines indicate the announcements of: QE1, QE2, Operation Twist, QE3, and the "Taper Tantrum," the first time the Fed mentioned the possibility of tapering these 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."[22]

To assess the viability of SSRs as a policy instrument, we estimate the same VAR as above, replacing the FFR 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 (2015b) SSR substituted as the policy instrument from 2009:I-2015:III 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 dark gray 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

[20] Bauer and Rudebusch (2016) include macroeconomic factors in a shadow rate model but do not use the shadow rate to describe the stance of policy. They argue instead for a measure based on when the markets anticipate a lift-off from the ZLB. Krippner (2014) also proposes alternative measures of policy but suggests that they may not be useful for evaluating the effects of policy in a linear framework. Damjanović and Masten (2016) used shadow short rates in the euro area and found the results to be senstive to the probability of sovereign default. Because our focus is on the U.S., we do not face that issue here.

[21] Therefore, we substitute values of the FFR with the shadow rate values from 2009:I-2015:III. The Fed officially lifted its target for the FFR away from zero in December 2015.

[22] For a more detailed discussion, see Krippner (2015b) and Wu and Xia (2016).

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 each section in Table 1 show $\mathcal{B}$ comparing models using, respectively, the Krippner (2015b) SSR and Wu and Xia (2016) SSR as the policy instrument. There is no evidence suggesting the need for a shift in the macro responses to either SSR in the VAR model over the entire post-war sample. These results always favor the constant-parameter model. The SSRs take on negative values, suggesting a more accommodative policy stance, which may help recreate the responses to the pre-ZLB FFR shocks.[23] Both SSRs are more successful than the FFR at preserving linearity in the model.

3.3 Policy Effects During the ZLB Period

Our results suggest that replacing the FFR with a SSR preserves the linearity across subsamples in a VAR estimated with data that includes the ZLB period. But are the effects of a SSR shock different when estimated using only data from the ZLB period? Wu and Xia (2016) treat the recession differently from the subsequent recovery period, even though the Fed was still employing unconventional policies. Wu and Xia (2016) argue for using the shadow rate only after the recession ends. Here, we consider whether SSRs might be a comprehensive proxy that can be used even during the recessionary period.

We reestimate the VAR, including only the data from the onset of the ZLB until the Fed lifted its target away from zero (2008:I through 2015:IV), a period when the SSR should provide more information than the FFR alone. Due to the limited amount of data for this period, we estimate the VAR with only one lag.[24] Figure 6 shows both the impulse responses of the benchmark VAR reestimated with one lag and a one-lag VAR where the SSR replaces the FFR. SSRs account for both the unconventional policy effects on macroeconomic variables and market expectations of future policy. Thus, responses to SSR shocks may capture more comprehensive policy effects during the economic contractions.

The impulse responses are estimated with less precision when using only ZLB data; however,

[23] Hännikäinen (2017) compares the marginal predictive power of the Krippner (2015b) 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) SSR produces more accurate forecasts. Alternatively, neither SSR has predictive power for real activity.

[24] Given the data limitations for this period, error bands are expected to be large and results will be only suggestive.

the median benchmark responses do tend to fall within the posterior coverage. For the ZLB period, the Wu-Xia SSR produces a larger decline in output than the Krippner SSR, which produces a larger decline than the FFR in the pre-ZLB period.[25] 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 one-lag version of the benchmark VAR; but neither of the SSRs replicate this 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.[26]

3.4 Quantifying Distance from the Benchmark Model

While we can eyeball graphical depictions of the impulse responses to assess similarity, we also desire a quantitative metric to see which of the alternative specifications are "closest" to the baseline, pre-crisis VAR. A joint test of parameter equivalence would not work for this purpose. Instead, we use a distance measure—the Kullback-Leibler Divergence (KLD)—that considers the proximity of the entire joint parameter distribution of each alternative to the baseline.[27] For this experiment, we take the benchmark, pre-ZLB posterior parameter distributions as the truth and measure the deviation when using the SSRs as proxies. We also compute the percentage overlap of the impulse response coverages using the benchmark FFR and the alternative policy series. The percentage overlap is obtained by determining the percentage of draws from a 90-percent coverage interval for the alternative impulse responses that lie *entirely* within the benchmark posterior.

The top panel of Table 2 shows the values of the KLD between the post-war, pre-ZLB benchmark (1960:I-2007:IV) and the full-sample (1960:I-2018:III) when using the FFR and each of the two

[25]Lombardi and Zhu (2018) construct a SSR using a factor model, treating the FFR as unobserved during the ZLB period. Structural shocks to their SSR also suggest greater stimulus than shocks to the FFR.

[26]For robustness, we repeat this exercise for a benchmark that includes only the Great Moderation data (1984:I-2007:IV). We reach the same qualititative conclusions.

[27]See Kullback and Leibler (1951) for more details regarding how to construct this distance. Because the KLD considers the parameter distribution, and thus accounts for parameter uncertainty, it should be viewed as an ordinal measure. Thus, we can assert that one alternative specifcation's VAR is 'further' from the baseline than another but we do not assert that they are "significantly different".

SSRs. Table 3 shows the percentage overlap between the posterior distributions of each set of impulse responses using the full sample (top half of the table) and the Great Moderation sample (bottom half of the table) as a benchmark. 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 and substantial overlap with the benchmark (ranging from 49% to 72% for three of the four variables).[28] The response of GDP to the Wu-Xia SSR overlaps most (89%) but all three policy measures are comparable, consistent with our full-sample results.[29]

When looking at only the ZLB period (2008:I-2015:IV), the Krippner SSR has the smallest KLD and has responses that overlap most with the benchmark. Interestingly, the response of inflation to the Wu-Xia SSR demonstrates the most consistency across subsamples. Examining data from the ZLB period in isolation reveals the benefit of using the SSRs as a proxy of policy. At the ZLB, the FFR did not exhibit meaningful variation; on the other hand, the SSRs do move and tend to preserve some of the pre-ZLB dynamics in the responses of the macro variables. However, we see from Table 3 that the overlap between the impulse response posteriors is small regardless of the alternative policy instrument. While the smaller overlap may result from the use of a one-lag VAR or result from the short sample, it also may suggest that, if the primary motivation is to model the ZLB-period alone, parameter breaks in the VAR might be necessary.

4 Robustness

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

4.1 Alternative Data Series

We consider a few variations of the dataset, in particular, alternative definitions of inflation, adding the unemployment rate, and adding measures of financial conditions. See Table 4.

[28]The 3-factor, $\underline{r} = 0$ SSR from Krippner (2015b) yields a KLD slightly smaller than the FFR for the full-sample and post-Great Moderation subsample. 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.

[29]If we limit the data to the post-Great Moderation sample (1984:I-2018:III), we find that the Krippner SSR replicates the benchmark better for nominal variables (inflation and commodity prices) but the Wu-Xia SSR replicates the benchmark better for GDP and provides a slight improvement for the policy rate. Overall, the performance of any alternative seems to be diminished when comparing only to the Great Moderation sample benchmark.

First, we substitute either CPI inflation or PCE inflation for the GDP deflator. Results for output, the policy instrument, and commodity prices remain robust. However, we observe some slight differences in which policy series produces the most consistent inflation response across subsamples. For the full sample, the FFR produced more consistent inflation responses than the SSRs when using the GDP deflator as the price measure; on the other hand, the Krippner SSR outperforms the other policy measures when using CPI or PCE inflation. Furthermore, the response of GDP deflator inflation to the Krippner SSR during the ZLB environment most closely resembled the benchmark response to the FFR. For PCE inflation, using ZLB data, the Wu-Xia SSR produced responses most consistent with the benchmark; however, no policy measure consistently reproduced the responses of CPI inflation at the ZLB.

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, to the FFR in the full sample, and to the two SSRs.[30] The magnitudes of the responses to the FFR and the Wu-Xia SSR over the full sample are 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 separately add two measures of financial conditions: (i) the Federal Reserve Bank of Chicago National Financial Conditions Index (NFCI) and (ii) the spread between rates on Baa-rated corporate debt and 10-year Treasury bonds.[31] 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.[32] When adding the NFCI to the VAR, the FFR produces the largest percentage of overlap in the distribution of impulse responses for inflation, commodity prices, and the policy rate using the full-sample dataset. The responses of GDP and financial conditions to the Wu-Xia shadow rate

[30] The unemployment rate shows a negligible, insignificant negative response at the very short horizon, followed by a significant increase after just a few quarters. This is consistent with the findings of Christiano et al. (1996) that real activity contracts with a delay in response to a tightening of monetary policy.

[31] We order the NFCI before the FFR in order to allow for a potential channel through which monetary policymakers respond to fluctuations in financial markets. Alternatively, we order the spread between Baa and 10-year Treasury bond rates after the FFR, as longer-term rates should respond on impact to any change in the short-term policy rate.

[32] We find evidence that the interest rate spread falls for a short period following a contractionary monetary policy shock. This is consistent with Merton (1974) in which corporate debt is viewed as a contingent claim on a firm's underlying value. When interest rates rise, the expected future value of a firm's assets would rise, lowering the risk of default, leading to a lower corporate credit spread. This finding has been supported by a number of subsequent studies including Longstaff and Schwartz (1995) and, more recently, Dupoyet et al. (2018).

over the full-sample are slightly more consistent with the benchmark. 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 credit spread responses over the full-sample period. The overlap of the distribution of impulse responses is comparable across policy rates. No policy rate produces consistent responses of inflation, the credit spread, and commodity prices with only data at the ZLB.

4.2 Alternative Identification

We have previously identified the monetary shock by computing the Cholesky decomposition of the covariance matrix, assuming the monetary instrument is ordered last. The literature on identifying monetary shocks using VARs, however, uses 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, unconventional policy may not result in changes in the fed funds futures market at any horizon.

Instead, we focus on two other methods of identifying monetary shocks: sign restrictions and alternative exclusion restrictions.[33] 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 results 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).[34]

The responses of all macro variables to a contractionary monetary policy shock are comparable across the alternative policy measures. The impulse responses for the pre-ZLB period and the full sample, including the ZLB period, generally overlap. When examining the ZLB period in isolation,

[33] Uhlig (2005) was the first to explore using sign restrictions to identify monetary shocks. Fry and Pagan (2011) have a recent survey. Leeper and Zha (2003) used exclusion restrictions to identify monetary shocks.

[34] The Fry and Pagan (2011) method constructs a Givens matrix to rotate the Cholesky decomposition of the reduced-form covariance matrix. The procedure is repeated numerous times, retaining only those draws that satisfy the sign restrictions. See Fry and Pagan (2011) for a more thorough discussion.

the responses of GDP, inflation, and commodity prices to shocks to the Krippner shadow rate more consistently fall within the posterior coverage from the pre-ZLB subsample.

Secondly, we consider alternative exclusion restrictions that 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:

$$B_0 = \begin{bmatrix} \text{x} & \text{x} & \text{x} & \text{x} & \text{x} & \text{x} \\ & \text{x} & \text{x} & & & \\ & \text{x} & \text{x} & \text{x} & \text{x} & \\ & & & \text{x} & & \\ & & & \text{x} & \text{x} & \\ & & & \text{x} & \text{x} & \text{x} \end{bmatrix},$$

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 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 in both the pre-ZLB and ZLB periods. However, 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.

5 Conclusions

Researchers attempting to measure the effects of monetary policy during the Financial Crisis and 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 consider a variety of potential treatments for measuring the effects of monetary policy at the ZLB: naïvely using the bounded FFR itself, including long-term interest rates or the Fed's balance sheet in addition to the FFR, or substituting a shadow rate for the FFR as a proxy measure of policy. Our results suggest that the channel through which policy affects real activity through long rates during the Financial Crisis is similar to the effect via short rates under normal conditions. Exogenous changes in the size of the Fed's balance sheet also produce expansionary responses of key macroeconomic variables. However, these treatments do not preserve linearity in the model.

The main benefit of utilizing the shadow rates is that they are able to take on negative values when the effective policy rate faces a binding constraint at zero. We find that the shadow rates act as a good proxy for monetary policy throughout the ZLB environment if using a dataset that spans both the pre-ZLB and ZLB periods. Considering only the Great Moderation period weakens our result but the qualitative features persist. Furthermore, when considering the ZLB period in isolation, shadow rates may be successful in characterizing the stance of monetary policy. Evidence for this period, however, is limited due to the small sample. Since ZLB episodes are relatively rare, the preferable solution would be to avoid changing the entire model to accommodate variation in the implementation of monetary policy. The shadow rates allow one alternative for addressing this issue while still maintaining a simple, linear characterization of the economy.

Examining the FFR alone may suggest that policy has become inactive or ineffective even if 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, the ZLB period beginning in December 2008 rendered the traditional policy tool impotent for stimulating economic activity. The Fed has successfully used 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

Aastveit, K. A., Carriero, A., Clark, T. E., Marcellino, M., August 2017. Have standard VARs remained stable since the crisis? Journal of Applied Econometrics 32 (5), 931–951.
URL https://doi.org/10.1002/jae.2555

Bauer, M. D., Rudebusch, G. D., 2016. Monetary policy expectations at the zero lower bound. Journal of Money, Credit and Banking 48 (7), 1439–1465.
URL http://hdl.handle.net/10.1111/jmcb.12338

Baumeister, C., Benati, L., June 2013. Unconventional monetary policy and the great recession: Estimating the macroeconomic effects of a spread compression at the zero lower bound. International Journal of Central Banking 9 (2), 165–212.

Black, F., December 1995. Interest rates as options. The Journal of Finance 50 (5), 1371–1376.
URL https://doi.org/10.1111/j.1540-6261.1995.tb05182.x

Blinder, A., Ehrmann, M., de Haan, J., Jansen, D.-J., 2017. Necessity as the mother of invention: Monetary policy after the crisis. Economic Policy 32 (92), 707–755.
URL https://doi.org/10.3386/w22735

Campbell, J. R., Evans, C., Fisher, J. D., Justiano, A., 2012. Macroeconomic effects of Federal Reserve forward guidance. Brookings Papers on Economic Activity 44, 1–80.

Chib, S., December 1995. Marginal likelihood from the Gibbs output. Journal of the American Statistical Association 90 (432), 1313–1321.

Christensen, J. H., Rudebusch, G. D., 2015. Estimating shadow-rate term structure models with near-zero yields. Journal of Financial Econometrics 13 (2), 226–259.
URL https://doi.org/10.1093/jjfinec/nbu010

Christiano, L. J., Eichenbaum, M., Evans, C., 1996. The effects of monetary policy shocks: Evidence from the flow of funds. Review of Economics and Statistics 78, 16–34.

Cúrdia, V., Woodford, M., 2011. The central-bank balance sheet as an instrument of monetary

policy. Journal of Monetary Economics 58 (1), 54–79.
URL https://doi.org/10.1016/j.jmoneco.2010.09.011

Damjanović, M., Masten, I., 2016. Shadow short rate and monetary policy in the Euro Area. Empirica 43 (2), 279–298.
URL https://doi.org/10.1007/s10663-016-9328-4

Dupoyet, B., Jiang, X., Zhang, Q., October 2018. A new take on the relationship between interest rates and credit spreads.

Feldkircher, M., Huber, F., 2018. Unconventional U.S. monetary policy: New tools, same channels? Journal of Risk and Financial Management 11 (4), 1–31.
URL https://doi.org/10.3390/jrfm11040071

Friedman, B. M., 2011. Learning from the crisis: What can central banks do? Challenges to Central Banking in the Context of Financial Crisis.

Fry, R., Pagan, A., December 2011. Sign restrictions in structural vector autoregressions: A critical review. Journal of Economic Literature 49 (4), 938–960.
URL https://doi/org/10.1257/jel.49.4.938

Gagnon, J., Raskin, M., Remache, J., Sack, B., March 2011. The financial market effects of the Federal Reserve's large-scale asset purchases. International Journal of Central Banking.

Gambacorta, L., Hofmann, B., Peersman, G., 2014. The effectiveness of unconventional monetary policy at the zero lower bound: A cross-country analysis. Journal of Money, Credit and Banking 46 (4), 615–642.
URL https://doi.org/10.1111/jmcb.12119

Gertler, M., Karadi, P., 2011. A model of unconventional monetary policy. Journal of Monetary Economics 58 (1), 17–34.
URL https://doi/org/10.1016/j.jmoneco.2010.10.004

Gorovoi, V., Linetsky, V., January 2004. Black's model of interest rates as options, eigenfunction expansions and Japanese interest rates. Mathematical Finance 14 (1), 49–78.
URL https://doi.org/10.1111/j.0960-1627.2004.00181.x

Hännikäinen, J., 2017. The shadow rate as a predictor of real activity and inflation: Evidence from a data-rich environment. Applied Economics Letters 24 (8), 527–535.
URL https://doi.org/10.1080/13504851.2016.1208347

Jeffreys, H., 1961. Theory of Probability, 3rd Edition. Oxford University Press.

Joyce, M., Miles, D., Scott, A., Vayanos, D., November 2012. Quantitative easing and unconventional monetary policy - an introduction. The Economic Journal 122 (564), 271–288.
URL https://doi.org/10.1111/j.1468-0297.2012.02551.x

Koop, G., Pesaran, H. M., Potter, S. M., 1996. Impulse response analysis in nonlinear multivariate models. Journal of Econometrics 74 (1), 119–147.
URL https://doi.org/10.1016/0304-4076(95)01753-4

Krippner, L., March 2012. Modifying Gaussian term structure models when interest rates are near the zero lower bound. Reserve Bank of New Zealand Discussion Paper Series.

Krippner, L., January 2013a. Measuring the stance of monetary policy in zero lower bound environments. Economics Letters 118 (1), 135–138.
URL https://doi.org/10.1016/j.econlet.2012.10.011

Krippner, L., 2013b. A tractable framework for zero lower bound Gaussian term structure models. Reserve Bank of New Zealand Discussion Paper Series.

Krippner, L., January 2014. Measuring the stance of monetary policy in conventional and unconventional environments. Centre for Applied Macroeconomic Analysis Working Paper (6/2014).

Krippner, L., 2015a. A comment on Wu and Xia (2015), and the case for two-factor shadow short rates. Center for Applied Macroeconomic Analysis Working Paper Series (48/2015).

Krippner, L., 2015b. Zero Lower Bound Term Structure Modeling: A Practitioner's Guide. Palgrave-Macmillan.
URL https://doi.org/10.1057/9781137401823

Kullback, S., Leibler, R., March 1951. On information and sufficiency. The Annals of Mathematical Statistics 22 (1), 79–86.

Leeper, E., Zha, T., 2003. Modest policy interventions. Journal of Monetary Economics 50 (8), 1673–1700.
URL https://doi.org/10419/100848

Lombardi, M., Zhu, F., December 2018. A shadow policy rate to calibrate U.S. monetary policy at the zero lower bound. International Journal of Central Banking 14 (5).

Longstaff, F., Schwartz, E., 1995. A simple approach to valuing risky fixed and floating rate debt. The Journal of Finance 50, 789–820.
URL https://doi.org/10.2307/2329288

Mallick, S. K., Mohanty, M., Zampolli, F., 2017. Market volatility, monetary policy and the term premium. BIS Working Papers (606).

Meaning, J., Zhu, F., March 2012. The impact of Federal Reserve asset purchase programmes: Another twist. BIS Quarterly Review, 23–32.

Merton, R. C., 1974. On the pricing of corporate debt: The risk structure of interest rates. The Journal of Finance 29, 449–470.
URL https://doi.org/10.2307/2978814

Swanson, E. T., November 2017. Measuring the effects of Federal Reserve forward guidance and asset purchases on financial markets. NBER Working PapersWorking Paper 23311.
URL https://doi.org/10.3386/w21816

Uhlig, H., 2005. What are the effects of monetary policy on output? Results from an agnostic identification procedure. Journal of Monetary Economics 52, 381–419.
URL https://doi.org/10.1016/j.jmoneco.2004.05.007

von Borstel, J., Eickmeier, S., Krippner, L., 2016. The interest rate pass-through in the Euro Area during the sovereign debt crisis. Journal of International Money and Finance 68, 386–402.
URL https://doi.org/10.1016/j.jimonfin.2016.02.014

Walsh, C. E., 2010. Using monetary policy to stabilize economic activity. In: Financial Stability and Macroeconomic Policy. pp. 245–296.

Williams, J. C., September 2011. Unconventional monetary policy: Lessons from the past three years. Presentation, Swiss National Bank Research Conference.

Wright, J. H., November 2012. What does monetary policy do to long-term interest rates at the zero lower bound? The Economic Journal 122 (564), F447–F466.
URL https://doi.org/10.1111/j.1468-0297.2012.02556.x

Wu, J. C., Xia, F. D., 2016. Measuring the macroeconomic impact of monetary policy at the zero lower bound. Journal of Money, Credit and Banking 48, 253–291.
URL https://doi.org/10.1111/jmcb.12300

A Tables and Figures

Bayes Factor Test for Parameter Instability in U.S. Monetary Policy					
Jeffrey's scale for evidence in favor of parameter instability in VAR(4) coefficients					
	Full-Sample (1960 − 2018)				
	$p = 4$				
Break after 2007:IV in:	Σ	$A^{RX}(L)$	Σ and $A^{RX}(L)$	$A(L)$	Σ and $A(L)$
Federal Funds Rate	−10.86	−14.57	−27.98	−146.89	−151.10
FFR + 10-year T-Bond Rate	−17.45	−12.64	−33.77	−248.16	−263.04
Krippner Shadow Rate	−36.16	−32.92	−72.63	−165.39	−201.53
Wu-Xia Shadow Rate	−28.88	−22.01	−53.47	−147.76	−164.90
Break after 2008:I in:	Σ	$A^{RX}(L)$	Σ and $A^{RX}(L)$	$A(L)$	Σ and $A(L)$
Federal Funds Rate	−2.70	−10.73	−14.87	−142.38	−148.44
FFR + 10-year T-Bond Rate	−15.81	−7.90	−25.99	−241.74	−257.97
Krippner Shadow Rate	−38.08	−33.80	−73.16	−164.82	−200.73
Wu-Xia Shadow Rate	−16.49	−23.08	−41.77	−147.22	−164.93
Break after 2008:II in:	Σ	$A^{RX}(L)$	Σ and $A^{RX}(L)$	$A(L)$	Σ and $A(L)$
Federal Funds Rate	0.36	4.13*	2.86*	−130.11	−137.56
FFR + 10-year T-Bond Rate	−12.50	5.88*	−8.39	−227.58	−245.53
Krippner Shadow Rate	−32.73	−33.58	−68.64	−160.09	−196.18
Wu-Xia Shadow Rate	−13.03	−21.98	−36.93	−141.71	−159.46
Break after 2008:III in:	Σ	$A^{RX}(L)$	Σ and $A^{RX}(L)$	$A(L)$	Σ and $A(L)$
Federal Funds Rate	1.85*	4.68*	4.95*	−127.93	−135.33
FFR + 10-year T-Bond Rate	−13.61	7.95**	−6.94	−218.68	−235.94
Krippner Shadow Rate	−32.99	−34.42	−68.06	−160.56	−194.26
Wu-Xia Shadow Rate	−12.71	−23.59	−34.30	−141.98	−160.75
Break after 2008:IV in:	Σ	$A^{RX}(L)$	Σ and $A^{RX}(L)$	$A(L)$	Σ and $A(L)$
Federal Funds Rate	0.07	−8.58	−8.23	−149.34	−156.77
FFR + 10-year T-Bond Rate	−14.74	−7.80	−22.17	−240.58	−258.48
Krippner Shadow Rate	−35.88	−29.34	−65.40	−177.82	−210.58
Wu-Xia Shadow Rate	−14.91	−20.00	−32.23	−156.06	−174.06

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.

Kullback-Leibler Divergence		
Benchmark:	**1960:I-2007:IV**	
Alternative:	**Full-Sample: VAR(4)**	**ZLB: VAR(1)**
	(1960 – 2018)	(2008 – 2015)
Federal Funds Rate	**26.89**	161.54
Krippner Shadow Rate	30.98	**80.36**
Wu-Xia Shadow Rate	31.53	122.94
Benchmark:	**1984:I-2007:IV**	
Alternative:	**Post-Great Moderation**	**ZLB**
	(1984 – 2018)	(2008 – 2015)
Federal Funds Rate	**122.74**	97.87
Krippner Shadow Rate	166.76	**53.51**
Wu-Xia Shadow Rate	135.22	73.89

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.

Percentage of Overlap - IRF Posteriors				
Benchmark:	**1960:I-2007:IV**			
Alternative:	**1960:I-2018:III: VAR(4)**			
	GDP	INF	PCOM	Policy
Federal Funds Rate	0.88	0.62	0.49	0.72
Krippner Shadow Rate	0.86	0.49	0.35	0.45
Wu-Xia Shadow Rate	0.89	0.48	0.40	0.58
Alternative:	**2008:I-2015:IV: VAR(1)**			
	GDP	INF	PCOM	Policy
Federal Funds Rate	0.00	0.00	0.00	0.00
Krippner Shadow Rate	0.14	0.01	0.00	0.18
Wu-Xia Shadow Rate	0.00	0.00	0.00	0.14
Benchmark:	**1984:I-2007:IV**			
Alternative:	**1984:I-2018:III: VAR(4)**			
	GDP	INF	PCOM	Policy
Federal Funds Rate	0.28	0.58	0.09	0.68
Krippner Shadow Rate	0.12	0.85	0.10	0.39
Wu-Xia Shadow Rate	0.41	0.60	0.08	0.69
Alternative:	**2008:I-2015:IV: VAR(1)**			
	GDP	INF	PCOM	Policy
Federal Funds Rate	0.00	0.00	0.00	0.00
Krippner Shadow Rate	0.03	0.08	0.00	0.17
Wu-Xia Shadow Rate	0.00	0.00	0.00	0.09

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.

Robustness: Alternative Data					
Baseline	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
GDP	GDP	GDP	GDP	GDP	GDP
Deflator	CPI	PCE	UR	Deflator	Deflator
PCOM	PCOM	PCOM	Deflator	PCOM	PCOM
SSR	SSR	SSR	PCOM	NFCI	SSR
			SSR	SSR	Baa-10yT

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.

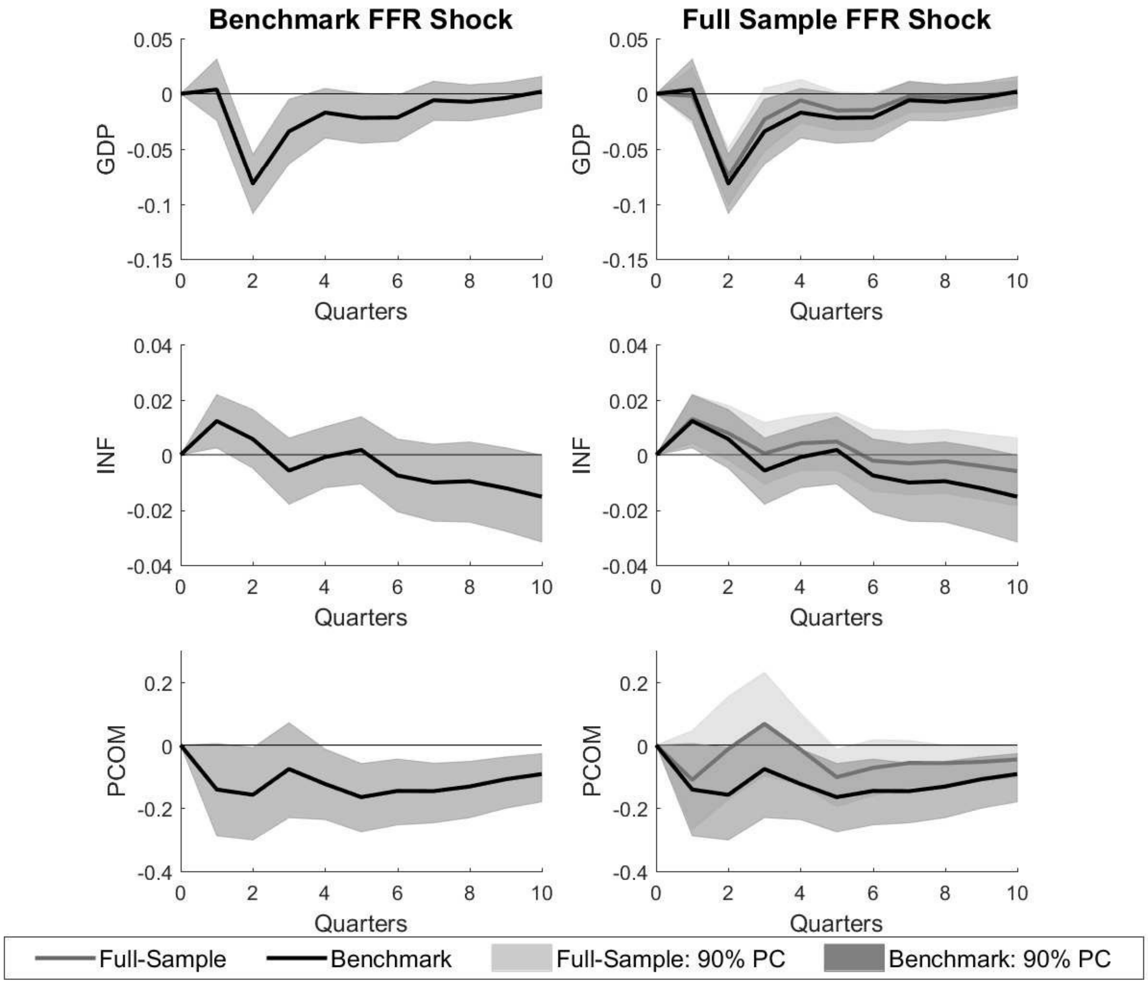

Figure 1: Impulse Responses with the FFR - Left Column: Benchmark IRF (1960:I-2007:IV): VAR(4) with GDP growth, GDP Deflator Inflation, Commodity Price Inflation, and the FFR as the policy instrument. The thick black line and the dark gray shaded area show the median point estimate and the 90% posterior 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-2018:III) using the FFR as the policy instrument through the ZLB period. The thick light gray line and the light 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 black line and the gray shaded region replicate the plots from the benchmark model.

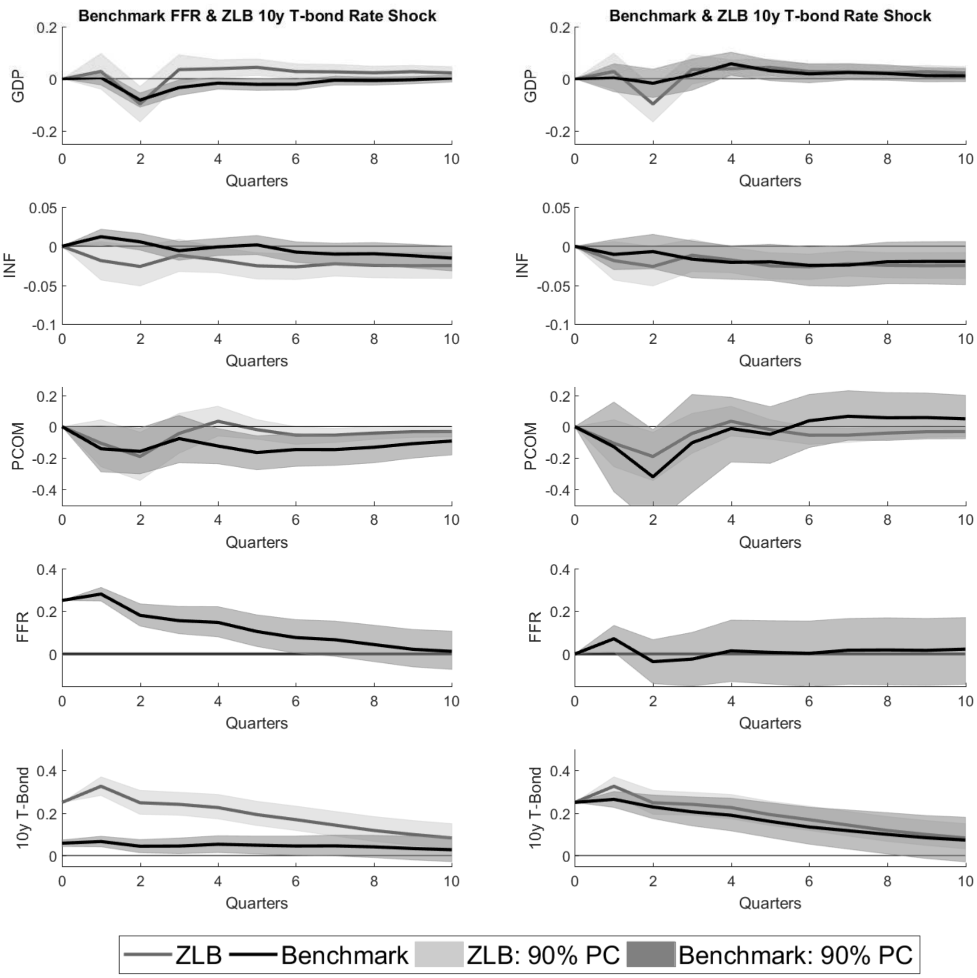

Figure 2: Generalized Impulse Responses in the ZLB Environment - Left panel: VAR(4) with GDP growth, GDP Deflator Inflation, Commodity Price Inflation, the FFR, and the 10-year Treasury Bond Rate. The thick black line and the dark gray shaded area show the median point estimate and the 90% posterior 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 light gray line and the light 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 duing the ZLB environment (2008:I-2015:IV), restricting the response of the FFR to be zero. Right panel: The dark gray 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 light gray areas showing the restricted generalized IRF responses to a 25 basis point shock to the 10-year T-Bond Rate in the ZLB period.

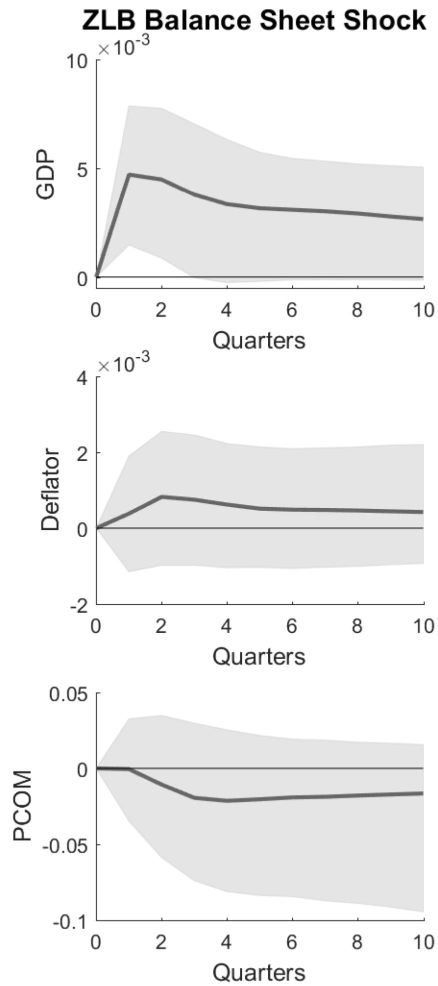

Figure 3: Generalized Impulse Responses to Balance Sheet Shocks in the ZLB period - The VAR(1) is estimated with GDP growth, GDP Deflator Inflation, Commodity Price Inflation, the FFR, and the size of the Fed's balance sheet scaled by GDP. The thick lines and the shaded areas show the median point estimate and the 90% posterior coverage, respectively, for the impulse responses to a one-standard-deviation increase in the balance sheet duing the ZLB environment (2008:I-2015:IV), restricting the response of the FFR to be zero.

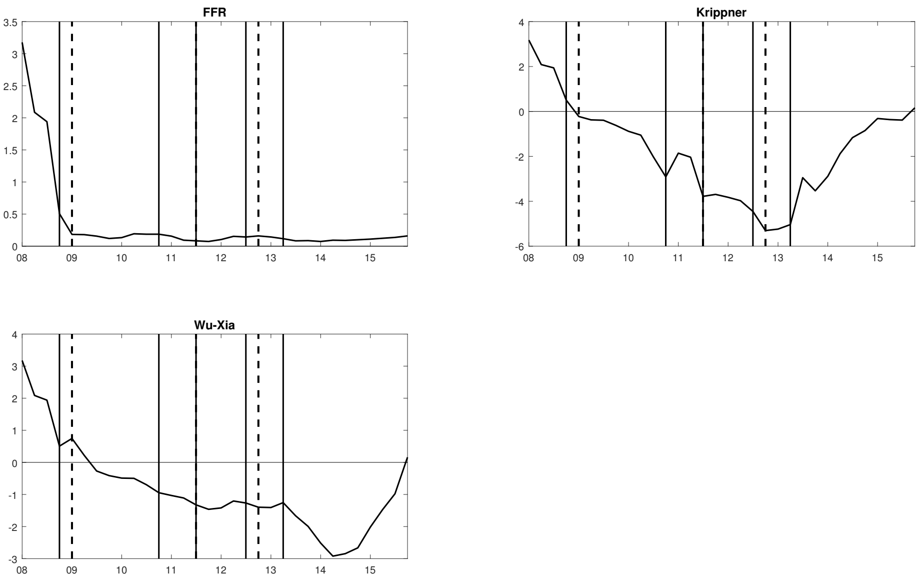

Figure 4: Policy Rates and Unconventional Policy Announcements - Plot of quarterly nominal FFR and shadow rates over the period from 2008:I - 2015:IV. The solid vertical lines (left to right) indicate the annoucements of: QE1, QE2, Operation Twist, QE3, and the first mentioning of tapering the quantitative 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.

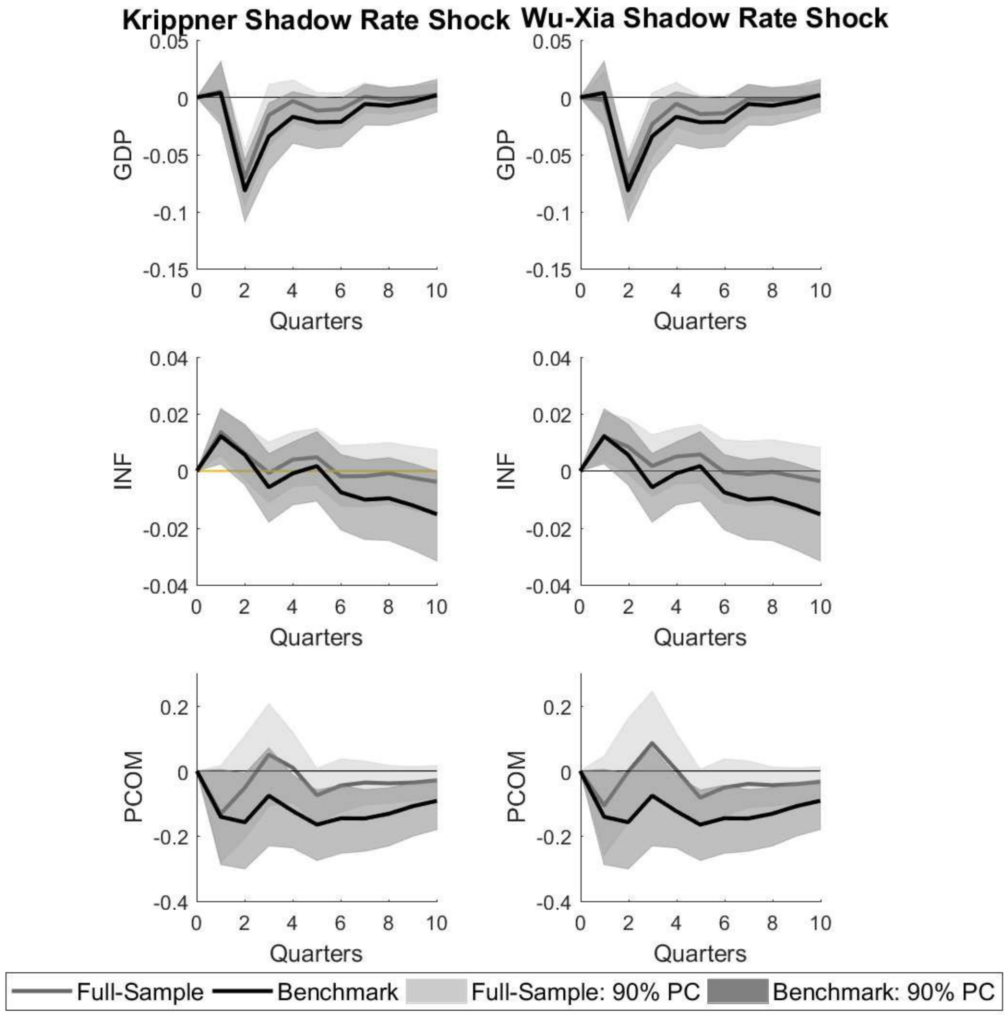

Figure 5: Impulse Responses Over the Full Sample with the Shadow Rates - Left Column: IRF of full-sample VAR (1960:I-2018:III) using the Krippner (2015) shadow rate as the policy instrument through the ZLB period. The thick light gray line and the light shaded area give the median IRF point estimates and 90% posterior coverage, respectively, incorporating data through the ZLB period without accounting for any potential changing macroeconomic dynamics. The thick black line and the dark gray 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.

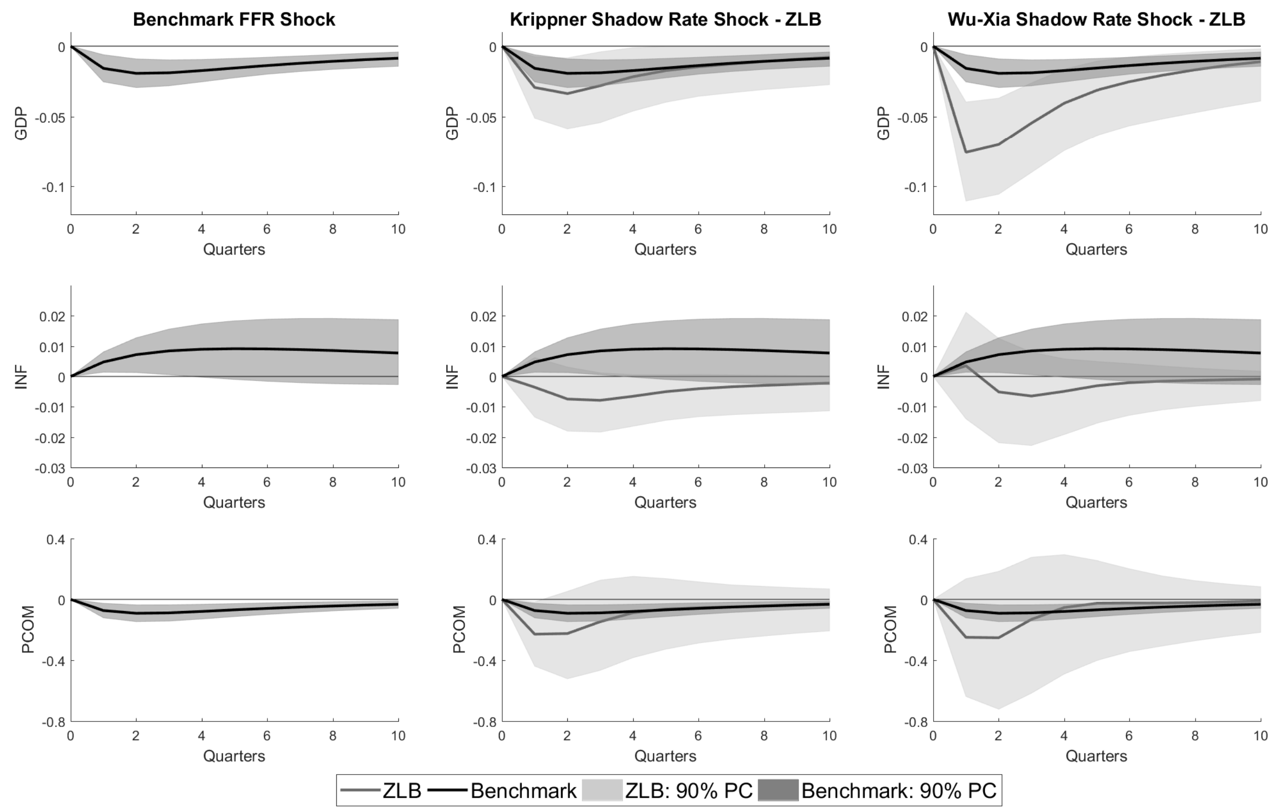

Figure 6: Impulse Responses in the ZLB Environment with Shadow Rates- First panel: Benchmark IRF (1960:I-2007:IV): VAR(1) with GDP growth, GDP Deflator Inflation, Commodity Price Inflation, and the FFR as the policy instrument. The thick black line and the dark gray shaded area show the median point 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:IV, and using the Krippner (2015) shadow rate as the policy instrument. The thick light gray line and the light shaded area give the median IRF point estimates and 90% posterior coverage, respectively, using only data from the ZLB period. The thick black line and the dark gray 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.

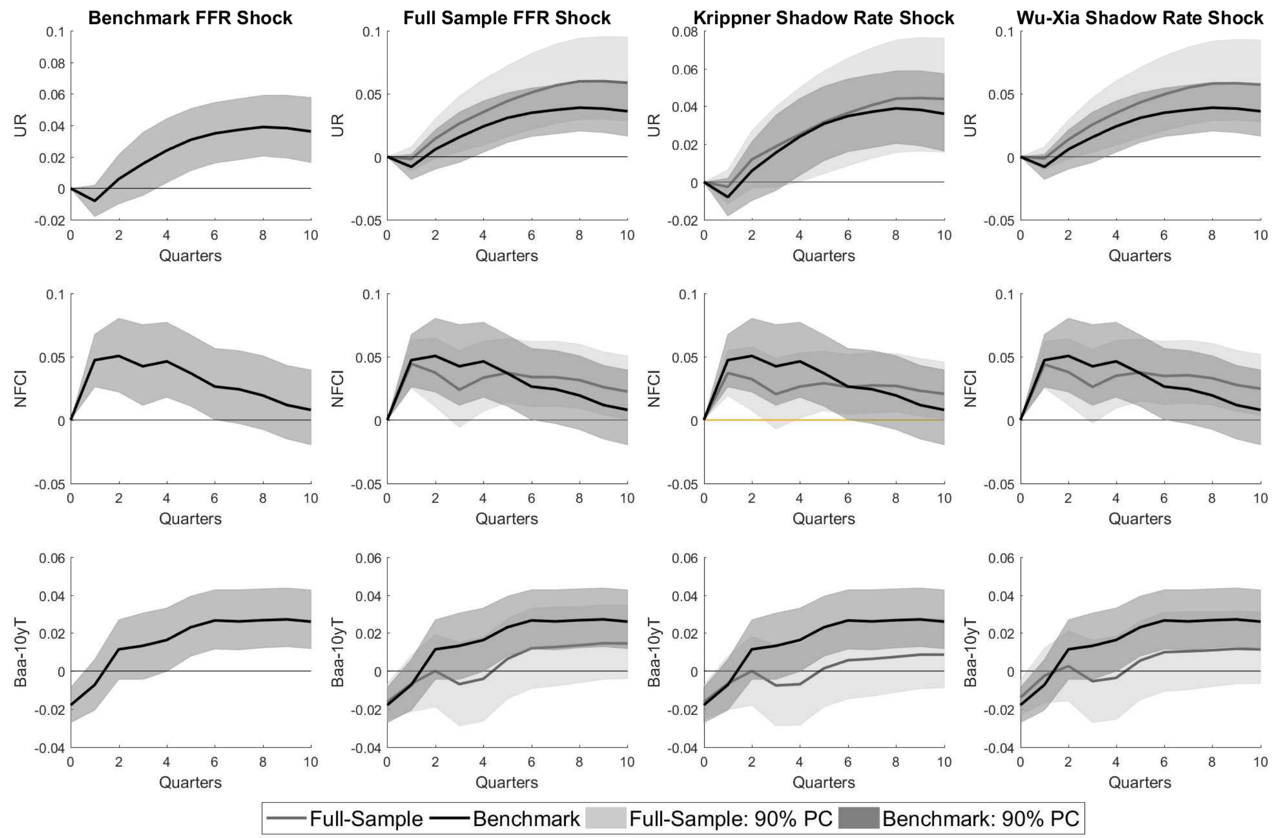

Figure 7: Impulse Responses of Alternative Data Series Over the Full Sample with the FFR and Shadow Rates - First column: Benchmark IRF (1960:I-2007:IV): VAR(4) with the FFR as the policy instrument. The thick black line and the dark gray shaded area show the median point estimate and the 90% posterior coverage, respectively, for the impulse responses to a 25-basis-point shock to the policy instrument. Second panel: IRF of full-sample VAR (1960:I-2018:III) using the FFR as the policy instrument through the ZLB period. The thick gray line and the light 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 black line and the dark gray 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.