Asset market responses to conventional and unconventional monetary policy shocks in the United States*

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Abstract

We quantify the responses of United States asset markets to domestic monetary policy shocks over conventional and unconventional monetary policy environments, and also gauge the potential usefulness of shadow short rates as a metric across those periods. Our results show that asset market responses to policy shocks have been larger since short-maturity nominal interest rates reached the zero lower bound. While short-maturity interest rates no longer provide a useful metric in that environment, appropriately robust shadow short rates are useful over both environments. The increased responses of asset markets in the unconventional period seem due to larger policy shocks rather than a change to their transmission.

Keywords: Asset markets; monetary policy shocks; shadow short rate; zero lower bound.

JEL classification: E43, E52, E65

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1 Introduction

In this paper we use event-study analysis to investigate the response of US asset markets to domestic monetary policy shocks over the period February 1996 to January 2016. As we discuss shortly below, this period covers environments where short-maturity interest rates were constrained by the lower bound and so could not provide a complete metric for monetary policy shocks. In that context, as we discuss further below, we also investigate a range of high-frequency shadow short rate (SSR) estimates to see which, if any, are suitable substitutes for short-maturity interest rates in the lower-bound period.

The broad motivation for our investigation is that understanding the impact of monetary policy shocks on asset markets is crucial for central banks to conduct monetary policy effectively. Such shocks, delivered via changes to the monetary policy instrument/s and communications of central banks, change market interest rates, exchange rates, and other asset prices, which influences the decisions of firms, households, banks, and investors, ultimately resulting in economic activity and inflation moving towards the central bank's targets.

Central banks conventionally conduct monetary policy by setting a (nominal) policy interest rate and often giving some conditional indication of settings in the near future. Those settings and indications are reviewed at regular intervals, and any component unanticipated by markets (the shock) transmits into asset prices as noted earlier.

However, policy interest rates reached near-zero levels, the so-called lower bound for interest rates, in the United States and many other major economies when central banks responded to the 2007-09 financial crisis with substantial monetary easing. In such an environment, central banks could not materially lower policy interest rates further, or credibly indicate an intention to do so, because the availability of physical currency effectively offers a risk-free investment at a zero rate of interest that would be more attractive than central bank deposits or buying securities that offer a negative interest rate.[1] To provide further monetary stimulus, central banks turned to unconventional monetary policy actions in addition to near-zero policy rate settings. For example, actions undertaken by the United States, the euro area, Japan, and the United Kingdom included direct lending to specific short term credit markets, large scale purchases of long term assets to increase the monetary base, and explicit guidance on future policy rates over longer horizons; see Fawley and Neely (2013) for a comparison of the unconventional monetary policy actions of those four respective central banks, and Bhattarai and Neely (2016) for a survey on US unconventional monetary policy.

Given these conventional and unconventional environments for operating monetary policy, we investigate whether monetary policy shocks within those environments affect asset prices differently. If so, then stabilizing economic activity and acheiving inflation targets may require central banks to adjust their policy responses accordingly between the two

[1] Mildly negative policy rate settings are possible, such as in the euro area, Japan, and Switzerland, but these are accompanied by material exemptions from negative returns on settlement account balances held at central banks. Market interest rates can also adopt milldly negative values for reasons such as avoiding the overhead costs of holding and transacting in physical currency, and safe-haven buying of fixed interest securities during times of market turbulence.

environments. This remains a live issue for central banks that remain in or close to lower bound environments, and the United States provides an ideal test case because it has already completed a lower bound period.

Our event study adds to the related literature on unconventional monetary policy shocks, as summarized in section 2, by identifying monetary policy shocks through heteroskedasticity in daily data on policy versus non-policy days; see Rigobon and Sack (2004) and Craine and Martin (2008).[2] Furthermore, we also estimate our model using a wider range of representative asset prices that are important to the economy from different perspectives, including the 90 day treasury rate, the 10 year treasury rate, corporate bond prices, the gold price, equity prices, real estate investment trust (REIT) prices,[3] and a major US dollar exchange rate. The related literature, which we summarize in section 2, typically focusses on the responses of one or two asset prices and uses event dummy variables.

We find that the directions of responses of asset prices to monetary policy shocks are generally the same in conventional and unconventional periods, and as one would anticipate in principle and in comparison to the related literature; i.e. higher interest rates and lower prices for a tightening shock. However, the responses are both more significant and generally larger in the unconventional period, a point to which we return below.

The notable exception to the results above is the 90 day rate, where the response in the conventional period is as expected, but the response in the unconventional period is smaller in magnitude and the opposite sign. Hence, while changes in the 90 day rate provide a reasonable metric for monetary policy surprises in the conventional period, as in Kuttner(2001), they are obviously deficient as a metric in the unconventional policy period (as ancitipated earlier, due to the known constraint from the lower bound).

The latter results leads to the second part of our investigation, i.e. testing whether shadow short rate (SSR) estimates can provide useful proxies for monetary policy shocks over both conventional and unconventional monetary policy periods. As background, estimated SSR series can freely take on negative values to reflect a near zero policy rate plus unconventional policy actions, and so they have been proposed as an alternative to short-maturity interest rates for quantitative monetary policy analysis and monitoring during unconventional monetary policy periods; see Bullard (2012), Krippner (2015), and Wu and Xia (2016) for the United States. Kortela (2016) and Lemke and Vladu (2016) are examples that calculate SSR series for the euro area. However, these and other studies indicate that SSR estimates can vary materially with respect to model specification and estimation choices, so it is an open question whether SSR estimates can provide a useful monetary policy metric.

Our event study framework provides a novel perspective for testing SSR estimates at a daily frequency, by using them in place of the 90 day rate data in our previous estimations.

[2] As mentioned earlier, event studies using changes in observed short-maturity interest rates are not possible over both periods due to the lower bound constraint. An alternative to event studies is a narrative approach proposed by Romer and Romer (1989 and 2004), who derive monetary policy shocks from intended changes in monetary policy around meetings of the Federal Open Market Committee. However, this approach can lead to unreasonably large monetary policy shocks; see Claus and Dungey (2012).

[3] REITs are an investment vehicle for real estate that are comparable to mutual funds. They invest in real estate through property and / or mortgages and often trade on major exchanges like a stock.

Indeed, our investigation is also the first to generate daily SSR estimates that can be used for such high-frequency tests. We find that SSR series from two-factor models estimated across the full range of maturities on the yield curve are robust enough to provide a useful metric for quantifying monetary policy shocks across conventional and unconventional periods. That is, SSR responses in the conventional period are similar to those for the 90-day rate, and SSR responses in the unconventional period remain similar to the conventional period. Conversely, SSR series estimated from three-factor models have counterintuitive responses to monetary policy shocks.

Our final exercise is to use a representative robust SSR series as a common monetary policy metric over the conventional and unconventional policy periods to investigate the reason for the larger responses to monetary policy shocks in the unconventional period. From that perspective, we find that the increased responses are likely due to larger monetary policy shocks rather than a change to the transmission of shocks.

The remainder of the paper proceeds as follows. In section 2, we review the recent literature on unconventional monetary policy event studies. Section 3 introduces the concept of SSR estimates and our daily SSR series. In section 4, we outline our event study framework and the data used in its estimation, and section 5 presents and discusses our empirical results. Section 6 investigates the larger responses to monetary policy shocks in the unconventional period. The final section concludes with a summary of our results and associated policy implications.

2 Unconventional monetary policy event studies

In this section we review the literature on the effect of unconventional monetary policy announcements on asset markets via event study analysis. The general strategy of such event studies is to consider a narrow set of announcements that are assumed to contain a surprise component, and then to assess the impact from that component on asset prices.[4]

The impact of quantitative easing policies on medium and long term interest rates has been examined in a number of studies. For example, Krishnamurthy and Vissing-Jorgensen (2011) use event study methodology to evaluate the effects of the Federal Reserve's first two asset purchase programs (QE1 in 2008-09 and QE2 in 2010-11). Specifically they test whether changes on quantitative easing announcement days differ from changes on other days by regressing the daily changes in various yields of interest on dummy variables, which take a value of one if there was a QE announcement on that day or the previous day. Two day changes are considered as some asset prices may have only reacted slowly because of low liquidity at the time. Employing both time series and event study methodology Gagnon, Raskin, Remache, and Sack (2011) gauge the impact of QE1 on longer term interest rates. Their event study analysis examines changes in interest rates using a one day window around official communications regarding asset purchases, while the time series analysis statistically estimates the impact of the Federal Reserve's asset purchases on the 10 year treasury term premium. Joyce, Lasaosa, Stevens, and Tong (2011), who examine

[4]Related to event studies, Meaning and Zhu (2011, 2012) and D'Amico and King (2013) investigate the effects of the volume and maturities of central bank purchases of government bonds on interest rates.

the reaction of asset prices to the Bank of England's QE announcements using event study analysis over a two day window and data from a survey of economists on the total amount of QE purchases expected, obtain quantitatively similar impacts on government yields as Gagnon et al. (2011) for the United States. Swanson (2011) also uses event study analysis and quantifies the potential impact of QE2 by measuring the effect on long term interest rates of the Federal Reserve's 1961 Operation Twist, which was a program similar to QE2.

Beyond interest rate effects, Joyce et al. (2011) examine the effects of quantitative easing on other asset prices (corporate debt and equities) by estimating the expected asset returns of changes in asset quantities. However, they find considerable uncertainty about the size of the impact because of the difficulty in disentangling the impact of monetary policy shocks from other influences. Rosa (2012), Kiley (2014), and Rogers, Scotti, and Wright (2014), who investigate co-movements between long term interest rates and equity prices in the United States in reaction to monetary policy shocks, find an attenuated response in equity prices since the zero lower bound on short term interest rates has been binding. Rosa (2012) uses event study analysis and identifies the surprise component of large scale asset purchase announcements from press reports. The methodology employed by Kiley (2014) is instrumental variable estimation using instruments correlated with the change in the 10 year treasury rate, while Rogers, Scotti, and Wright (2014) use intradaily data around announcement times with 30 and 120 minute windows to identify the causal effect of monetary policy surprises.

Neely (2015) evaluates the effect of QE1 on exchange rates. Using daily data and event study analysis he finds that the US dollar depreciated in response to asset purchase announcements by the Federal Reserve. His estimation period is extended by Glick and Leduc (2013), who compare how the US dollar reacts to changes in unconventional monetary policy compared to conventional monetary policy changes. Monetary policy surprises are identified from changes in interest rate futures prices in a 60 minute window around policy announcements and found to have a significant impact on the value of the US dollar. However, Glick and Leduc (2013) find virtually no response to unconventional monetary policy surprises over a longer window, i.e. a day later.

The effects of other methods of unconventional monetary policy accommodation have not received as much attention in the literature, but Christensen, Lopez, and Rudebusch (2014) offer empirical evidence that central bank lending facilities helped to lower liquidity premiums in markets early in the global financial crisis. Regarding forward guidance, Woodford (2012) provides a summary of the principles by which it can influence financial markets and also an overview of supporting empirical evidence. Femia, Friedman, and Sack (2013) investigate market reaction to forward guidance by focusing on the use of calendar dates and economic thresholds in FOMC statements. To quantify the impact of forward guidance and large scale asset purchases Swanson (2015) estimates the response of financial markets in a 30 minute window around monetary policy announcements using principal components analysis. His results suggest that forward guidance has a limited influence on the 10 year treasury rates and no significant effect on corporate bond yields. In contrast, large scale asset purchases have a large effect on both yields. Moreover, both policies significantly influence medium term treasury rates, equity prices and exchange rates.

We add to the literature on unconventional monetary policy in three respects. First we use identification by heteroskedascitity instead of event dummy variables. Second, we use a wide range of asset prices in our observable dataset to quantify the impact of conventional and unconventional monetary policy announcements. Third, we use our framework to investigate the potential of using estimated SSR series as a metric for monetary policy shocks. Hence, we introduce shadow short rates in the following section before proceeding with our analysis.

3 Shadow short rates

In this section, we first outline the intuition underlying SSR estimates and their potential as a monetary policy metric across conventional and unconventional monetary policy periods. In section 3.2 we outline the different series that we subsequently include in our asset price datasets for our empirical analysis of monetary policy shocks.

3.1 SSR intuition

Figure 1 illustrates the concept of obtaining SSR estimates using a shadow/lower-bound yield curve model. The observed yield curve data, which are subject to a lower bound constraint, are used to estimate a lower-bounded yield curve, which is itself composed of a shadow yield curve and the option effect. The option effect accounts for the availability of physical currency, which provides investors with the means to avoid any realizations of negative short-maturity interest rates that could otherwise potentially occur at any time up to each given maturity.

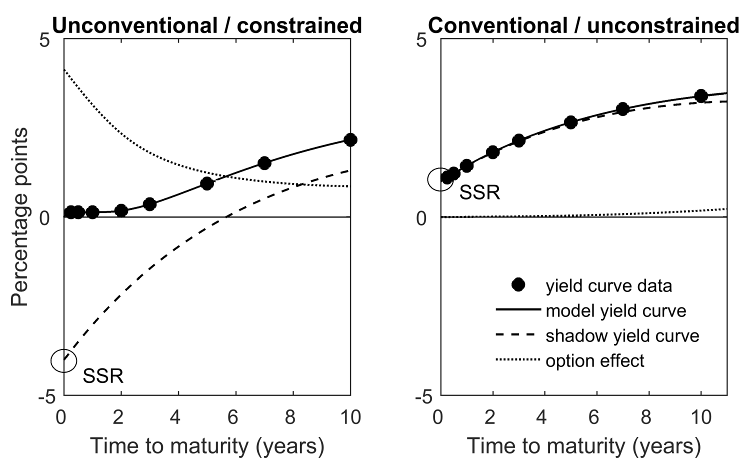

Figure 1: Concept of shadow yield curves and their associated SSRs implied by a shadow/lower-bound model estimated with observed yield curve data.

Panel 1 of figure 1 provides a stylized example of a yield curve constrained by the lower bound, which represents an unconventional monetary policy environment. The SSR is the shortest maturity rate on the shadow yield curve, which in this case is negative, thereby indicating that the stance of monetary policy is more accommodative than a near-zero policy rate setting alone. Panel 2 of figure 1 provides an example of yield curve data in a conventional environment, i.e. not materially constrained by the lower bound. In this case, the option effect is negligible, and so the SSR is essentially identical to the short-maturity rate.

An SSR series is therefore a potential metric for the stance of monetary policy across conventional and unconventional monetary policy regimes. However, SSR series are estimated quantities rather than a unique observable variable, and are therefore subject to sometimes very material variations with respect to the model specification and the data used for estimation. For this reason, no single SSR series should be regarded as a true or ideal metric. However, it is possible to vet different SSR series to assess whether some, if any, are useful and/or better than others. In this paper, we do so using daily SSR series and test them with respect to their consistency with monetary policy shocks.[5]

3.2 Estimated SSR series

To investigate the properties of estimated SSR series with respect to monetary policy shocks in our event study framework, we first need to generate a range of SSR series at a daily frequency. The SSR series presently available in the literature are at a monthly frequency, e.g. Wu and Xia (2016) and Lombardi and Zhu (2014), or a quarterly frequency, e.g. Johannsen and Mertens (2016).

We use the generic shadow/lower-bound framework from Krippner (2013, 2015) to estimate our range of daily SSR series. An overview of that framework and its estimation is outlined in appendix A. We use various model specification and data combinations within that framework to cover those already available in the literature. Hence, we use:

- models with two factors (Level and Slope) and three factors (Level, Slope, and Bow) in the specification for the shadow term structure.
- lower bound values calibrated at 0 bps and 25 bps, and estimated lower bound values.
- datasets with maturities that span 0.25 to 30 years to maturity, or 0.25 to 10 years.

Figure 2 plots our SSR series generated with two-factor models. The figure focuses on the unconventional monetary policy period because, as noted in section 3.1, the SSR estimates over the conventional monetary policy period are very similar to each other (being close to observed short-maturity interest rate series).

Regarding robustness, the profiles and dynamics of our two-factor SSR series are similar, but there are some notable differences in magnitudes among the series. To provide an initial visual inspection of the different SSR series as monetary policy metrics, we have indicated all of the major unconventional monetary policy events listed in table 1 with down arrows for easings and up arrows for tightenings in figure 3. However, our results in section 5 provide the formal and systematic test results.

[5]Krippner (2017) tests the consistency of monthly SSR estimates with respect to their performance in macroeconomic vector autoregressions, among other properties.

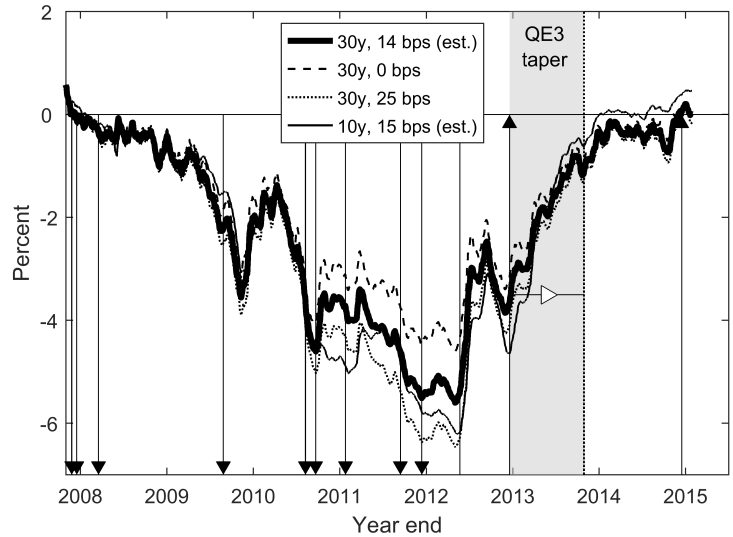

Figure 2: SSR series estimated from a two-factor model with different lower bound parameters and yield curve data sets.

Table 1: Major unconventional monetary policy events

Date	Announcement
25/11/2008	QE1 announced (↓)
16/12/2008	Federal funds rate target set to a range of zero to 25 basis points (↓)
18/03/2009	Additional QE1 security purchases announced (↓)
27/08/2010	QE2 foreshadowed (↓)
09/08/2011	Calendar forward guidance announced (↓)
21/09/2011	Operation Twist (↓)
25/01/2012	Calendar forward guidance extended (↓)
13/09/2012	QE3 announced and calendar forward guidance extended (↓)
12/12/2012	QE3 extended and unemployment based forward guidance announced (↓)
22/05/2013	QE3 tapering foreshadowed (↑)
18/12/2013	QE3 tapering commenced (↑)
16/12/2015	Federal funds rate target set to a range of 25 to 50 basis points (↑)

Note: ↓ easing, ↑ tightening

Figure 3 plots our SSR series generated with three-factor models. The magnitudes, profiles, and dynamics of the SSR series are markedly different between the SSR estimates.[6] This phenonemon has been variously documented; see Bauer and Rudebusch (2015), Christensen and Rudebusch (2015), and Krippner (2017).

[6]For ready comparibility, we have deliberately plotted the SSRs on the same scale as for the two factor results. The minimum value of the "30Y, 25 bps" series is –12.4 percent.

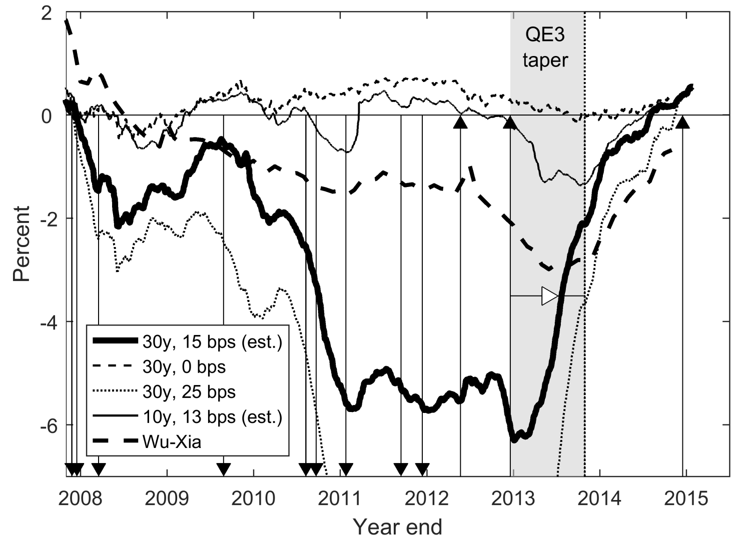

Figure 3: SSR series estimated from a two-factor model with different lower bound parameters and yield curve data sets.

In addition, the movements in the three-factor SSR series are often inconsistent with the major unconventional monetary policy events noted earlier. For example, our 10Y, 13 bps (est.) series indicate a large implied policy easing between May 2013 and May 2014, despite the removal of unconventional monetary accommodation first being foreshadowed in May 2013 and then progressively implemented from December 2013. Such an easing is also evident in the end-of-month SSR series from Wu and Xia (2016), which is obtained from a three-factor model closely related to the Krippner (2015) framework we use, and also yield curve data out to 10 years, but with a calibrated lower bound parameter of 25 basis points.

4 Empirical framework and data

In this section we first outline our latent factor model, and then the datasets that underlie the results we report in section 5.

4.1 Latent factor model

The principle behind latent factor models, which are a popular tool in the finance literature, is that they identify monetary policy shocks via heteroskedasticity in daily financial market data between monetary policy event days and non-monetary policy days; see Rigobon and Sack (2004) and Craine and Martin (2008). In notation, the financial market data on non-monetary policy days may be expressed as the following linear function of common (systematic) and idiosyncratic (diversifiable) factors

$$y_{j,t} = \alpha_j a_t + \delta_j d_{j,t} \tag{1}$$

where $y_{j,t}$ is the demeaned first difference of the financial market variable j at time t for $t = 1, .., T$, a_t is a shock common to all assets and $d_{j,t}$ represents idiosyncratic shocks to $y_{j,t}$.[7]

The principle of identification through heteroskedasticity is that reactions to monetary policy shocks m_t are in addition to the common and idiosyncratic shocks on non-monetary policy days. Monetary policy days T^{MP} can be exogenously identified so long as central banks make public and explicit monetary policy announcements. In that case, the additional monetary policy factor m_t applies only on monetary policy days

$$y_{j,t} = \alpha_j a_t + \delta_j d_{j,t} + \beta_j m_t \tag{2}$$

where $t \in T^{MP}$, while equation 1 applies on all other days, $t \in T^{OTH}$ and $T^{MP} + T^{OTH} = T$.

All factors, a_t, m_t, and $d_{j,t}$ for $j = 1, ..., N$, where N is the number of assets, are assumed to be independent with zero mean and unit variance. The parameters α_j, δ_j, and β_j are the factor loadings, where β_j is the response of asset j to monetary policy shocks.

Re-writing equations 1 and 2 in matrix form gives

$$Y_t = \Lambda H_t \text{ for } t \in T^{OTH} \text{ and } Y_t = \Lambda H_t + \Phi m_t \text{ for } t \in T^{MP} \tag{3}$$

Y_t is an $(N \times 1)$ vector of $y_{j,t}$, H_t is an $((N + 1) \times 1)$ vector of shocks, where the common shock a_t is in the first row and the idiosyncratic shocks are in the remaining N rows. The matrices Λ and Φ contain the factor loadings and Λ is $(N \times (N + 1))$ and Φ is $(N \times 1)$. Using the independence assumption and the first and second moment assumptions for the latent factors yields

$$\Omega^{OTH} = \Lambda\Lambda' \text{ and } \Omega^{MP} = \Lambda\Lambda' + \Phi\Phi' \tag{4}$$

where Ω^i with $i = OTH, MP$ is the variance covariance matrix of Y_t. Ω^{MP} applies on the exogenously identified monetary policy days and Ω^{OTH} on all other days. Writing out the first elements of Ω^{MP} gives

$$\Omega^{MP} = \begin{bmatrix} \alpha_1^2 + \delta_1^2 + \beta_1^2 & & \\ \alpha_1\alpha_2 + \beta_1\beta_2 & \alpha_2^2 + \delta_2^2 + \beta_2^2 & \\ \vdots & & \ddots \\ \cdots & \cdots & \end{bmatrix} \tag{5}$$

Ω^{OTH} is analogous with $\beta_j = 0$ for all j.

The latent factor model is estimated using generalized method of moments (GMM) techniques where the model's theoretical second moments in equation 4 are matched to the data moments. In the case of an overidentified model, which occurs when $N \geqslant 6$, the Hansen (1982) method for combining the generated moment conditions with the number of parameter estimates is implemented; see Claus and Dungey (2012) for details.[8]

[7]Principal component analysis on the data supports the inclusion of just one common factor. The first principal component for all of our empirical specifications explains at least 81 percent or more of the sample variance.

[8]In the empirical application below, we use the identity matrix as the weighting matrix as the inverse of

4.2 Data and estimation

We estimate the latent factor model separately for the US conventional and unconventional monetary policy periods. The conventional period is from 1 February 1996 to 12 September 2008, when short term interest rates were comfortably above the zero lower bound. The beginning of this period is determined by the availability of real estate investment trust data discussed further below, but that is not as limiting as it might appear. That is, the Board of Governors of the Federal Reserve only began making explicit monetary policy announcements on scheduled days from January 1994, and hence the exogenous identification of monetary policy days T^{MP} is only possible after that time. The end of the conventional period is immediately prior to the bankruptcy of Lehman Brothers, which was announced during the weekend. The unconventional period is from 15 September 2008, the Monday after the bankruptcy of Lehman Brothers, to 28 January 2016. We have chosen the latter date to include the end of the lower-bound period, i.e. the FFR was raised to a 0.25 to 0.50 percent range on 16 December 2015), but to avoid any effect from subsequent FFR target increases.[9]

We obtain information on monetary policy days from the Federal Reserve Board's website. We include all policy announcement days (see Kuttner 2001 and Gürkaynak, Sack, and Swanson 2005) as well as days of the Chair's semi-annual monetary policy report to Congress (see Rigobon and Sack 2004).[10] We also identified 25 November 2008, 1 December 2008, and 22 May 2013 as monetary policy announcement days. 25 November 2008 marks the beginning of QE1. The 25 November 2008 press release was followed by a speech on 1 December 2008 by Chair Bernanke, in which he stated that "the Fed could purchase longer-term treasury or agency securities on the open market in substantial quantities". On 22 May 2013 Chair Bernanke signaled the tapering of QE3 in his testimony on the economic outlook before Congress. In addition, during the period of unconventional monetary policy we included as announcement days speeches by the Chair at the Annual Economic Symposium in Jackson Hole. Our identification of unconventional monetary policy days is in line with Rogers, Scotti and Wright (2014). The full period includes 221 monetary policy days $\left(T^{MP} = 221\right)$ and 4,590 all other days $\left(T^{OTH} = 4,590\right)$. The conventional period has 135 monetary policy days and 3,157 all other days, and the unconventional period has 86 monetary policy days and 1,433 all other days.

Regarding the daily financial market data, we have chosen a wide range to broadly represent various perspectives of financial markets that are relevant to the economy. We include the benchmark 90 day treasury rate as the observable short maturity rate, and the benchmark 10 year treasury constant maturity rate as a long term government-risk rate. We

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the variance covariance matrix leads to a loading of close to zero for the 10 year treasury rate idiosyncratic factor in the latter part of the sample period. This is likely a reflection of the binding lower bound for short term nominal interest rates over the sample period. Using equal weights is not expected to bias the results. In fact Altonji and Segal (1996) show that equal weights are generally optimal in small samples. Although the total sample size is large, the number of policy days is relatively small.

[9] Our unconventional period covers a short period where the FFR target was lowered, prior to the setting of the 0 to 0.25 percent range on 16 December 2008. However, that periods may be regarded as unconventional, because liquidity measures were implemented in the wake of the bankruptcy of Lehman Brothers, and QE1 was announced on 25 November 2008.

[10] During 2003 the Chair delivered three monetary policy testimonies to Congress.

include the gold fixing price at 10:30 AM (London time) in the London bullion market in US dollars, shifted forward by one day to account for time zone differences. For equity prices we use the Standard & Poor's (S&P) 500 stock price index. We include corporate bond prices by calculating a bond price index from Moody's seasoned Aaa corporate bond yields.[11] For real estate investment trust prices we use the Wilshire US real estate securities total market index, which are total market returns (including reinvested dividends) of publicly traded real estate equity securities. Finally, we include a representative major exchange rate in our data set, i.e. the New York close mid rate for the US dollar / British pound exchange rate (an increase [decrease] in the exchange rate indicates a depreciation [appreciation] of the US dollar).[12] The latter is sourced from Bloomberg, while the remainder of the data is sourced from the Federal Reserve Economic Database (FRED) on the Federal Reserve Bank of St. Louis website.

For the variables described above, we calculate demeaned first differences over the conventional and unconventional periods for estimating the latent factor model. The first differences are calculated directly for the interest rate data, and as changes in the logarithm of the level for the asset prices and the exchange rate.

The alternative dataset replaces the 90 day treasury rate with the SSR estimates that we have already discussed in section 3.2. Appendix A details the yield curve data used to obtain those estimates, which are all sourced from Bloomberg.

5 Empirical results and discussion

In this section, we first present and then discuss the range of results obtained from our datasets and the latent factor model.

5.1 Results

Tables 2 and 3 report the results associated with the 90 day rate dataset, which we discuss in section 5.2, and the results associated with the dataset with the SSR series obtained from the two-factor model with an estimated lower bound parameter, and the 0.25 to 30 year yield curve data. We use the latter as the representative SSR dataset, for space reasons when reporting results, but we discuss the results for the other SSR datasets in section 5.3 after discussing those for the representative SSR dataset. All results are available from the authors on request.

The parameter estimates in table 2 are the responses to a one standard deviation tightening monetary policy shock, with significance levels indicated and the standard errors in parentheses. The interest rate responses are in basis points and the asset price responses

[11] Corporate bond yields could be used directly; it does not change our results, except that higher yields would equate to lower prices.

[12] We use this exchange rate because an end-of-day fix is available, which is after the afternoon policy announcements from Federal Reserve meetings, and it also corresponds with the US end-of-day fixings for our other asset prices (except gold, as noted). An end-of-day effective exchange rate would be more desirable, but we are not aware of such a series being available. For example, the Federal Reserve provides noon exchange rate fixings, which would not be suitable for our analysis.

are in percentage points. Note that our estimation results are symmetric, so responses for an easing monetary policy shock will be opposite in sign, but we maintain the tightening perspective throughout our results and discussions.

Table 2: Monetary policy response estimates

	Period 1		Period 2	
	90 day	SSR	90 day	SSR
Short rate	3.265 **	1.474 **	-0.227 **	2.123 *
	(0.199)	(0.306)	(0.137)	(0.148)
10 year treasury rate	2.999 **	3.525 **	8.191 **	8.174 **
	(0.209)	(0.198)	(0.086)	(0.086)
Corporate bond prices	0.238	-0.100	-0.890 **	-0.648 **
	(0.254)	(0.358)	(0.142)	(0.153)
Gold price	-0.118	-0.263	-0.752 **	-0.700 **
	(0.268)	(0.356)	(0.134)	(0.151)
Equity prices	-0.518 **	-0.482 *	-0.423 **	-0.569 **
	(0.269)	(0.355)	(0.151)	(0.157)
REIT prices	-0.183	-0.018	-0.771 **	-0.935 **
	(0.269)	(0.358)	(0.158)	(0.158)
Exchange rate	-0.052	-0.185	-0.321 **	-0.360 **
	(0.268)	(0.357)	(0.137)	(0.152)

Period 1: Conventional monetary policy, 1 February 1996 to 12 September 2008.
Period 2: Unconventional monetary policy, 15 September 2008 to 28 January 2016.
90 day: The short rate is the 90 day treasury rate.
SSR: The short rate is the shadow short rate.
Level of significance: ** 5 percent, * 10 percent.

Table 3 contains differences in the responses to monetary policy shocks from table 2, between the two periods and between the 90 day dataset and the representative SSR dataset. The standard errors and levels of significance are obtained from a Monte Carlo simulation that we require to obtain the results in section 6, and which we will outline there.

Table 3: Monetary policy response differences

	Period 2 90 day less Period 1 90 day	Period 1 SSR less Period 1 90 day	Period 2 SSR less Period 2 90 day	Period 2 SSR less Period 1 SSR
Short rate	-3.492 **	-1.791 **	2.350 **	0.649 *
	(0.240)	(0.364)	(0.200)	(0.338)
10 year treasury rate	5.192 **	0.527 *	-0.017	4.649 **
	(0.228)	(0.290)	(0.121)	(0.217)
Corporate bond prices	-1.128 **	-0.338	0.242	-0.548
	(0.289)	(0.438)	(0.213)	(0.385)
Gold price	-0.634 **	-0.144	0.052	-0.438
	(0.300)	(0.444)	(0.201)	(0.389)
Equity prices	0.095	0.036	-0.146	-0.087
	(0.306)	(0.451)	(0.218)	(0.385)
REIT prices	-0.588 *	0.165	-0.164	-0.917 **
	(0.308)	(0.450)	(0.224)	(0.389)
Exchange rate	-0.269	-0.133	-0.039	-0.175
	(0.299)	(0.443)	(0.205)	(0.387)

Period 1: Conventional monetary policy, 1 February 1996 to 12 September 2008.
Period 2: Unconventional monetary policy, 15 September 2008 to 28 January 2016.
90 day: The short rate is the 90 day treasury rate.
SSR: The short rate is the shadow short rate.
Level of significance: ** 5 percent, * 10 percent.

5.2 Monetary policy responses with 90 day rate dataset

The first column of table 2 shows the results for the conventional period with the 90 day rate dataset. These estimates provide a useful point of reference for the other results, because changes in short-maturity interest rates were often been used to proxy monetary policy shocks in event studies conducted in conventional monetary periods. The signs of the responses are generally as one would expect from a tightening monetary policy shock. That is, the 90 day and 10 year interest rates increase, asset prices decrease, and the exchange rate appreciates. However, the responses are only statistically significant for the 90 day and 10 year interest rates and equity prices. The response of corporate bond prices is counterintuitively positive, but insignificant.

The third column of table 2 shows the results for the unconventional period. The responses to monetary policy shocks for all variables, except the 90 day rate as we discuss below, are all as expected, i.e. the 10 year rate increases, asset prices fall, and the exchange rate appreciates. However, the responses are now all larger (apart from equity prices) and all are statistically significant. Our result for the exchange rate is counter to that of Glick and Leduc (2013) who find virtually no effect of unconventional monetary policy surprises on the value of the US dollar over one day.

The first column of table 3 confirms that the responses to monetary policy shocks are generally larger in the unconventional period. For example, the response of the 10 year rate increases by around 5 basis points, which is statistically significant. This result is consistent with earlier findings that quantitative easing influences longer term interest rates (e.g. Krishnamurthy and Vissing-Jorgensen 2011, and Gagnon, Raskin, Remache, and Sack 2011). The responses of corporate bond prices, the gold price, and REIT prices are also larger in magnitude by statistically significant amounts. Similarly the exchange rate responds more strongly, but the difference is not statistically significant. We find attenuated response of equity prices in the unconventional period, which is consistent with Rosa's (2012) and Kiley's (2014) results, although our result is insignificant.

Regarding the 90 day rate, it is clear that changes to the 90 day rate are now seriously deficient as a monetary policy metric. The response to a monetary policy shock is opposite in sign and an order of magnitude smaller than in the conventional period. Hence, changes to the 90 day rate should not be used as a measure of monetary policy shocks during the unconventional period. Of course, our results and recommendation should not come as a surprise, because it is readily apparent from even casual observation that movements in 90 day rates have been constrained by the lower bound in the unconventional period. Similarly, the large and significant change for the 90 day rate response, the first entry in column 1 of table 3, is simply a reflection of its deficiencies as a monetary policy metric in the unconventional period.

Related to the previous paragraph, it is possible that our estimated responses for the asset prices other than the 90 day rate might be influenced by its properties in the unconventional period. Hence, we have repeated the analysis after omitting the 90 day rate from our dataset, and we find substantially similar results to those reported in tables 2 and 3. The main difference is that the responses of equity prices are no longer significant in both periods, and the exchange rate response is not significant in the unconventional period.

From a policy perspective, our results indicate that the US Federal Reserve has been able to influence wider financial markets in a similar manner across conventional and unconventional monetary periods, despite not having the freedom to materially lower the Federal Funds Rate in the latter period. Indeed, the influences appear larger in the unconventional period, which is a point we will return to in section 6 and the conclusion.

5.3 Monetary policy responses with SSR datasets

The second column of table 2 shows the results for the conventional period with the representative SSR dataset. First note that the response for the SSR series is significant and similar to that for the 90 day rate dataset, which indicates that changes in our representative SSR offers similar information with respect to monetary policy shocks as 90 day rates. However, the magnitude of the SSR response is smaller than for the 90 day rate, and the first entry in column 2 of table 3 shows that the difference is significant. The difference is because SSR series are estimated from yield curve data and therefore reflect a wider set of information, including actual and expected policy rate changes for longer horizons, than the 90 day rate.

The remaining parameter estimates in the second column of table 2 show that the 10 year rate, asset price, and exchange rate responses in the conventional period are similar whether the 90 day rate or representative SSR dataset is used. The corporate bond price response now has the expected negative sign, but it is insignificant. Column 2 of table 3 confirms the similarity of the responses for the representative SSR and 90 day rate datasets; all differences in responses are insignificant, except for a marginally significant difference for the 10 year rate at the 10 percent level.

The third column of table 2 shows the results for the unconventional period using our representative SSR dataset. The SSR response to monetary policy shocks remains similar to the conventional period, in sign, magnitude, and statistical significance. The responses of the remaining variables are similar to the responses for the 90 day rate dataset in the unconventional period, which is evident from the third column of table 3. The only significant difference between responses is for the 90 day rate versus the SSR, which again reflects that the former no longer provides a useful monetary policy metric in the unconventional period.

These results suggest that, unlike the 90 day rate, changes to the SSR have the potential to be used as a metric for monetary policy shocks in both the conventional and unconventional periods. The latter reflects that SSRs can continue to move freely in the unconventional period, which is the underlying principle of shadow / lower bound term structure models.

The fourth column of table 3 contains the difference in responses between the conventional and unconventional period based on our representative SSR dataset. All responses are larger in the unconventional period, although only the SSR, 10 year rate, and REIT price responses are significant. The latter results are interesting because those variables relate closely to the type of securities targeted by the Federal Reserve in the QE programs. QE2, Operation Twist, and QE3 involved purchases of US treasury bonds, hence influencing the 10 year rate and the SSR estimated from yield curve data, while REITs are related to mortgage-backed securities which were purchased in QE1 and QE3. The increased response for REITs may also reflect their sensitivity to interest rates through two channels. First, a decline in interest rates during the unconventional monetary policy period lowered the discount rate for expected future net income, thereby producing a present value effect. Second, the decline in interest rates also lowered the cost of borrowing for real estate investment vehicles, which are typically highly leveraged, thereby producing a net income effect.

To test the robustness of our results for the representative SSR in the unconventional period, and the other daily SSR series we obtained, we have repeated our estimations using each of the SSR estimates that we presented in section 3.2. The results are summarized in table 4, and all responses are significant to the 5 percent level.

The first point of note is that all responses except those for the short rate are very similar, and all are of the expected sign. The consistency of the SSR responses with the responses of the other asset classes therefore offers a test of whether the SSR series is useful as a monetary policy indicator.

For the SSR series estimated from two-factor models and benchmark maturity interest rates spanning 0.25 to 30 years, we find SSR responses that are substantially similar. When using the SSR series estimated from the two-factor model with interest rates spanning

0.25 to 10 years, the response is smaller, and it is also smaller and insignificant in the conventional period. Those results are consistent with less information being contained in the yield curve data spanning 0.25 to 10 years than spanning 0.25 to 30 years. For all of the SSR series estimated from three-factor models with interest rates spanning 0.25 to 30 years, we find counterintuitive negative responses to tightening monetary policy shocks in the unconventional period. Furthermore, there is substantial variation in the magnitudes of the responses.

The results above suggest that SSR series estimated from two-factor models with yield curve data spanning 0.25 to 30 years are the best from those we have estimated and tested in this paper. Those series have responses to monetary policy shocks that are of the correct sign and that are significant over both the conventional and unconventional policy periods. Furthermore, the estimates of those SSR series and their responses are relatively robust to changes in the lower bound specification.

Table 4: Monetary policy response estimates in unconventional period

Short rate	90d	SSR	SSR	SSR	SSR	SSR	SSR	SSR	SSR
Factors	n/a	2	2	2	2	3	3	3	3
Lower bound (1)	n/a	14e	0	25	15e	15e	0	25	13e
Data (2)	n/a	30	30	30	10	30	30	30	10
Short rate	-0.23	2.12	2.36	1.96	0.35	-1.26	-2.01	-0.95	-0.30
10 year rate	8.19	8.17	8.17	8.18	8.19	8.19	8.19	8.19	8.19
Corp. bond p.	-0.89	-0.65	-0.64	-0.66	-0.91	-0.82	-0.69	-0.88	-0.91
Gold price	-0.75	-0.70	-0.71	-0.70	-0.72	-0.71	-0.69	-0.71	-0.71
Equity price	-0.42	-0.57	-0.57	-0.57	-0.40	-0.50	-0.53	-0.43	-0.40
REIT price	-0.77	-0.93	-0.94	-0.93	-0.79	-0.82	-0.85	-0.79	-0.78
Exchange Rate	-0.32	-0.36	-0.36	-0.36	-0.33	-0.33	-0.34	-0.33	-0.32

(1) Lower bound values in bps, and e indicates an estimated value.

(2) 30 indicates yield curve data spanning 0.25 to 30 years, 10 indicates 0.25 to 10 years.

6 Normalized monetary policy responses

As noted in section 5.2, the responses of asset prices to monetary policy shocks has been larger in the unconventional period compared to the conventional period. On the assumption that changes in the representative two-factor SSRs provide a reasonably consistent and robust measure of monetary shocks across conventional and unconventional periods, as indicated by the results from section 5.3, we can use those SSR changes to indicate how much of the increased responses can be attributed to larger monetary policy shocks versus a larger transmission of similar sized shocks.

As background, the literature often assumes, reasonably, that monetary policy shocks are the dominant factor for changes to financial market prices on monetary policy days, and that the change in the short-maturity rate provides a metric for the monetary policy shock. These assumptions may be reflected in our model by setting $\alpha_1 = \delta_1 = 0$ in equation

2, obtaining $y_{1,t} = \beta_1 m_t$. Then the monetary policy shock series as proxied by changes to an SSR series is:

$$m_t = \frac{y_{1,t}}{\beta_1} \tag{6}$$

Substituting equation 6 into equation 2 for the remaining elements, i.e. $j \neq 1$, and taking the first derivative with respect to the monetary policy shock y_1 yields the normalized response of asset j to a one basis point monetary policy surprise as proxied by the change in the SSR:

$$\frac{\partial y_j}{\partial y_1} = \frac{\beta_j}{\beta_1} \tag{7}$$

Table 4 reports the monetary policy responses normalized with respect to the SSR as a proxy for monetary policy shocks. We report the standardized responses for the 10 year rate, asset prices, and the exchange rate respectively for the conventional and unconventional monetary policy period in columns 1 and 2 of table 4.

To obtain standard errors and levels of significance for the normalized results, we use a Monte Carlo simulation. Specifically, we simulate 10,000 responses using the estimated parameters and associated covariance matrices from the original estimations (i.e. those underlying table 2 and the full results in appendix B), calculate the associated normalized responses with respect to the SSR response for each simulation, and then calculate the 5 and 10 percent levels of significance from the resulting distribution. The reason for using this method is to appropriately allow for the non-normal distribution that results from dividing one random variable by another. However, for brevity we summarize the distribution using the standard errors reported in the tables, rather than the actual percentiles used to determine the levels of significance.

The first three columns of table 4 show the normalized results for the responses reported in table 2, apart from those for the 90 day rate dataset in the unconventional period.[13] The results in terms of signs and significance are similar to those reported in table 1. The main difference is that for the SSR dataset in the conventional period, only the 10 year rate response remains significant.

Table 4: Normalized monetary policy responses

[13] The results for the 90 day rate dataset in the unconventional period are not reported, given the deficiencies discussed earlier. In addition, the 90 day response distribution of –0.227 (0.137) spans zero with relatively high probability, which would make any normalizations highly variable.

	Period 1 90 day	Period 1 SSR	Period 2 SSR	Period 2 SSR less Period 1 SSR
Short rate	1	1	1	0
10 year treasury rate	0.919 **	2.392 **	3.850 **	1.459
	(0.104)	(1.086)	(0.476)	(1.145)
Corporate bond prices	0.073	-0.068	-0.305 **	-0.237
	(0.092)	(0.428)	(0.12)	(0.438)
Gold price	-0.036	-0.178	-0.330 **	-0.152
	(0.094)	(0.437)	(0.125)	(0.452)
Equity prices	-0.159 *	-0.327	-0.268 **	0.059
	(0.098)	(0.463)	(0.143)	(0.480)
REIT prices	-0.056	-0.012	-0.440 **	-0.428
	(0.095)	(0.431)	(0.169)	(0.459)
Exchange rate	-0.016	-0.125	-0.170 **	-0.044
	(0.095)	(0.434)	(0.118)	(0.446)

Period 1: Conventional monetary policy, 1 February 1996 to 12 September 2008.
Period 2: Unconventional monetary policy, 15 September 2008 to 28 January 2016.
90 day: The short rate is the 90 day treasury rate.
SSR: The short rate is the shadow short rate.
Level of significance: ** 5 percent, * 10 percent.

The final column of table 4 shows the difference in the normalized responses for the SSR dataset between the conventional and unconventional periods. All of these differences are insignificant, which suggests that the response to a monetary policy shock of a given size has not changed from the conventional to the unconventional period. In other words, we find no evidence that the transmission of monetary policy into financial markets has changed. By implication then, the larger responses in the unconventional period appear to be due to an increase in the size of monetary policy shocks.

We have repeated our exercise above using the SSR series obtained with the two-factor model, the calibrated lower bounds of zero and 25 bps, and the 0.25 to 30 year dataset. We find the normalized responses and the changes in normalized responses are very similar to the results reported in table 4.

7 Conclusion and policy implications

The global financial crisis and the subsequent "great recession" of 2008-09 was followed by unprecedented monetary easing by central banks around the world. The US Federal Reserve initially responded by lowering its policy rate, the federal funds rate, to near zero levels. Having exhausted that conventional means of monetary policy easing by late 2008, the Federal Reserve also implemented unconventional monetary policy measures, e.g. asset purchases and forward guidance on policy rates, to provide additional stimulus.

Our event-study analysis, using daily observable financial market data and idenfication via heteroskedasticity on monetary policy versus non-monetary policy days, quantifies the response of US asset markets to monetary policy shocks accross the conventional and unconventional monetary policy periods noted above. We found that the responses of interest rates, asset prices, and the exchange rate to monetary policy shocks all became significant in the unconventional period, and increased from the conventional to the unconventional period.

We found, as expected, that changes in the 90 day rate no longer provide a useful metric for monetary policy shocks in the unconventional period. In that context, our event-study framework provided a means of testing whether changes in a range of daily shadow short rate (SSR) series that we estimated might provide a useful substitute for 90 day rates. We found that SSR series estimated from two-factor shadow/lower-bound models and data spanning 0.25 to 30 years were the best of those we tested. Those series were relatively robust to the choice of lower bound parameter, and showed significant responses of the correct sign with respect to monetary policy shocks (i.e. consistent with the 90 day rate responses in the conventional period, and with the responses of the other financial market variables). Conversely, we found the SSR series estimated from three-factor models to be very sensitive and their changes were counterintuitive with respect to monetary policy shocks.

Finally, using our representative two-factor SSR as a consistent monetary policy metric over both periods, we provided evidence that the increased response of asset markets noted above appears more likely due to larger monetary policy shocks in the unconventional period, rather than changes in the transmission of shocks.

We draw three policy implication from our results. First, central banks are able to influence wider financial markets in a similar manner across conventional and unconventional monetary periods, despite not having the freedom to materially lower the policy rate in the latter period. Second, estimated SSR series subject to appropriate vetting appear to provide a useful quantitative indicator of monetary policy across conventional and unconventional periods. Third, central banks should be aware of potentially larger financial markets reactions in response to surprise monetary policy announcements during unconventional monetary policy periods, relative to previous experience in the conventional period. Such responses might be mitigated by using more cautious statements. As a practical example, we note the large response in the wake of Chair Bernanke's 22 May 2013 comments on tapering the QE3 asset purchase program (the so-called "taper tantrum"). Subsequent comments from Federal Open Market Committee (FOMC) members settled financial markets with caution that any tapering would be gradual, and any subsequent normalization of the policy rate would be some way off.

A Overview of the shadow/lower bound framework

In this appendix, we outline the generic shadow / lower bound framework, the specifications we use to estimate our SSR series, and provide an overview of the estimation process.[14]

A.1 Generic SLM framework

The concept of SLMs was originally introduced in Black (1995) and is based on the lower bound mechanism

$$\underline{\mathrm{r}}\left(t\right)=\max\left[\mathrm{r}\left(t\right),\ \mathrm{r}_{\mathrm{LB}}\right] \tag{8}$$

where $\mathrm{r}(t)$ is the SSR that can freely adopt negative values, and $\underline{\mathrm{r}}(t)$ is the lower bounded or actual short rate which is constrained to a minimum value of the lower bound parameter r_{LB}. Unfortunately, the direct application of Black's (1995) framework with any dynamic process to represent the SSR is relatively intractable and examples are generally limited; e.g. Bomfim (2003) and Kim and Singleton (2012). However, Krippner (2015) derives a framework with a Gaussian affine term structure model process for the SSR that closely approximates the Black (1995) framework and is much more tractable, for any number of factors.[15] The key result is the closed form analytic expression for lower bounded forward rates $\underline{\mathrm{f}}(x_t,\tau)$

$$\underline{\mathrm{f}}\left(x_t,\tau\right)=\mathrm{r}_{\mathrm{LB}}+\left[\mathrm{f}\left(x_t,\tau\right)-\mathrm{r}_{\mathrm{LB}}\right]\cdot\Phi\left[z\left(x_t,\tau\right)\right]+\omega\left(\tau\right)\cdot\phi\left[z\left(t,\tau\right)\right] \tag{9}$$

with

$$z\left(x_t,\tau\right)=\frac{\mathrm{f}\left(x_t,\tau\right)-\mathrm{r}_{\mathrm{LB}}}{\omega\left(\tau\right)} \tag{10}$$

where τ is the time to maturity, and $\Phi\left[\cdot\right]$ and $\phi\left[\cdot\right]$ are respectively the unit normal cumulative density and density functions. The shadow forward rate function $\mathrm{f}(x_t,\tau)$ and volatility function $\omega\left(\tau\right)$ are dependent on the model specification in terms of the state variables x_t and their associated parameters, which we discuss below. Equation 9 is the basis for the measurement equation when estimating shadow / lower bound models because it provides model results that can be compared to yield curve data.

The state equation is obtained from the vector Ornstein-Uhlenbeck process that the state variables follow under the physical $\mathbb{P}$ measure, i.e.

$$x_t=\theta+\kappa\left[\theta-x_{t-1}\right]+\sigma \tag{11}$$

where x_t is the $N\times 1$ vector of state variables with a long run value of θ, a mean reversion

[14] The MatLab programs used to produce the rates are available at http://www.rbnz.govt.nz/research-and-publications/research-programme/additional-research/measures-of-the-stance-of-united-states-monetary-policy/comparison-of-international-monetary-policy-measures.

[15] Wu and Xia (2016) derive the discrete time equivalent. Krippner (2015a), Christensen and Rudebusch (2015) and Wu and Xia (2016) show that the approximation is within a maximum of less than 6 basis points for the 10 year maturity (and less for shorter maturites), and within 14 basis points for the 30 year maturity; see Krippner (2015).

matrix κ and a volatility matrix σ.[16] The linear market price of risk specification $\Pi(t) = \gamma + \Gamma x_t$ provides the risk adjusted $\mathbb{Q}$ measure process for the state variables, which is analogous to equation 11 with $\tilde{\kappa} = \kappa + \Gamma$ and $\tilde{\theta} = \tilde{\kappa}^{-1}(\kappa\theta - \gamma)$. The state variables x_t and parameters $\tilde{\kappa}$, $\tilde{\theta}$, and σ define closed form analytic expressions for $\mathrm{f}(x_t, \tau)$ and $\omega(\tau)$ which, together with the parameter r_{LB}, define the closed form analytic expression $\underline{\mathrm{f}}(x_t, \tau)$ in equation 9.

Once the shadow / lower bound model is estimated, with a suitable non-linear Kalman filter, the SSR point estimate is

$$\mathrm{r}(t) = a_0 + b_0' x_t \tag{12}$$

which is the zero maturity rate on the estimated shadow forward rate or interest rate curve. SSRs can freely take on negative values and a negative SSR can, in principle, be interpreted as a combination of a near zero policy rate setting plus unconventional policy actions (e.g. quantitative easing, forward guidance, etc.) that is more accommodative than a near zero policy rate setting alone.

A.2 Specifications and estimation

Our shadow / lower bound models use either the two- or three-factor arbitrage free Nelson and Siegel (1987) models to represent the shadow yield curve within the Krippner (2015) framework noted in section A.1. The shadow forward rate specification for the two-factor model is:

$$\mathrm{f}(x_t, \tau) = L_t + S_t \cdot \exp\left(-\tilde{\phi}\tau\right) + \mathrm{VE}(\tau) \tag{13}$$

where L_t and S_t are respectively the Level and Slope state variables, $\tilde{\phi}$ is the mean reversion parameter for the Slope state variable, and the shadow term structure volatility effect $\mathrm{VE}(\tau)$ is

$$\mathrm{VE}(\tau) = \sigma_1^2 \cdot \frac{1}{2}\tau^2 - \sigma_2^2 \cdot \frac{1}{2}\left[G\left(\tilde{\phi}, \tau\right)\right]^2 + \rho\sigma_1\sigma_2 \cdot \tau G\left(\tilde{\phi}, \tau\right) \tag{14}$$

where σ_1 and σ_2 are the annualized standard deviations of Level and Slope innovations, ρ is the correlation of the innovations, and

$$G(x, \tau) = \frac{1 - \exp(-x\tau)}{x};\ G(x, 0) = 1 \tag{15}$$

The two-factor volatility function $\omega(\tau)$ is:

$$\omega(\tau) = \sqrt{\sigma_1^2 \cdot \tau + \sigma_2^2 \cdot G\left(2\tilde{\phi}, \tau\right) + 2\rho\sigma_1\sigma_2 \cdot \tau G\left(\tilde{\phi}, \tau\right)} \tag{16}$$

The shadow forward rate specification for the three-factor model is:

$$\mathrm{f}(x_t, \tau) = L_t + S_t \cdot \exp\left(-\tilde{\phi}\tau\right) + B_t \cdot \tilde{\phi}\tau \exp\left(-\tilde{\phi}\tau\right) + \mathrm{VE}_3(\tau) \tag{17}$$

where B_t is the Bow state variable (often referred to as "Curvature"). The expressions for

[16] All parameter vectors and matrices should be taken as being conformable to x_t.

$\text{VE}_3(\tau)$ and $\omega_3(\tau)$ are more complex than for the two-factor model, so are not provided here. They are available in Krippner (2015) or Christensen and Rudebusch (2015, 2016).

Using the specifications above within equation 9, and allowing for a non-zero estimated lower bound parameter r_{LB} defines model lower bounded forward rates $\underline{\text{f}}(x_t, \tau)$. We numerically integrate $\underline{\text{f}}(x_t, \tau)$ as follows

$$\underline{\text{R}}\,(x_t, \tau) = \frac{1}{\tau} \int_0^{\tau} \underline{\text{f}}\,(x_t, \tau)\ \text{d}\tau \tag{18}$$

to obtain model interest rates $\underline{\text{R}}(x_t, \tau)$ so that we can estimate the model using interest rate data. The measurement equation is

$$\underline{\text{R}}\,(x_t, \tau) = \underline{\text{R}}\,(t, \tau) + \eta_t \tag{19}$$

where $\underline{\text{R}}(t, \tau)$ is the yield curve data for time to maturity τ and η_t is the estimated residual. The standard deviations of residuals are specified to be homoskedastic, as in Bauer and Rudebusch (2015) and Wu and Xia (2016). The data we use are daily zero coupon interest rates with maturities of 0.25, 0.5, 1, 2, 3, 5, 7, 10 and 30 years. These are overnight indexed swap (OIS) rates, which are from derivative contracts that settle on the realized federal funds rate, from 6 January 2006 (when the full set of yield curve data is first available) to 28 January 2016 (the latest observation at the time of the analysis). We use government rates as a proxy for OIS rates from 31 January 1995 (the start of the Bloomberg data set) to 5 January 2006. Note that we pro-rata the splicing of the two data sets over the first year of their overlap to ensure there is no possibility of any artificially induced changes to the SSR estimates around the splice date.

We estimate the models using the iterated extended Kalman filter as detailed in Krippner (2015). The iterated extended Kalman filter allows for the non-linearity of the measurement equation, which arises because $\text{f}(x_t, \tau)$ and $\underline{\text{R}}(x_t, \tau)$ are non-linear function of the Level and Slope state variables (due to the normal probability functions). The result is an estimated set of parameters and state variables $L(t)$ and $S(t)$. For the two- and three-factor model, the SSR is given by

$$\text{r}\,(t) = L_t + S_t \tag{20}$$

B Full estimation results

This appendix provides the full estimation results that underlie the summaries reported in the main text.[17]

All tables show the parameter estimates (with standard errors in parentheses) of the common shock, the idiosyncratic shocks, and the monetary policy shock for the two interest rates, the four asset prices, and the exchange rate. These are reported in basis points for the interest rates and in percentage points for the asset prices and the exchange rate, and they should be interpreted as the estimated responses to a one standard deviation monetary policy shock.

[17] Estimation results for the entire sample period are available upon request.

Table A1: 90 day rate / conventional policy (1-Feb-1996 to 12-Sep-2008)

	Common (a_t) γ_i	Idiosyncratic ($d_{i,t}$) δ_i	Monetary policy (m_t) β_i
90 day treasury rate	1.363 **	-5.512 **	3.265 **
	(0.281)	(0.106)	(0.199)
10 year treasury rate	2.843 **	5.143 **	2.999 **
	(0.474)	(0.273)	(0.209)
Corporate bond prices	-1.543 **	0.000	0.238
	(0.192)		(0.254)
Gold price	-0.160	-0.933 **	-0.118
	(0.239)	(0.381)	(0.268)
Equity prices	0.363 *	1.093 **	-0.518 **
	(0.245)	(0.348)	(0.269)
REIT prices	0.307	-1.107 **	-0.183
	(0.242)	(0.330)	(0.269)
Exchange rate	-0.137	0.484	-0.052
	(0.242)	(0.733)	(0.268)

Level of significance: ** 5 percent, * 10 percent

Table A2: SSR / conventional policy (1-Feb-1996 to 12-Sep-2008)

	Common (a_t) γ_i	Idiosyncratic ($d_{i,t}$) δ_i	Monetary policy (m_t) β_i
SSR	1.741 **	2.515 **	1.474 **
	(0.155)	(0.167)	(0.306)
10 year treasury rate	5.729 **	0.000 **	3.525 **
	(0.087)	(0.000)	(0.198)
Corporate bond prices	-0.541 **	1.832 **	-0.100
	(0.163)	(0.198)	(0.358)
Gold price	-0.077	0.929 **	-0.263
	(0.162)	(0.383)	(0.356)
Equity prices	0.241 *	-1.134 **	-0.482 *
	(0.162)	(0.328)	(0.355)
REIT prices	0.164	-1.144 **	-0.018
	(0.163)	(0.310)	(0.358)
Exchange rate	-0.065	-0.483	-0.185
	(0.163)	(0.734)	(0.357)

Level of significance: ** 5 percent, * 10 percent

Table A3: 90 day rate / unconventional policy (15-Sep-2008 to 28-Jan-2016)

	Common (a_t) γ_i	Idiosyncratic ($d_{i,t}$) δ_i	Monetary policy (m_t) β_i
90 day treasury rate	0.308 *	-3.680 **	0.227 *
	(0.206)	(0.098)	(0.137)
10 year treasury rate	2.850 **	5.164	-8.191 **
	(0.455)		(0.086)
Corporate bond prices	-0.857 **	0.000	0.890 **
	(0.195)		(0.142)
Gold price	0.083	0.000	0.752 **
	(0.204)		(0.134)
Equity prices	1.580 **	0.000	0.423 **
	(0.168)		(0.151)
REIT prices	1.963 **	-2.444 **	0.771 **
	(0.315)	(0.299)	(0.158)
Exchange rate	0.282 *	0.615	0.321 **
	(0.315)	(0.587)	(0.137)

Level of significance: ** 5 percent, * 10 percent

Table A4: SSR / unconventional monetary policy (15-Sep-2008 to 28-Jan-2016)

	Common (a_t) γ_i	Idiosyncratic ($d_{i,t}$) δ_i	Monetary policy (m_t) β_i
SSR	1.467 **	2.835 **	2.123 **
	(0.208)	(0.164)	(0.148)
10 year treasury rate	5.074 **	-3.030 **	8.174 **
	(0.670)	(1.135)	(0.086)
Corporate bond prices	-0.839 **	-0.325	-0.648 **
	(0.179)	(1.161)	(0.153)
Gold price	-0.062	-1.289 **	-0.700 **
	(0.164)	(0.277)	(0.151)
Equity prices	1.038 **	1.075 **	-0.569 **
	(0.194)	(0.391)	(0.157)
REIT prices	1.225 **	2.861 **	-0.935 **
	(0.210)	(0.162)	(0.158)
Exchange rate	0.181	0.642	-0.360 **
	(0.210)	(0.557)	(0.152)

Level of significance: ** 5 percent, * 10 percent

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