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JEL Classification

E43, E52, E65

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Asset markets and monetary policy shocks at the zero lower bound*

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Abstract

This paper quantifies the impact of monetary policy shocks on asset markets in the United States and gauges the usefulness of a shadow short rate as a measure of conventional and unconventional monetary policy shocks. Monetary policy surprises are found to have had a larger impact on asset markets since short term interest rates reached the zero lower bound. Our results indicate that much of the increased reaction is due to changes in the transmission of shocks and only partly due to larger monetary policy surprises.

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1 Introduction

Monetary policy affects the decisions of economic agents, and ultimately economic activity and inflation, through intermediate changes in current and expected interest rates and asset prices. In this paper we investigate the impact of monetary policy shocks on asset markets in the United States over the period February 1996 to April 2014. We consider the response of interest rates,

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corporate bond prices, equity prices, real estate investment trust (REIT) prices, the price of gold and the US dollar / Japanese yen exchange rate. We examine whether asset markets have reacted differently to monetary policy surprises when short term nominal interest rates are at or near the zero lower bound and unconventional methods of monetary policy accommodation are employed.

Short term interest rates reached the zero lower bound in several countries, including the United States, when central banks responded to the 2007-09 financial crisis with aggressive monetary easing. While the institutional details differ from country to country, central banks conventionally conduct monetary policy by setting the interest rate at which they lend and receive high powered money (also known as outside money or monetary base) with the inter-bank market, and by buying and selling short term debt securities to target short term nominal interest rates around that setting. But when nominal interest rates reach zero, conventional monetary policy cannot lower interest rates further because the availability of physical currency effectively offers a risk-free investment at a zero rate of interest, which is more attractive than central bank deposits or buying securities that offer a negative interest rate.[1] To provide further monetary stimulus beyond a zero policy rate, central banks have turned to unconventional policies. For example, unconventional policies implemented by the central banks of Japan, the United Kingdom, the United States and the euro area include 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. A comparison of the Federal Reserve's unconventional monetary easing programs with those of the Bank of Japan, the Bank of England and the European Central Bank can be found in Fawley and Neely (2013).

Typically, to quantify the effects of monetary policy shocks, event study analysis building on Kuttner (2001) has been used. The assumption in event studies is that only monetary policy surprises have an immediate impact on short term interest rates and monetary policy shocks can be proxied by observable changes in a short term market interest rate on monetary policy event days. If observed changes in a short term interest rate on monetary policy event days

[1] The occasional minor exceptions are due to institutional features, such as the overhead costs of holding and transacting in physical currency, market liquidity, idiosyncratic supply and demand shocks for specific interest rate securities, etc., and periods where high quality fixed interest securities are purchased during times of market turbulence. Japan, the United States, Germany, Sweden and Switzerland are examples of countries that have realized slightly negative interest rates for short maturity securities, historically and / or at present.

measure monetary policy shocks, then regressing the change in the price of an asset on the change in the short term interest rate gives a consistent estimate of the impact of monetary policy shocks on the price of that asset. However, if other factors, like macroeconomic announcements, for example, also affect the short term interest rate on event days, then the observed change in the short term interest rate measures the unobservable monetary policy shock with an error and regressing the change in the price of an asset on the change in the short term interest rate leads to an omitted variable bias and inconsistent estimates of the impact of monetary policy shocks.[2] Event study analysis is further severely complicated by the binding zero lower bound because when short term rates are at or near zero they can no longer proxy policy shocks.

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 (FOMC).[3] However, the difficulty with this approach is that it can lead to unreasonably large monetary policy shocks; see Claus and Dungey (2012). A third approach, which is applied here, is a latent factor model where monetary policy shocks are identified through heteroskedasticity in daily data; see Rigobon and Sack (2004) and Craine and Martin (2008). We adopt this methodology because the estimation of a latent factor model allows us to directly gauge the usefulness of a shadow short rate, which we use as a proxy for conventional and unconventional monetary policy shocks, as well as quantify the impact of monetary surprises on asset markets. Using the parameter estimates from the latent factor model, we can assess the effectiveness of the shadow short rate as a measure of monetary policy shocks by calculating the omitted variable bias, as proposed by Craine and Martin (2008), of equating monetary policy shocks with changes in a short term interest rate on monetary policy event days. If the shadow short rate is a reasonable approximation for monetary surprises, then the bias estimator should be quantitatively small.

The shadow short rate is a synthetic summary measure that is derived from yield curve data and essentially reflects the degree to which intermediate and longer maturity interest rates are lower than would be expected if a zero policy

[2] One strategy to address the omitted variable bias in event studies is to use ultra high frequency data, typically windows of five to ten minutes around monetary policy announcements. Although ultra high frequency data may address the omitted variable bias, immediate responses are likely to be plagued by initial overreaction (Thornton 2014).

[3] The FOMC is a committee within the United States Federal Reserve System that sets monetary policy by specifying the short term objective of the central bank's open market operations.

rate prevailed in the absence of unconventional policy measures. We use the shadow short rate estimated by Krippner's (2013a) zero lower bound (ZLB) model. Krippner's ZLB model is based on the principle that the actual short term interest rate $\underline{r}(t)$, which is subject to the ZLB, may be viewed as the sum of two components: (i) a shadow short rate $r(t)$ that can take positive or negative values; and (ii) an expression $\max\left[-r\left(t\right),0\right]$ that accounts for investors' option to hold physical currency to avoid a negative return if the shadow short rate is negative. The shadow short rate can be obtained from a shadow / ZLB model applied to yield curve data across both normal and unconventional monetary policy periods and therefore provides a consistent measure of a short term interest rate for quantitative analysis. However, it is important to note that the shadow short rate is an estimated quantity and when it is negative it is not a market interest rate at which economic agents can borrow and lend.[4] Rather, a negative shadow short rate is best seen as a convenient summary measure of how unconventional monetary policy stimulus has influenced intermediate and longer maturity rates relative to just a zero policy rate alone.

Figure 1 plots our estimated shadow short rate together with the effective federal funds rate, which is the US central bank's policy rate.[5] The graph shows that the effective federal funds rate and the shadow short rate move closely together when interest rates are unconstrained by the zero lower bound, but they diverge when the federal funds rate approaches or reaches zero. Hence, there is a small and temporary divergence around the US deflation scare of 2003 as a steepening of the slope of the yield curve provided additional monetary stimulus due to expectations that short term interest rates would remain low. Moreover, a large and persistent divergence developed in late 2008 after the federal funds rate hit the zero lower bound and the shadow short rate evolved to increasingly negative values along with unconventional monetary easing. The shadow short rate started rising in May 2013 following expectations of reduced monetary stimulus by the central bank.

The use of an estimated shadow short rate to quantify monetary policy shocks over normal and unconventional monetary policy periods adds a novel aspect to the fast growing literature on unconventional monetary policy. More-

[4] The market short term interest rates that economic agents face in zero lower bound monetary policy environments are zero or near zero (i.e. zero plus any typical margins).

[5] The federal funds rate is the interest rate at which depository institutions trade balances held at the Federal Reserve (federal funds) with each other, usually overnight, on an uncollateralized basis. The effective federal funds rate is a weighted average of the interest rate at which depository institutions traded federal funds.

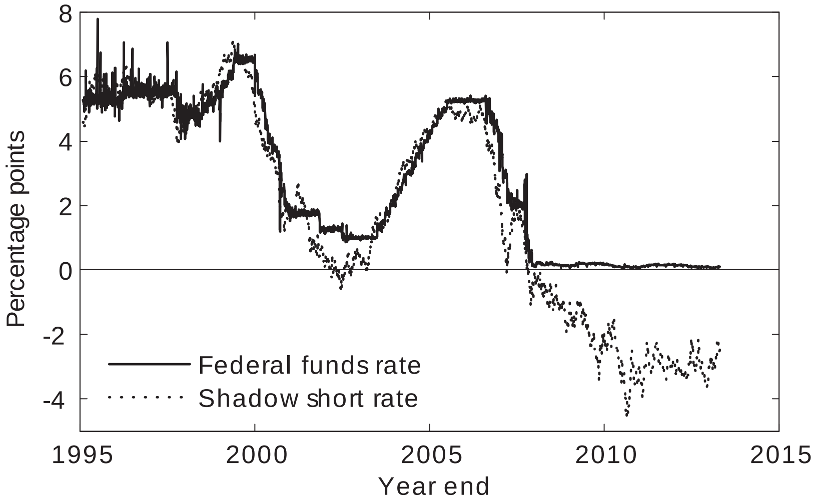

Figure 1: The shadow short rate estimated from a two-factor ZLB-GATSM, plotted with the effective federal funds rate.

over, a consistently estimated shadow short rate allows us to investigate whether the size of monetary policy shocks and / or the responses of different asset markets have changed with the transition from operating monetary policy by conventional means to operating at the zero lower bound along with unconventional methods of monetary policy easing.

Our empirical analysis yields three main findings. First, our results show that the omitted variable bias from equating monetary policy shocks with changes in Krippner's (2013a) shadow short rate on monetary policy event days is low. This suggests that an appropriately calibrated shadow short rate is a useful proxy for monetary policy surprises and this proxy can be employed to measure unconventional monetary policy shocks, analogous to conventional short term interest rates. Second, we find that the impact of monetary policy shocks on asset markets, except equity prices, has been larger since the Federal Reserve began to use unconventional methods of monetary policy easing from late 2008 compared to the conventional period prior. The responses of interest rates at both ends of the yield curve, the price of gold, corporate bond prices and the exchange rate all increase during the unconventional period, while for equity prices the impact of monetary policy shocks has attenuated. Third, the rise in response is not uniform across asset markets suggesting important changes in the transmission of monetary policy shocks during the unconventional compared to the conventional monetary policy period. The 10 year treasury rate and REIT prices in particular seem to respond more strongly to unconventional monetary policy changes. The response of the 10 year treasury rate to a 25 basis point monetary policy shock doubles from 11 basis point to 22 basis points, while for REIT prices we found an insignificant response during normal monetary policy settings but a significant impact during the zero lower bound period.

The next section reviews the recent literature on unconventional monetary policy. Section 3 describes the methodology behind obtaining the shadow short rate and section 4 discusses the empirical framework and data used in the estimation of the latent factor model. Section 5 presents the empirical results and the last section offers concluding remarks.

2 Unconventional monetary policy

The effects of asset purchase programs and quantitative easing have been investigated by many authors. In this section we focus on the announcement literature, which examines the effects of monetary policy announcements on asset markets mainly using event study analysis.[6] Event study analysis has been severely complicated by the binding zero lower bound because short term rates that are at or near zero can no longer proxy monetary policy surprises. To investigate the impact of unconventional monetary policy shocks the strategy of event studies typically is to consider a narrow set of announcements that the authors argue are complete surprises.

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) evaluate the effects of the Federal Reserve's first two asset purchase programs (QE1 in 2008-09 and QE2 in 2010-11) using event study methodology. 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

[6] Instead of announcements some researchers investigate the effects of central bank purchases of securities on asset markets; e.g. Meaning and Zhu (2011) and D'Amico and King (2012).

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 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 to disentangle the impact of monetary policy shocks from other influences. Rosa (2012), Kiley (2013) 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 (2013) is instrumental variable estimation using instruments correlated with the change in the interest rate of interest, which is 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 (2012) 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 study 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 (2009) 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.

We add to the literature on unconventional monetary policy by quantifying monetary policy surprises with a shadow short rate that is consistently estimated over both the normal and unconventional monetary policy periods and by empirically investigating whether the size of monetary policy shocks and / or the responses of different asset markets have changed.

3 Estimation of the shadow short rate

In this section, we outline the estimation of the shadow short rate that we later assess with other interest rate and asset price data in our empirical analysis of monetary policy shocks. The shadow short rate we employ is estimated using a particular model within Krippner's (2013a) zero lower bound modelling framework. We provide a summary of the framework and the model used and refer readers to Krippner (2013a) for further details.

Krippner's (2013a) ZLB framework, which is developed as a close approximation to the ZLB framework of Black (1995), is based on the principle that an actual short term interest rate $\underline{r}(t)$ at time t may be viewed as the sum of two components: (i) a shadow short rate $r(t)$ that can take positive or negative values; and (ii) an expression $\max\left[-r\left(t\right),0\right]$ that accounts for investors' option to hold physical currency to avoid a negative return if the shadow short rate is negative. In sum, $\underline{r}(t) = r\left(t\right) + \max\left[-r\left(t\right),0\right]$. Therefore $\underline{r}(t) = r\left(t\right)$ if $r\left(t\right) \geqslant 0$ or $\underline{r}(t) = r\left(t\right) - r\left(t\right) = 0$ if $r\left(t\right) < 0$, which therefore establishes the zero lower bound for the short term interest rate.

Given the shadow rate / currency option decomposition of the short term rate, the whole observed actual yield curve (i.e. interest rates as a function of time to maturity at time t, all subject to the zero lower bound) may be analogously viewed as the sum of two components: (i) a shadow yield curve as a function of maturity that would exist if physical currency was not available; and (ii) an option effect that the availability of physical currency provides to investors to avoid any realizations of negative shadow short rates that could potentially occur at any time up to each given maturity. Krippner (2013a) represents the shadow yield curve with a generic continuous-time Gaussian affine term structure model (GATSM) and calculates the associated option effect to create the generic continuous-time shadow / ZLB-GATSM framework, which we abbreviated to the ZLB framework.

Figure 2 provides an example of a ZLB yield curve, and the shadow yield curve and physical currency option effect components. It shows that, given an observation of yield curve data that is materially constrained by the ZLB, we can decompose it into the shadow yield curve with negative interest rates for some maturities and the option effect due to the availability of physical currency. The shadow short rate, which is the shortest maturity rate on the shadow yield curve, is conceptually analogous to a policy rate, which is the shortest maturity rate on the yield curve in a normal monetary policy environment. If the yield curve was not materially constrained by the zero lower bound on nominal interest rates, then the physical currency option effect would be negligible, and so the shadow short rate and the policy rate would be almost identical (see Figure 1). Hence, the ZLB model uses a consistent framework across conventional and unconventional monetary policy regimes and the estimated shadow short rate should provide a single comparable gauge of monetary policy across those two regimes.

The shadow short rate we use in the estimation of the latent factor model is derived from a two-factor shadow yield curve within the ZLB framework, which we summarize below.[7] Supplementary analysis, which is available on request, showed that this specification gives the best trade-off between goodness of fit to our yield curve data and robustness to our parameter sensitivity checks. In particular, we found that one-factor models did not fit the data very closely while the shadow short rate and yield curve component estimates for three-factor models are sensitive to small variations in the parameters.

[7] For a one-factor application of the ZLB model see Krippner (2013b). Christensen and Rudebusch (2013, 2014) apply the Krippner (2013a) framework to a three-factor arbitrage-free Nelson and Siegel (1987) model, while Wu and Xia (2014) develop a discrete-time ZLB model that is analogous to the Krippner (2013a) and Christensen and Rudebusch (2013, 2014) models.

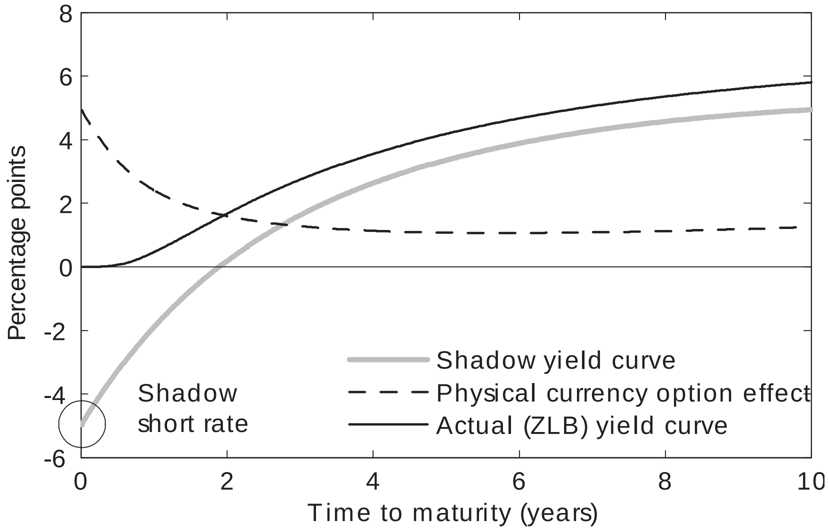

Figure 2: The concept of the shadow yield curve and the shadow short rate implied by the actual zero lower bounded yield curve.

The ZLB model represents the shadow yield curve using a two-factor arbitrage-free Nelson and Siegel (1987) model. Hence, the two state variables $s_1(t)$ and $s_2(t)$ respectively represent the Level and Slope components of the shadow yield curve and adding the associated option effect defines the ZLB yield curve in terms of $s_1(t)$ and $s_2(t)$. More specifically, the shadow forward rate curve $f(t,\tau)$ and its volatility $\omega(\tau)$ are functions of the two state variables, the model parameters and time to maturity τ. The ZLB forward rate $\underline{f}(t,\tau)$ is a function of $f(t,\tau)$ and $\omega(\tau)$, and $\underline{f}(t,\tau)$ is evaluated to provide model estimates of the observed yield curve data $\underline{R}(t,\tau_1),\ldots,\underline{R}(t,\tau_K)$ for the estimation process.

In summary, the shadow yield curve $f(t,\tau)$ is

$$\begin{aligned} f(t,\tau) = {} & s_1(t) + s_2(t)\cdot\exp(-\lambda\tau) \\ & -(\sigma_1)^2\cdot\tfrac{1}{2}\tau^2 - (\sigma_2)^2\cdot\tfrac{1}{2}\left[G(\lambda,\tau)\right]^2 \\ & -\rho\sigma_1\sigma_2\cdot\tau G(\lambda,\tau) \end{aligned} \tag{1}$$

where λ is the mean reversion parameter for the Slope state variable, σ_1 and σ_2 are the annualized standard deviations of Level and Slope innovations, ρ is the correlation of the innovations and

$$G(x,\tau) = \tfrac{1-\exp(-x\tau)}{x};\ G(x,0) = 1 \tag{2}$$

The volatility function $\omega(\tau)$ is

$$\omega(\tau) = \sqrt{(\sigma_1)^2 \cdot \tau + (\sigma_1)^2 \cdot G(2\lambda, \tau) + 2\rho\sigma_1\sigma_2 \cdot \tau G(\lambda, \tau)} \tag{3}$$

and the ZLB yield curve is

$$\underline{f}(t, \tau) = f(t, \tau) \cdot \Phi\left[\frac{f(t,\tau)}{\omega(\tau)}\right] + \omega(\tau) \cdot \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left[\frac{f(t,\tau)}{\omega(\tau)}\right]^2\right) \tag{4}$$

where $\Phi[\cdot]$ is the cumulative unit normal distribution function. The functions $f(t, \tau)$ and $\omega(\tau)$ are used to obtain $\underline{f}(t, \tau)$ over a linear grid of maturities from 0 to τ_{Max} with spacing $\Delta\tau$

$$\underline{f}(t, \tau) = \left[\underline{f}(t, 0),\ ...,\ \underline{f}(t, i\Delta\tau),\ ...,\ \underline{f}(t, \tau_{Max})\right] \tag{5}$$

where τ_{Max} is the longest maturity of the observed yield curve data and we use a value of 0.01 for $\Delta\tau$.

The ZLB interest rate for each required maturity $\underline{R}(t, \tau_k)$ is obtained as the mean of $\underline{f}(t, \tau)$ values from $\underline{f}(t, 0)$ up to $\underline{f}(t, \tau_k)$

$$\begin{aligned} \underline{R}(t, \tau_1) &= \text{mean}\left[\underline{f}(t, 0),\ ...,\ \underline{f}(t, \tau_1)\right] \\ &\vdots \\ \underline{R}(t, \tau_K) &= \text{mean}\left[\underline{f}(t, 0),\ ...,\ \underline{f}(t, \tau_{Max})\right] \end{aligned} \tag{6}$$

We estimate the ZLB model from the yield curve data described in section 4.3 using the iterated extended Kalman filter. The iterated extended Kalman filter allows for the non-linearity of the measurement equation, i.e. $\underline{R}(t, \tau)$, which arises because the option effect is a non-linear function of the Level and Slope state variables. The result is an estimated set of parameters and state variables $s_1(t)$ and $s_2(t)$ and the shadow short rate is then[8]

$$r(t) = s_1(t) + s_2(t) \tag{7}$$

It is important to emphasize that we use the shadow short rate as a convenient means of quantifying monetary policy shocks, but the shadow short rate is not actually an effective interest rate or a market rate at which economic agents can borrow and lend. A negative market interest rate would imply that savers pay an interest rate to borrowers, which obviously would not occur in practice.

[8] These estimates are available from the authors by request.

Rather, the shadow short rate is a summary measure derived from yield curve data that essentially reflects the degree to which intermediate and longer maturity rates are lower than would be expected if a zero policy rate prevailed in the absence of unconventional policy measures. In that respect, the lower interest rates along the yield curve provide an avenue for additional monetary stimulus and the shadow short rate summarizes that effect.[9]

4 Empirical framework and data

In the remainder of this paper we quantify the impact of monetary policy shocks on interest rates and asset prices in the United States and gauge the usefulness of the shadow short rate as a proxy for monetary policy surprises. In this section we present the empirical framework and discuss the data used in the estimations.

4.1 Latent factor model

To investigate the responses of interest rates and asset prices to monetary policy surprises, we identify monetary policy shocks (on monetary policy days) through heteroskedasticity and apply a latent factor model to daily data; see Rigobon and Sack (2004) and Craine and Martin (2008) for detailed descriptions of the approach. Latent factor models, which are a popular tool in the finance literature, express yields or prices as a linear function of common (systemic) and idiosyncratic (diversifiable) factors

$$y_{j,t} = \alpha_j a_t + \delta_j d_{j,t} \tag{8}$$

where $y_{j,t}$ is the demeaned first difference of the yield or the price of an asset 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 $y_{j,t}$.[10] The idea of identification through heteroskedasticity recognizes that reactions to monetary policy shocks m_t are in addition to these common and idiosyncratic shocks. Monetary policy days T^{MP} can be exogenously identified as long as central banks make explicit monetary policy

[9] Quantifying the specific transmission would be an interesting exercise for future work. Also, Krippner (2014) proposes an alternative measure of monetary stimulus estimated from ZLB models, which may provide a further alternative measure of monetary policy shocks.

[10] Principal component analysis on the data supports the inclusion of just one common factor. For all empirical specifications, the first principal component explains about 80 percent or more of the sample variance. The first normalized eigenvalue is 0.81 and above. Detailed results are available from the authors.

announcements. In that case, the additional monetary policy factor m_t applies only on monetary policy days

$$y_{j,t} = \alpha_j a_t + \delta_j d_{j,t} + \beta_j m_t \tag{9}$$

where $t \in T^{MP}$ while equation (8) 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 the β_j's give the responses to monetary policy shocks. The common shock, a_t, to all assets may be, but does not necessarily represent, macroeconomic shocks. The model imposes two restrictions. Monetary factors are heteroskedastic and orthogonal to non-monetary factors and non-monetary factors are homoskedastic.

Re-writing equations (8) and (9) in matrix form gives

$$Y_t = \Lambda H_t \text{ for } t \in T^{OTH} \text{ and } Y_t = \Lambda H_t + \Phi m_t \text{ for } t \in T^{MP} \tag{10}$$

where 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 gives

$$\Omega^{OTH} = \Lambda\Lambda' \text{ and } \Omega^{MP} = \Lambda\Lambda' + \Phi\Phi' \tag{11}$$

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

$$\Omega^{MP} = \begin{bmatrix} \alpha_1^2 + \delta_1^2 + \beta_1^2 & & \\ \alpha_1\alpha_2 + \beta_1\beta_2 & \alpha_2^2 + \delta_2^2 + \beta_2^2 & \\ \vdots & & \ddots \\ \cdots & \cdots & \end{bmatrix}. \tag{12}$$

Ω^{OTH} is analogous with $\beta_j = 0, \forall j$. The model is estimated using generalized method of moments (GMM) techniques where the model's theoretical second moments in equation (11) are matched to the empirical moments of the data. 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.[11]

4.2 The shadow short rate as a proxy for monetary policy shocks

If the shadow short rate is a reasonable approximation for monetary policy shocks, then fully anticipated monetary policy announcements should have no immediate impact on the shadow short rate and a change in the shadow short rate on monetary policy event days measures monetary surprises. However, if other factors, like macroeconomic announcements, also affect the shadow short rate on event days, then the change in the shadow short rate measures the monetary policy shock with an error. In that case regressing the change in the price of an asset on the change in the shadow short rate would lead to an omitted variable bias and inconsistent estimates of the impact of monetary policy shocks.

To assess the usefulness of the shadow short rate as a proxy for monetary surprises, we quantify the omitted variable bias by calculating Craine and Martin's (2008) bias estimator. The bias estimator is derived from the parameter estimates of the latent factor model and given by

$$bias_j = \frac{\beta_j}{\beta_1}\left(1 - \frac{\beta_1}{\frac{\omega}{\beta_1}}\right) - \frac{\alpha_j \alpha_1}{\omega} \tag{13}$$

with the shadow short rate in the first row of the $(N \times 1)$ vector Y_t and $\omega = \alpha_1^2 + \delta_1^2 + \beta_1^2$. If the shadow short rate is a reasonable approximation for monetary surprises, the bias estimator should be quantitatively small and changes in the shadow short rate approximate monetary policy shocks. Moreover, a different coefficient on the monetary factor of the shadow short rate during the normal and unconventional monetary policy regimes would indicate that the size of monetary policy shocks has changed between the two estimation periods.

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

If the shadow short rate is only driven by monetary policy shocks, then $\alpha_1 = \delta_1 = 0$ and

$$y_{1,t} = \beta_1 m_t \tag{14}$$

or

$$m_t = \frac{y_{1,t}}{\beta_1} \tag{15}$$

Substituting equation (15) into equation (9) with $j \neq 1$ and taking the first derivative with respect to the policy shock, measured by the change in the shadow short rate y_1, yields

$$\frac{\partial y_j}{\partial y_1} = \frac{\beta_j}{\beta_1} \tag{16}$$

and equation (16) gives the normalized response of asset j to a one basis point monetary policy surprise. The normalized response provides an indication of whether the transmission of shocks has been altered between the two monetary policy regimes. For example, if asset markets react more strongly during the period of unconventional monetary policy because monetary policy shocks have become larger, the normalized responses are expected to stay the same. But if they become larger, then this would suggest a change in the transmission of shocks.

4.3 Data

The latent factor model is estimated for two sample periods: (i) 1 February 1996 to 12 September 2008 when short term interest rates are comfortably above the zero lower bound; and (ii) 15 September 2008 to 16 April 2014 when the zero lower bound is binding. The beginning of the estimation period is determined by the availability of real estate investment trust data discussed further below.

Since January 1994 the Board of Governors of the Federal Reserve has been making explicit monetary policy announcements allowing the exogenous identification of monetary policy days T^{MP}. 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 testimony to Congress (see Rigobon and Sack 2004).[12] We also identify 25 November 2008, the beginning of QE1, as a monetary policy announcement day when the Federal Reserve stated its intention to purchase mortgage backed, treasury and agency securities. The

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

full period includes 207 monetary policy days $\left(T^{MP} = 207\right)$ and 4543 all other days $\left(T^{OTH} = 4543\right)$. The two samples have 139 monetary policy and 3153 all other days prior to short term interest rates hitting the zero lower bound and 68 monetary policy days and 1390 all other days when the zero lower bound is binding.

To obtain the shadow short rate we use daily zero coupon government rates sourced from Bloomberg, with maturities of 0.25, 0.5, 1, 2, 3, 5, 7, 10, and 30 years and the sample period from 30 December 1994 (the first available data point) to 18 April 2014 (the last data point at the time of estimation).[13] We also source from Bloomberg the US dollar / Japanese yen exchange rate, which is the New York close mid rate. An increase (decrease) in the exchange rate indicates a depreciation (appreciation) of the US dollar.

All other data are from the Federal Reserve Economic Database (FRED) on the Federal Reserve Bank of St. Louis website. We include the 10 year treasury constant maturity rate and use 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. For bond prices we calculate a bond price index from Moody's seasoned Aaa corporate bond yields. The index is constructed as follows using data from 3 January 1983 to 17 April 2014. We make the approximate assumptions that the bond is issued at par (price of 1) on the given day with a notional maturity of 25 years. The latter assumption is justified because Moody's uses the yields of corporate bonds with the given rating maturities and maturities between 20 and 30 years to obtain the indicative recorded yield. The par assumption is justified by the fact that the continually renewing basket of bonds (i.e. allowing for new issues and dropouts due to rating changes and / or maturities falling below 20 years) retains average issue prices at approximately 1. We revalue the bond on the following business day using a semi-annual bond price formula (the basis for US bonds) that precisely accounts for interest accrual returns and capital gains or losses (given the assumptions already made). The log bond return is then log (new price / original price) = log (new price) given the original price equals 1. The log bond price index is the cumulative sum of the log bond returns and the level of the bond price index is obtained by taking the exponential. For real

[13] Our supplementary analysis, which is available on request, showed that it is best to use the information from the full yield curve when estimating the shadow short rate, rather than just maturity spans of up to 10 years as often used in the yield curve literature.

estate investment trust (REIT) 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.

5 Empirical results

This section reports the estimation results of applying the latent factor model to demeaned first differences of interest rates and asset prices. We consider two periods: (i) normal monetary policy; and (ii) the unconventional monetary policy period.[14]

5.1 Normal monetary policy period

Table 1 reports the estimation results for normal times from 1 February 1996 to 12 September 2008 (which is immediately prior to the weekend announcement of the Lehman Brothers' bankruptcy). The table shows the parameter estimates (and standard errors in parentheses) of the common shock, the idiosyncratic shocks and the monetary policy shock for the two interest rates and five asset prices. The parameter estimates, which are reported in basis points for the interest rates and in percentage points for the asset prices, give the responses to a one standard deviation shock.

The results in Table 1 show that monetary policy surprises have a statistically significant impact on all the variables except REIT prices. The coefficients for the shadow short rate and the 10 year treasury rate have the same sign, which is opposite to the sign on corporate bond, gold and equity prices and on the exchange rate. An unexpected easing in monetary policy reduces interest rates and increases asset prices, while a tightening has the opposite effects.

Monetary policy shocks are an important influence on the slope of the yield curve and the short rate responds more than the longer maturity yield. An unexpected one standard deviation tightening raises the shadow short rate by about 8.9 basis points, while the 10 year treasury rate increases by 3.9 basis points from mean. For asset prices the impact of monetary policy surprises is largest for gold followed by the exchange rate, equities and corporate bonds. The price of gold declines about 0.41 percentage point from mean following an unexpected

[14] The sample variances on non-policy days are considerably larger in the second sample period compared to the first. This is not surprising given given the second period covers the financial crisis and the ensuing 'great recession'. In line with the homoskedasticity assumption for the common shocks, we did not estimate the model over the entire sample period.

one standard deviation tightening and rises by the same amount following an easing. This result is in line with Frankel (2008). The US dollar appreciates about by 0.38 percentage points following a tightening surprise and depreciates by the same magnitude following an unexpected easing. The responses of equities and corporate bonds are about 0.31 and 0.21 percentage points respectively. For REIT prices the effect of monetary surprises is statistically insignificant and virtually zero during normal monetary policy times.

Table 1: Estimation results during normal monetary policy (1 February 1996 to 12 September 2008)

	Common (a_t) γ_i	Idiosyncratic ($d_{i,t}$) δ_i	Monetary policy (m_t) β_i
Shadow short rate	6.152 **	4.237 **	8.947 **
	(0.865)	(1.261)	(0.078)
10 year treasury rate	5.429 **	-2.069	3.937 **
	(0.764)	(2.008)	(0.120)
Corporate bond prices	-0.510 **	0.344	-0.211 *
	(0.117)	(1.039)	(0.141)
Gold price	-0.079	0.922 **	-0.410 **
	(0.116)	(0.384)	(0.137)
Equity prices	0.310 **	-1.155 **	-0.305 **
	(0.116)	(0.310)	(0.139)
REIT prices	0.223 **	-1.256 **	0.004
	(0.116)	(0.282)	(0.138)
Exchange rate	-0.089	-0.655	-0.377 **
	(0.116)	(0.541)	(0.138)

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

Monetary policy surprises dominate non-policy shocks for the shadow short rate with a factor loading of 8.9 basis points on the monetary policy shock compared to 6.2 basis points for the common shock and 4.2 basis points for the idiosyncratic shocks. But for the 10 year treasury rate and asset prices non-monetary shocks explain most of the variation.

5.2 Unconventional monetary policy period

The second estimation considers the influence of monetary policy shocks during the period of unconventional monetary policy (15 September 2008 to 16 April

2014). During the initial part of this period, the Federal Reserve offered liquidity facilities, announced the QE1 program (November 2008) and cut the federal funds target rate to effectively zero (December 2008). Subsequent unconventional easing was delivered using further quantitative measures (QE2, Operation Twist, and QE3) and forward guidance announcements (conditional statements on the likely horizon for which zero policy rates would be maintained).[15] The results are reported in Table 2.

Table 2: Estimation results for the unconventional monetary policy period (15 September 2008 to 16 April 2014)

	Common (a_t) γ_i	Idiosyncratic ($d_{i,t}$) δ_i	Monetary policy (m_t) β_i
Shadow short rate	7.246 **	5.303 **	9.468 **
	(0.372)	(0.514)	(0.069)
10 year Treasury rate	5.038 **	-4.014 **	8.413 **
	(0.259)	(0.341)	(0.074)
Corporate bond prices	-0.722 **	-0.579	-0.531 **
	(0.109)	(0.620)	(0.107)
Gold price	-0.185 **	-1.273 **	-1.050 **
	(0.107)	(0.280)	(0.106)
Equity prices	0.907 **	1.430 **	-0.211 **
	(0.111)	(0.259)	(0.108)
REIT prices	1.180 **	2.786 **	-0.903 **
	(0.114)	(0.141)	(0.109)
Exchange rate	-0.378 **	0.653	-0.441 **
	(0.114)	(0.543)	(0.107)

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

The table shows that the factor loadings on the monetary policy shock have the expected impact, i.e. the sign on interest rates is opposite to that on asset prices, and they are statistically significant for all variables. Moreover, the effect of monetary policy shocks increases during the Federal Reserve's use of unconventional methods of monetary easing for all variables, except equity prices, compared to normal times. In particular, the response of the 10 year treasury rate more than doubles from 3.9 basis points to 8.4 basis points, while the factor

[15] Gürkaynak, Sack and Swanson (2005) show that forward guidance can be important and should be considered a separate policy shock. This cannot be accomodated in the present model but is subject to on ongoing research by the authors.

loading on the monetary policy shock for the shadow short rate increases from 8.9 basis points to 9.5 basis points. In addition, monetary policy surprises now explain more of the variation in the 10 year treasury rate than common shocks. This result supports earlier findings (e.g. Krishnamurthy and Vissing-Jorgensen 2011 and Gagnon, Raskin, Remache and Sack 2011) that quantitative easing has altered longer term interest rates.

For asset prices, the increase in response is largest for REIT prices from virtually zero (and statistically insignificant) to 0.9 percentage points. We think this stronger effect is likely due to two main channels. First, a decline in interest rates during the unconventional monetary policy period lowered the discount rate for expected future rental income, thereby producing a present value effect. Second, the decline in interest rates also lowers the cost of borrowing for real estate investment vehicles, which are typically highly leveraged, thereby producing a net income effect.

The response of the price of gold and the exchange rate rises to about 1.05 and 0.44 percentage points possibly due to some investors' expectations that quantitative easing may lead to higher inflation. The result for the exchange rate is in contrast to 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 response of corporate bond prices rises to about 0.53 percentage points, while for equity prices monetary policy shocks have a smaller impact during the period of unconventional policy settings compared to the period prior. The result for equity prices is in line with Rosa's (2012) and Kiley's (2013) finding of an attenuated response since the zero lower bound on interest rates has been binding.

The greater response of asset markets to monetary policy surprises during the unconventional monetary policy period indicates that policy shocks have become larger and / or that markets react more strongly to shocks. We investigate this issue further after assessing the usefulness of the shadow short rate as a proxy for monetary policy shocks.

5.3 The shadow short rate as a proxy for monetary policy shocks

To gauge the usefulness of the shadow short rate as a proxy for monetary policy shocks Table 3 reports Craine and Martin's (2008) bias estimator. The bias estimator measures the omitted variable bias from equating monetary policy shocks with changes in the shadow short rate on monetary policy event days. The first two columns show the size of the bias during the normal monetary policy period using the shadow short rate as a proxy for monetary policy shocks compared to a short term interest rate that is often employed in event studies, which is the 90 day treasury rate rate.[16] The third column gives the bias estimator for the unconventional monetary policy period using the shadow short rate. The 90 day rate can no longer be used as it has been at or near the zero lower bound over this period.

Table 3: Bias estimators for the conventional and unconventional monetary policy periods

	Normal monetary policy		Unconventional monetary policy
	Shadow short rate	90 day treasury rate	Shadow short rate
10 year treasury rate	-0.065	0.176	0.206
Corporate bond prices	0.013	-0.003	0.004
Gold price	-0.015	-0.026	-0.045
Equity prices	-0.028	-0.029	-0.049
REIT prices	-0.010	-0.016	-0.095
Exchange rate	-0.013	-0.012	-0.006

Normal monetary policy: 1 February 1996 to 12 September 2008
Unconventional monetary policy: 15 September 2008 to 16 April 2014

The omitted variable bias has been found to be small during normal monetary policy times (see Craine and Martin 2008) and this finding is confirmed by our results. All the biases tend to be small and similar in magnitude to those reported in Craine and Martin (2008) although the bias is somewhat larger for the 10 year rate in the estimation using the 90 day rate as a proxy for monetary policy shocks. Furthermore, the biases in the shadow short rate estimation are generally comparable to those using the 90 day rate except for the 10 year rate, which is lower in the estimation using the shadow short rate. Also, the biases for the 10 year rate and corporate bond prices have opposite signs in the two sets of estimation. Equating changes in the shadow short rate to monetary surprises

[16] The estimation results using the 90 day rate are reported in Table A1 in the appendix.

somewhat overestimates the impact of monetary policy shocks on the 10 year rate but underestimates it for corporate bond prices. The opposite holds true for the 90 day rate estimation. The effects are underestimated for the 10 year rate and overestimated for corporate bond prices.[17] Using the shadow short rate for the period of unconventional monetary policy, the size of the bias becomes smaller for corporate bond prices and the exchange rate, but it increases for all other variables.

Overall, the small biases produced by the shadow short rate indicate that it is a good approximation for conventional and unconventional monetary policy shocks. Changes in the shadow short rate on monetary policy days are mainly driven by monetary surprises and the increase in the coefficient on the monetary factor of the shadow short rate between the normal and unconventional monetary policy regimes (reported in Tables 1 and 2) is due to monetary policy shocks having become larger.

5.4 Normalized responses to monetary policy shocks

Next, we assess whether the transmission of monetary policy shocks to asset markets has been altered. We equate changes in the shadow short rate with monetary policy surprises and compute normalized responses, which are reported in Table 4. The normalized responses are calculated by dividing the monetary policy shock response of each asset by the monetary policy factor loading on the shadow short rate or β_j/β_1 (see equation 16). They show the reaction of asset markets to a one basis point surprise during normal monetary policy times (first column) and when short term interest rates are at or near the zero lower bound (second column).

The normalized responses suggest that during normal monetary policy times a one basis point monetary tightening increases the 10 year treasury rate by 0.44 basis points or that a 25 basis point monetary policy surprise changes the 10 year rate by 11 basis points. This finding is comparable to Gürkaynak, Sack and Swanson (2005), who estimate that a 25 basis point reduction in the federal funds rate causes a 10 basis point decline in the 10 year rate, and adds further support that the shadow short rate is a good proxy for monetary policy shocks.

[17] A negative sign for the bias (equation 13) means that the responses to common shocks, α_j, are large leading to an overestimation of the reaction to monetary policy shocks if common shocks are not accounted for in the empirical application.

Table 4: Normalized responses to monetary policy shocks during the conventional and unconventional monetary policy periods

	Normal monetary policy	Unconventional monetary policy
Shadow short rate	1.000	1.000
10 year treasury rate	0.440	0.889
Corporate bond prices	-0.024	-0.056
Gold price	-0.046	-0.111
Equity prices	-0.034	-0.022
REIT prices	0.000	-0.095
Exchange rate	-0.042	-0.047

Normal monetary policy: 1 February 1996 to 12 September 2008
Unconventional monetary policy: 15 September 2008 to 16 April 2014

Comparison of the normalized responses during the two monetary regimes shows that the reaction of asset markets is larger, except for equity prices, during the period of unconventional monetary policy than the period prior, but the increases in response are not uniform among the different financial assets. A one basis point monetary policy surprise, which has virtually no impact on REIT prices during normal times, is estimated to lead to a 0.095 percentage point change during unconventional monetary policy times. The response of the price of gold, corporate bond prices and the 10 year treasury rate more than doubles and that of the exchange rate increases by about 10 percentage points. The impact of a one basis point monetary policy shock on equity prices declines from 0.034 to 0.022 percentage points and the estimated response for the unconventional monetary policy period is comparable to the result reported in Rogers, Scotti and Wright (2014). Rogers, Scotti and Wright (2014) estimate that a 25 basis point surprise reduction in the 10 year rate causes equity prices to increase by 0.7 percentage point, while our results suggest that a 25 basis point monetary policy surprise lowers the 10 year rate by 22 basis points and raises equity prices by 0.6 percentage points.

Overall, the results suggest that the use of unconventional monetary policy tools has increased the response of asset markets to monetary policy surprises but to varying degrees. The greater reaction of asset markets is the result of changes in the transmission of shocks and only partly due to larger monetary policy shock.

6 Concluding remarks

The global financial crisis and subsequent 'great recession' led to aggressive monetary easing by central banks around the world. The Federal Reserve responded to the financial crisis and economic slowdown by reducing its short term policy rate, the federal funds rate, to near zero. Having exhausted that conventional means of monetary policy easing by late 2008, the Federal Reserve implemented unconventional monetary policy measures (e.g. asset purchases and forward guidance on policy rates) to provide additional stimulus. In this paper we quantified the impact of monetary policy shocks on US asset markets during the normal and unconventional monetary policy periods and assessed the usefulness of a shadow short rate as a measure of monetary policy surprises.

We found that the shadow short rate, which is consistently estimated over both periods, is a reasonable approximation of both conventional and unconventional monetary policy shocks. Since the Federal Reserve began to use unconventional methods, the impact of monetary policy surprises on asset markets, except equity prices, is estimated to have been larger compared to the conventional period prior. The responses of interest rates at both ends of the yield curve, the price of gold, corporate bond prices and the exchange rate all increase during the unconventional period, while for equity prices the impact of monetary policy shocks has attenuated. Further we found an insignificant response of real estate investment trust prices to monetary policy shocks during normal policy settings but a significant impact during the zero lower bound period. The increase in response is not uniform across all asset markets. Our results indicate that much of the increased reaction is due to changes in the transmission of shocks and only partly due larger monetary policy surprises. A more detailed investigation of the altered transmission of monetary policy shocks is left for future research.

A Estimation results using the 90 day rate

Table A1: Normal monetary policy (1 February 1996 to 12 September 2008)

	Common (a_t) γ_i	Idiosyncratic ($d_{i,t}$) δ_i	Monetary policy (m_t) β_i
90 day treasury rate	0.769 **	-5.673 **	6.133 **
	(0.390)	(0.101)	(0.114)
10 year Treasury rate	4.622 **	3.960 *	2.988 **
	(2.186)	(2.550)	(0.167)
Corporate bond prices	-0.680 **	0.000	-0.135
	(0.336)		(0.169)
Gold price	-0.109	-0.929 **	-0.360 **
	(0.170)	(0.382)	(0.160)
Equity prices	0.299 *	1.153 **	-0.339 **
	(0.213)	(0.314)	(0.162)
REIT prices	0.317 *	-1.231 **	-0.160
	(0.219)	(0.294)	(0.162)
Exchange rate	-0.179	0.677 *	-0.185
	(0.219)	(0.524)	(0.160)

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

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