The Long-term Rate and Interest Rate Volatility in Monetary Policy Transmission

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Abstract

Abstracts: As monetary policy tools exert increasing impacts on the longer end of the yield curve, this paper considers a long-term real rate as an alternative policy indicator in a structural VAR framework. Based on an event study of FOMC announcements, we advance a measure of the unexpected policy influence on long-term interest rate volatility. Monetary policy shocks identified by this volatility measure as an external instrument drive significant swings in credit market sentiments and real output, while the policy shocks motivated by unexpected policy rate changes lead to muted responses. Our results support the validity of the risk-taking channel, in which risk perception in financial markets plays an indispensable role in monetary policy transmission.

Keywords: Monetary Policy Transmission; Risk-Taking Channel; Structural VAR; High-Frequency Identification
JEL classification codes: E3, E4, E5

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1 Introduction

Conventionally, monetary economists use changes in short-term interest rates, e.g., the federal funds rate for the United States, to gauge monetary policy stances and identify monetary policy shocks. The Taylor rule, in its various iterations, provides theoretical support for these practices. However, from December 2008 to November 2015, when the federal funds rate was essentially lowered to its zero lower bound (ZLB), the measurement of monetary policy incurred two challenges: first, short-term rates became uninformative; second, those unconventional monetary policy tools were designed to affect longer-term interest rates. Both of these impose question marks on the validity of a Taylor rule strategy in monetary policy identification.

One potential solution is to construct measures sensitive to policy rate changes during the non-ZLB period and otherwise unconstrained by the ZLB. For instance, Krippner (2013), Lombardi and Zhu (2014) and Wu and Xia (2016) use parametric estimations from a factor approach to construct "shadow policy rates" that can accommodate negative values and may give insight on how far the nominal short-term rate would reach if unconstrained by the ZLB. alternatively, Freedman (1994) proposes the Monetary Conditions Index, which is derived from a linear combination of short-term interest rates and exchange rates, to infer monetary policy action.

Those alternative measures are based on the common wisdom that monetary policy only exerts influence through short-term rates. However, unconventional monetary policy tools extensively applied during the ZLB period may have affected longer-term interest rates. For instance, the Federal Reserve increasingly relies on communication, such as forward guidance, to implement monetary policy, particularly since the possibilities to steer the economy via short-term rate policy has been limited by the effective zero lower bound (refer to Cœuré (2017) and Blinder (2018)). Woodford (2012) and Swanson and Williams (2014) show that the forward guidance strategy affects the two-year–and even longer maturity–Treasury yields through guiding expectations on future policy rates. Another example of these unconventional tools is a series of large-scale asset purchases (LSAP) programs between late 2008 and October 2014. These programs expanded the Federal Reserve's balance sheet with direct purchases of longer-term Treasury securities and mortgage-backed securities in private markets. The explicit intention, evident by empirical findings, was to depress longer-term interest rates. (Gagnon, 2010; Gagnon et al., 2011; d'Amico et al., 2012; Rosa, 2012; Swanson, 2015).

Former FOMC Chair Bernanke summarized that

"Forward rate guidance affects longer-term interest rates primarily by influencing investors' expectations of future short-term interest rates. LSAPs, in contrast, most directly affect term premiums." Bernanke (2013)

In light of those challenges, we suggest the 10-year real interest rate (i.e., the 10-year TIPS bond yield) as an alternative monetary policy indicator with three main considerations. First, we expect this measure to be sensitive to variations in short-term rates and the real economy. Second, this measure should be unrestricted by the ZLB. Third, it should reflect the non-negligible impact of unconventional monetary policy tools on the longer end of the yield curve.

Admittedly, quantifying monetary policy actions through longer-term rates is a relatively new approach, though it has been gradually gaining attention. In an SVAR model, Wright (2012) identifies the impact of LSAPs through heteroskedasticity of the reduced-from residual from the 10-year Treasury yield. Weale and Wieladek (2016) include the 10-year Treasury yield in an SVAR model to show how purchases of government bonds by the Bank of England and the Federal Reserve affect long-term yields. Gurkaynak et al. (2004) and Swanson (2017) extract factors from prices of financial assets, including a variety of long-term securities, to measure the effects of policy rate changes, forward guidance, and LSAPs. They specifically identify the factor most closely related to LSAPs as the only one that affects long-term interest rates.

Considering a long-term interest rate—such as the 10-year real yield—as the policy indicator imposes a challenge in the identification of exogenous monetary policy shocks. Specifically, which part of fluctuation in the long-term rate should contribute to the impact of monetary policy shocks? And which component may be due to the contemporaneous responses of the long-term rate to other structural shocks?

Our identification approach in the structural VAR model stems from that in Gertler and Karadi (2015). They advance a VAR identification strategy with external instrumental variables in which unexpected changes in the Fed Funds futures contracts, captured by an event-study approach, facilitate the identification of monetary policy shocks from movements in the policy indicator (the one-year Treasury yield). However, simply applying the aforementioned strategy to identify policy shocks in a long-term rate could be counterproductive. Figure 1 highlights that the 10-year rate seems to be considerably more volatile than the federal funds rate and the one-year Treasury yield. It may be conjectural to assert that unexpected funds rate changes should reflect the overall impacts of FOMC announcements on a long-term rate. In the alternative, we seek after the second-moment variation in interest rate to instrument the structural monetary policy shocks.

Empirically, we notice that the Federal Reserve seems to maintain different degrees of intention on the two ends of the yield curve. Interest rate volatility is

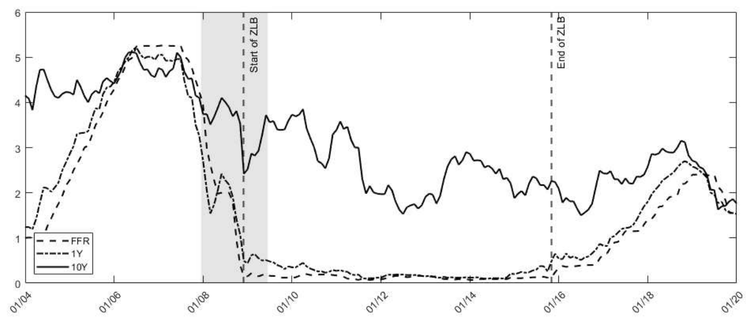

Figure 1: The Federal funds rate, the one- and ten-year Treasury yields

frequently under-explored in the context of monetary policy transmission.

As to the short end of the yield curve, it might be reasonable to allow for a level change of the short-term rate, within a tight window around FOMC announcements, to fully represent the exogenous monetary policy actions. This could be an appropriate mechanism because of the Federal Reserve's explicit commitment to the policy rate target. The near-term expectation of the federal funds rate may immediately adjust to a newly announced target if the Federal Reserve constantly fine tunes the discrepancy of the policy rate from its target range via open market operations. As a result, the fluctuation of the policy rate, ex-post an FOMC meeting, may be marginal in assessing the effects of policy actions and is often ignored in the measurement of monetary policy. Not until recent exploratory work of Bundick et al. (2017) and Bauer et al. (2019) do we realize that even the volatility of short rates conceives important information of monetary policy for asset pricing and real activities [1].

For the other end of the yield curve, the Federal Reserve does not explicitly express and maintain a target for any long-term rates. After an FOMC press release, the new information content in the statement may induce heteroskedastic

[1] Bundick et al. (2017) include their measure in a SVAR model and incur the price puzzle, in which the price abnormally reacts in the same direction as the monetary policy shocks.

variation in long-term rate fluctuations around ex-post steady states. In other words, the investigation of event study should not be restricted to changes in the expected levels of long rates, but also shed light on shifts in conditional volatility.

Theoretically, recent developments in the topic of risk-taking channel of monetary policy transmission reconfirm our focus on the critical but less explored role of interest rate volatility. Borio and Zhu (2012) formally propose the concept of the risk-taking channel and review how monetary policy affects banks' perceived risk. The countercyclical nature of perceived risk in the risk-taking channel is isomorphic to the external financing premium in a financial accelerator model (Bernanke et al., 1999). Difference also exists. Rather than the physical constraint in borrowers' balance sheets which is centered in the financial accelerator models, risk perception and risk tolerance of financial intermediaries in the risk-taking channel contribute to their commitment to lending behavior and in turn affect economic activities. Utilizing data in banking sector, Adrian and Shin (2008),Altunbas et al. (2009), Gambacorta (2009), Delis et al. (2012), Bruno and Shin (2015) and Dell'Ariccia et al. (2017) supply evidence for the impact of monetary policy on the risk-taking behavior of financial intermediaries.

As to the measurement of risk, it is not rare to utilize the volatility implied by options prices to gauge the perceived risk in a given market. Fleming et al. (1995), Fleming (1998) and Christensen and Prabhala (1998) evaluate the perceived risk in stock market, and Carlson et al. (2005), Emmons et al. (2006) and Swanson (2006) indicate the perceived uncertainty in the policy rate. Several market-based measures of interest rate volatility – such as the MOVE index, the TIV index of Choi et al. (2017) and TYVIX index of the Chicago Mercantile Exchange – are focused on expected volatility of longer-term interest rates and provide us access to this analysis.

Responding to monetary policy announcements, the unrestricted fluctuation of long-term rates and varying risk perception of financial intermediaries suggests a novel and probably viable venue to identify monetary policy shocks from the risk-taking channel, encompassing the diversified information and actions announced in FOMC press releases.

In detail, our econometric model considers the 10-year TIPS yield as the policy indicator in a structural VAR model with a financial variable. Monetary policy shocks are identified via high-frequency (i.e., daily) external instruments. We capture two monetary policy surprises via an event-study approach and adopt them as external instruments for identification. One, borrowed from Gertler and Karadi (2015), is based on an event study of policy-induced changes in the three month ahead Fed Funds futures. It is ideal to identify the exogenous monetary policy impact in the state-of-art interest rate channel. Another monetary policy surprise specifically designed for the risk-taking channel is the volatility surprise. It intercepts the jumps of expected volatility of the 10-year Treasury bond price around policy announcements. Unlike the conditional volatility calculated from GARCH-type models, this options-implied volatility is model free and market based, offering the real time variation in the risk percieption in a longer-term bond market. We convert those two event-specific series into monthly frequency and instrument for two monetary policy shocks in different transmission channels in a Gertler and Karadi (2015)-type SVAR model.

The impulse responses show that contractionary policy shocks motivated by both surprises can stimulate reasonable surge in the long-term real rate and decline in the price level without incurring the price puzzle put forth by Eichenbaum (1992), but only the policy shocks transmitting through risk-taking channel drives swings of financial frictions and real output. Policy shocks driven by unexpected policy rate changes exert neglegible influence in credit market constraint and real activities. Our findings corroborate the financial accelerator models (Bernanke et al., 1999) in which financial intermediation amplify the policy impact on economic activity. Besides, Banks' risk evaluation seems play a central role, triggering the soar of credit premium and the decline of lending activities. Our findings also question the validity of cost-of-capital effect in Neoclassical theory of investment as interest rate hikes make no difference in industrial production.

This paper extends a typical SVAR model identifying with external instrument to examine the validity of two different monetary transmission channels within a comparable framework. Furthermore, we are the first to utilize high-frequency options data to gauge the exogenous impact of monetary policy on expected volatility of a long-term interest rate[2]. This measure has the potential to be an alternative monetary policy shock to indicate the risk-side impact of monetary policy.

The rest of the paper proceeds as follow. Section 2 presents our econometric framework of structural VAR model and identification strategy. Section 3 introduce our measure of monetary-policy-induced difference in the uncertainty of long-term rate and its role in identifying monetary policy shocks in the risk-taking channel. Section 4 describes the data and sample period in the SVAR model. Section 5 lays out the empirical results, and Section 6 discusses their implications on the monetary policy transmission. Section 7 concludes.

2 Econometric Framework

Our econometric analysis is based on an SVAR model encompassing a high-frequency identification (HFI) scheme to identify monetary policy shocks.

[2]An array of papers study policy impacts on realized interest rate volatility via observing model-based conditional variance (see Arnold and Vrugt (2010), Abad and Chuliá Soler (2013), and more). We focus on model-free options-implied expected volatility.

The HFI approach is developed based on Stock and Watson (2012) and Mertens and Ravn (2013). It identifies monetary policy shocks with the assistance of external instrumental variables. This method is originally designed to deal with the sensitivity of the included endogenous financial variables to structural shocks (Bagliano and Favero, 1999; Cochrane and Piazzesi, 2002; Faust et al., 2004; Mertens and Ravn, 2013). In an SVAR model with financial variables, recursive timing restrictions in the conventional Cholesky identification could be questionable. It is arduous to justify that those financial variables, given their high-frequency fluctuations, do not contemporaneously respond to certain structural shocks. In contrast, HFI does not restrict the timing of contemporaneous responses.

The distinguishing feature of the identification scheme via external instruments is the separation of policy instruments and policy indicators. A policy instrument is captured in the high-frequency financial data, such as the Fed Funds futures or the option-implied volatility of the 10-year rate, by imposing an "adequately small" time window on each FOMC meeting announcement. Policy instruments produced by this event study manner measure the unexpected impact of monetary policy caused by FOMC announcements and carry relevance to monetary policy shocks. If time windows are appropriately designed to cope with the impact of economic news, those instruments should be orthogonal to other structural economic shocks. A policy indicator is one of the endogenous variables in the lower-frequency VAR. It reflects the impact of monetary policy actions and represents monetary policy stances. The challenge in identification is that a contemporaneously unexpected movement in the policy indicator may be attributed to monetary policy shocks as well as accommodative policy actions or other structural shocks. To tease out the exogenous monetary policy effects, we utilize policy instruments as instrumental variables to estimate the unbiased contemporaneous responses of the policy indicator to structural monetary policy shocks. This method combines the features of event study with the structural identification in VAR models.

In general econometric representation, let Y_t be a vector of n economic and financial variables. A and $C_j \ \forall \ j \geqslant 1$ are conformable coefficient matrices, while ϵ_t is a vector of structural white noise shocks. Matrix A denotes the contemporaneous interactions among endogenous variables. The structural shocks are orthogonal to each other and normalized to one standard deviation. Then the general structural form of the VAR model is given by

$$AY_t = \Sigma_{j=1}^{p} C_j Y_{t-j} + \epsilon_t \tag{1}$$

The straightforward OLS estimation of structural form VAR may incur the endogeneity issue. Pre-multiplying both sides of the equation with A^{-1} derives the reduced form representation

$$Y_t = \Sigma_{j=1}^{p} B_j Y_{t-j} + u_t \tag{2}$$

where u_t is the vector of reduced form residuals. Parameters in reduced form VAR can be estimated by equation-by-equation ordinary least square regressions. Since the structural shocks are of the concern, the reduced form residuals are related to the structural shocks in the following mapping function

$$u_t = S\epsilon_t \tag{3}$$

with $B_j = A^{-1}C_j$ and $S = A^{-1}$. Matrix S is the mapping from structural shocks to reduced form residuals. By normalizing structural shocks ϵ_t to an identity matrix, the reduced form variance-covariance matrix is

$$E_t[u_t u_t^{'}] = SS^{'} = \Sigma \tag{4}$$

Consider $y_t^p \in Y_t$ as the policy indicator and ϵ_t^p as the associated structural policy shock. Then, let s $(n \times 1)$ denote the column in matrix S that corresponds to the impact of structural policy shocks $\epsilon_t^p(1 \times 1)$ on elements in the vector of reduced form shocks u_t. Since our primary question is how economic and financial variables in Y_t respond to monetary policy shocks, we thus need to estimate parameters in the following equation. We only identify the monetary policy shocks and impose no restrictions on other structural parameters.

$$Y_t = \Sigma_{j=1}^{p} B_j Y_{t-j} + s\epsilon_t^p \tag{5}$$

The difficulty of identification lies in the estimation of the mapping vector s that is related to monetary policy shocks. The reduced form residual of policy indicator u_t^p is estimable via OLS regression in the policy indicator equation, but it requires restrictions to identify the portion of u_t^p driven by structural monetary policy shocks and exogenous to other economic shocks.

Identification by external instrument considers monetary policy surprises constructed through an event study method in high-frequency data as the exogenous component of monetary policy. Event-study monetary policy surprises are qualified as policy instruments Z_t if they are strongly correlated with monetary policy shocks ϵ_t^p (relevance condition), but orthogonal to other structural shocks ϵ_t^q (exogeneity condition).

$$E[Z_t \epsilon_t^{p\prime}] \neq 0 \tag{6}$$

$$E[Z_t \epsilon_t^{q\prime}] = 0 \tag{7}$$

The two-stage identification process is similar to the 2-stage least square regression in univariate analyses. The reduced form residual in the policy equation u_t^p is endogenously related to other reduced form residuals u_t^q due to the contemporaneous interactions among variables in Y_t. In the first stage regression, we adopt externally identified monetary policy surprises as policy instruments to tease out the component of u_t^p affected by contemporaneous monetary policy shocks ϵ_t^p.

$$`u_t^p = \gamma Z_t + \epsilon_t \tag{8}$$

In the second stage, we obtain the relationship between responses of other included variables and that of policy indicator to a unit increase of monetary policy shocks by equation (9). s^q link the contemporary variation of non-policy variables u_t^q to a unit of monetary policy shock ϵ_t^p and s^p denote how the VAR residual in the policy indicator equation react to one unit of ϵ_t^p. Since the reduced form residual u_t^p may be partially endogenous to u_t^q, we make use of the exogenous component γZ_t ($\hat{u_t^p}$) derived from the first stage to acquire unbiased estimation of relative changes of u_t^q to u_t^p in response of a unit increase of monetary policy shock $\frac{s^q}{s^p}$.

$$u_t^q = \frac{s^q}{s^p} \hat{u_t^p} + e_t \tag{9}$$

With the estimated $\frac{s^q}{s^p}$, reduced form residuals u_t and the reduced form variance-covariance matrix Σ, we thus derive the estimation of s^p and s^q.[3]

Importantly, this econometric framework imposes no restrictions that the

[3] See Appendix A for more details about the algorithm for identification.

policy indicator must be a short-term rate, and that policy instrument should be a variable describing behavior of the policy rate.

3 Measuring the Exogenous Impact of Monetary Policy in the Risk-Taking Channel

To identify the monetary policy shocks in the risk-taking channel in the aforementioned SVAR model, we propose a new measure of monetary policy impact on the risk perception of interest rate in financial markets. Apart from other options-price-based monetary policy uncertainty measures like those introduced by Bundick et al. (2017) and Lakdawala et al. (2019), our measure takes into account the expected volatility of a longer-term interest rate; it reflects the risk-side impact of monetary policy on the farther end of the yield curve.

3.1 Risk perception in the long-term rate

We evaluate the risk perception in long-term rates through the conditional volatility inferred from derivatives of the 10-year Treasury bond. There are two advantages of this options-implied volatility over the typical GARCH-model-based measures. First, it is model free and directly converted from real-time options prices so that no model uncertainty involves. Second, consistent with the definition of risk, our approach measures the expected volatility rather than the volatility realized in the history.

The volatility of concern is the expected 30-day volatility of 10-year Treasury note futures. The 10-year Treasury note futures are contracts with payoffs tied to the 10-year Treasury note price. These future contracts are the most liquid exchange-traded medium- to long-term interest rate derivatives in the world. Denoting by $P_{t,T}^{(120)}$ the time-t value of a 10-year (i.e., 120 periods in monthly frequency) T-note future expiring at T. Option contracts are tied to futures contracts, with payoff $max(P_{T,T}^{(120)} - K, 0)$ for call options, and $max(K - P_{T,T}^{(120)}, 0)$ for put options, where K is the strike price. These 10-year T-note options are effectively options on 10-year Treasury yield, since the nominal yield on a T-note maturing in 10 years is inversely mapped with the T-note price.

$$log(y_t^{(120)}) = -\frac{1}{n} log(P_t^{(120)}) \tag{10}$$

For a given trading date t and an expiration date T we can estimate the T-t day variance of an asset (VAR) with the forward value of a portfolio of at- and out-of the-money options on the asset expiring at T. The conditional variance of future 10-year T-note can be calculated from a portfolio of out-of-the-money 10-year T-note puts and calls:

$$VAR_t(P_{t,T}^{(120)}) = [e^{r\tau}\{\sum_{K_i} 2\frac{\Delta K_i}{K_i^2} p_{t,T}(K_i) + \sum_{K_j} 2\frac{\Delta K_j}{K_j^2} c_{t,T}(K_j)\} - (\frac{F}{K^*} - 1)^2] \tag{11}$$

where $p_{t,T}(K_i)$ (and $c_{t,T}(K_j)$) are prices of out-of-money put (call) options with strike $K_i \leq K^* \leq K_j$. K^* is the at-the-money strick, which is theoretically equal to the future price $P_{t,T}^{(120)}$. $2\frac{\Delta K_j}{K_j^2}$ is the number of options at strike K included in the portfolio. $e^{r\tau}$ is a discount factor that converts the price of each option to a future value. The term $(\frac{F}{K^*} - 1)^2$ compensates for the error introduced by the substitution of K^* for the future price. It is larger than zero when no listed strike price is equal to the future value.

Applying Equation (11) to options data, the Cboe Global Markets, Inc. (Cboe) calculates the annualized options-implied 30-day standard deviation of 10-year T-note futures, which is referred to as the CBOE/CBOT 10-year U.S. Treasury Note Volatility Index (ticker: $TYVIX$). It is denoted monthly as follows in such 10 years is equal to 120 months:

$$TYVIX = 100 * \sqrt{\frac{365}{30} VAR_t(P^{(120)}_{t,t+1})} \quad (12)$$

The TYVIX is denoted as a percentage of foward 10-year T-note price and subject to changes in price level. As per Swanson (2006), I convert it into the TYVIX in basis points (TYVIXBP) by multiplying it with the spot month 10-year T-note future price:

$$TYVIXBP = P^{(120)}_{t,t+1} * TYVIX \quad (13)$$

TYVIXBP is not subject to the forward price changes and is thus comparable at different time points in a sample with considerable T-note price fluctuation.

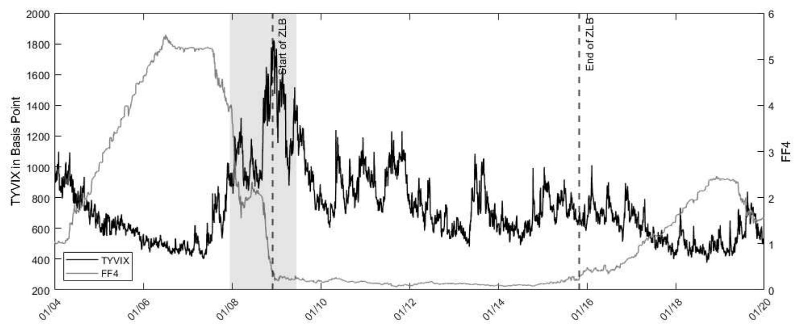

Figure 2: The TYVIX index in basis points and three month Fed funds futures (Daily)

Figure 2 plots the TYVIX in basis points. In the long-run, it shows a negative relationship with the short-term interest rate. It soared to a peak at the outbreak of the financial crisis and experienced a gradual decline during the zero-lower-bound period. Its two peaks are coincided with two local troughs of the federal funds future rate in August 2003 and December 2008. These inverse movements may suggest that the turns of expansionary monetary policy paths introduce more uncertainty in the long-term interest rate.

3.2 Four-day time window

We adopt a four-day time window around each FOMC announcement to capture the surprise of monetary policy in terms of interest rate volatility. It is because a wider time window, compared with the typical one-day window in previous studies, sometimes better capture the policy impact.

For illustration, the security price movement around a policy announcement can be segmented into two phases, such as the formation phase and verification phase. The formation phase refers to the price shift shortly before the announcement date. In this phase, investors trade securities because of the upcoming announcement without actual knowledge of the unannounced policy. The verification phase refers to the price shift right after the announcement. Investors verify their beliefs based on the realized policy decision; cash the gain when they get right and, otherwise, suffer a loss.

We notice that the dramatic price change on an announcement date not only reflects the exogenous policy impact but also results from mean reversion to the price variation during the formation phase. This mean-reverting movement is often associated with the event-driven trading activities instead of the reaction to policies.

Table 1 summarizes three typical scenarios of price movement around an event: only the first one does not have the mean reverting pattern. First, some investors may have insider information or collect sufficiently adequate information to make a winning bet on a given policy decision before the official news release. Their rational bets may lead the security price to gradually approach the ex-post level ahead of the official statement. Second, event-driven trading activities - trading on rumors, hedging, speculation, etc. - may boost the demand for certain securities, such as options, and push up their prices before an event. The increase (decrease) in trading volume before (after) an announcement could result in a hump shaped reaction in a security price. Third, some investors may avoid uncertainty by selling off a security prior to a foreseeable event and then buy it back later. In this case, its price may demonstrate a crater shape response. Unlike the other two, the first scenario is the only one that fits for a one-day window. It is because, although information may leak to the public before the announcement, the same-day price movement is still mainly driven by the information of the policy actions rather than event-specific trading activities. This argument may not be applied to the other two scenarios, in which event-specific trading is non-negligible.

Table 1: Summary of price patterns around policy events

$E(r^F - r^V)$	Pattern around events	Senario	Suitable window
Zero	Accelerating trend	Information leak	One day
Positive	Hump shape	Increased volume	Four day
Negative	Crater shape	Uncertainty avoidance	Four day

Note: $E(r^F - r^V)$ is the expected difference between the return in the formation phase and that in the verification phase.

We test for the necessity of a wider time window by examining the mean reversion behavior. We regress the difference between the formation and verification phases on a constant. An assumption is that expansionary and contractionary monetary policy actions are announced in a random manner. If no apparent event-driven trading activities present, the price movements in the formation and verification phases should be irrelevant or positively correlated and thus the expected value of the difference between the two phases, $E(r^F - r^V)$, is zero. Merely in this case should a one-day window be adequate. In contrast, when $E(r^F - r^V)$ is equal to a non-zero figure, a turning kink emerges between the two phases, suggesting that the security price is affected by the trading due to the event occurrence. Then the shift on the announcement date is polluted and may not truely reflect the policy effect.

Table 2: Test for the neccessity of a wider time window on security prices

$(r^F - r^V)$	MP1	FF4	10Y	TYVIXBP	MOVE
C	0.29	0.49	0.10	5.06^{***}	1.81^{***}
	(0.58)	(0.60)	(0.28)	(0.48)	(0.63)
Obs.	158	158	158	158	158
Durbin Watson	1.96	1.89	2.24	2.36	2.25
F-Stat.	0.25	0.65	0.12	110.38	8.15

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. HAC-robust standard deviation in parentheses.
$E(r^F - r^V)$ is the expected difference between the return in the forming phase and that in the verifying phase. C is the constant term.

Table 2 shows the test results for various security prices. Interest rate levels, such as spot month, three month funds future rate, and ten-year Treasury yield, demonstrate price trend consistent with the "information leak" scenario. As to the second-moment variation of interest rates, such as the TYVIXBP and MOVE indexes, a hump shape price reaction is identified around FOMC announcements.

Figure 3 particularly plots the fluctuation of the TYVIXBP, the variable of concern, around a "typical" FOMC announcement. The point values are averaged from 158 FOMC news releases from 2003 to 2020. This hump-shape price pattern may be due to an elevated volume of trading predicated on rumors and on the hedging of uncertainty as the official press release approaches. Since we aim to capture the impact of monetary policy rather than the FOMC-event-driven fixed effect, a four-day window should be more appropriate than a one-day one. If we take the plot in Figure 3 as the price reaction around one particular statement, our proposed event-study measure on TYVIXBP captures the difference between the dash lines B and A. In Appendix C, we provide additional institutional explanation for selecting this four-day window.

Figure 4 exhibits the proposed event-study volatility surprise, whose naming is analogous to the monetary policy surprise in Kuttner (2001). Data points in the volatility surprise represent changes in the TYVIXBP during the unified

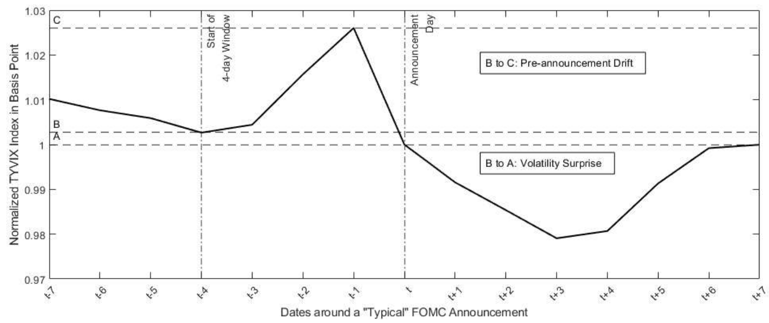

Figure 3: Averaged TYVIXBP index from -7D to +7D of FOMC decisions

4-day time windows around FOMC announcements. A positive volatility surprise indicates that a policy announcement induces an increase in the expected volatility of long-term rate and vice versa. To fit the volatility surprise in our monthly SVAR model, we convert it into a monthly time series following a procedure discussed in Appendix B (The monthly series is also shown in Figure 4).

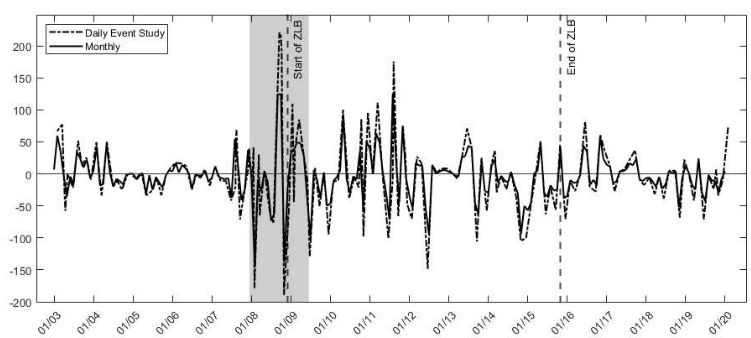

Figure 4: The volatility surprise (Event study & Monthly)

In the next two subsections, we evaluate whether this volatility surprise is relevant to monetary policy actions and empirically examine its impacts on Treasury yields.

3.3 Volatility Surprise and Unconventional Policy Actions

To identify monetary policy shocks as an external instrument, the volatility surprise should be relevant to monetary policy actions even during the zero lower bound period.

Table 3 summarizes the monetary policy narratives, actions and the volatility surprise. In general, changing forward guidance communication style and switching the direction of large-asset purchases seem to be associated with a positive volatility surprise. This consist with the observation that the public perceive more uncertainty in the long term when the Fed sees new development of the economy and switches gear for its monetary policy. Investors also doubt the effectiveness of adopting novel policy actions in depressing the further end of the yield curve. Excluding those announcements that introduce directional changes to policy tools, forward guidance and large-scale asset purchases, in general, generate a negative volatility surprise and enhance the stability of longer-term rates.

As a robustness check for the four-day time window, we further look at the relationship between volatility surprises captured by different time windows and unconventional monetary tools (Table 4). In detail, we regress volatility surprises captured by different time windows on the dummy variables of announcements related to LSAPs and forward guidance. The dummies of unconventional policy tools are based on narratives in FOMC statements. To retain consistency with the literature, we adopt identical narratives as Swanson (2017). Because almost all FOMC announcements since the ZLB period contain sentences regarding forward guidance, we only mark those announcements that change the communication styles in the forward guidance dummy, for instance, the switch from a calendar threshold to an outcome-based threshold. Since the Federal Reserve primarily implements those unconventional tools during the ZLB period, we truncate the

Table 3: Event study of quantitative easing and forward guidance

Dates	Policy actions	VOL	mpu	ΔLASP direction	ΔFG Language	Description
2008/11/25	QE1	0.81	-3.33	Y		The Fed began buying $600 billion in mortgage-backed securities and $100 billion in other debt.
2008/12/16	QE1/FG	-0.78	-4.33			ZLB is reached and the Fed introduce clear forward guidance phrase: exceptionally low levels of the federal funds rate for some time."
2009/0 3/18	QE1/FG	1.44	-2.67		Y	Change in language about low rates to "for an extended period" from previous statement which said "for some time"
2010/11/03	QE2	-1.66	-1.00			the Fed announced it would buy $600 billion of Treasury bills, bonds, and notes by March 2011.
2011/08/09	FG	2.98	-4.67		Y	Introduction of calendar based forward guidance: "exceptionally low levels for the federal funds rate at least through mid-2013."
2011/09/21	MEP	-1.12	0.00			The Fed sold or redeemed a total of $667 billion of shorter-term Treasury securities and used the proceeds to buy longer-term Treasury securities.
2012/01/25	FG	-1.19	-0.67			The fed funds rate is likely to stay near zero "at least through late 2014."
2012/09/13	QE3/FG	0.03	-0.67			Hold the fund rate near zero "at least through mid-2015".
2012/12/12	FG	0.15	0.00		Y	Adopt outcome-based threshold on employment and projected inflation between and two years ahead.
2013/06/19	Taper Tantrum	1.21	0.33	Y		the Fed's announcement of future tapering of its policy of quantitative easing.
2014/12/17	FG	-0.98	-0.33			The Fed replaces the "considerable time" language with a vow to be "patient" in raising interest rates.
2015/03/18	FG	0.03	-1.33			The FOMC replaces the indication that "it can be patient" with the indication that an increase in the target range "remains unlikely at the April FOMC meeting".
Std. Dev (full sample)		1	1			

Note: VOL is the volatility surprise and mpu is the market-based monetary policy uncertainty proposed by Lakdawala et al. (2019).
Both event-study series are normalized to unit standard error.
The fifth column marks the initiation and the taper tantrum of large-scale asset purchases. The sixth column marks changes in forward guidance languages.

Table 4: Comparison of the time windows for volatility surprises (Event study)

VOL	1D	2D	3D	4D	5D
FG	27.07	54.644	68.64^{**}	73.92^{**}	73.92^{**}
	(22.40)	(37.30)	(34.06)	(34.17)	(34.17)
LASP	-68.66^{***}	-72.66^{***}	-74.98^{***}	-71.46^{***}	-71.46^{***}
	(16.60)	(22.76)	(22.16)	(22.27)	(22.27)
Obs.	88	88	88	88	88
R^2	-0.228	0.061	0.100	0.112	0.107

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
Note: HAC Robust standard errors in parentheses

sample to that period.

Table 4 shows the superiority of the four-day time window, as volatility surprises captured by this window has the highest correlation with announcements of unconventional monetary policy tools than those measured in other time windows. It confirms our hypothesis that the pre-FOMC-announcement drift in the volatility are mostly consisted of noise, rather than the informational effect of monetary policy.

3.4 Volatility Surprise and Term Premium

How does the volatility surprise, a second-moment measure, affect a long-term interest rate? Based on a simple model and some empirical evidence, we verify the conjecture in Woodford (2012) that "term premia are affected by expectations about the short-rate process (in particular, the degree of uncertainty about future short rates)". This subsection lays the foundation for our identification strategy – utilizing the volatility surprise to identify the policy-induced exogenous movement in a long-term interest rate.

Similar to Bundick et al. (2017) stylized model, the representative household chooses C_{t+s} and $b^{(n)}_{t+s+1}$ for all bond maturities n and all future periods s by solving the problem:

$$maxE_t \sum_{s=0}^{\infty} \beta^s log(C_{t+s}) \tag{14}$$

subject to the intertemporal household budget constraint in each period,

$$C_t + \sum_{n=1}^{N} p_t^{(n)} \frac{b_{t+1}^{(n)}}{P_t} \leq e_t + \sum_{n=1}^{N} p_t^{(n-1)} \frac{b_t^{(n)}}{P_t} \tag{15}$$

The first order conditions are derived as

$$\frac{1}{C_t} = \lambda_t \tag{16}$$

$$p_t^{(1)} = E_t\{\beta \frac{\lambda_{t+1}}{\lambda_t} \frac{P_t}{P_{t+1}}\} \tag{17}$$

$$p_t^{(n)} = E_t\{\beta \frac{\lambda_{t+1}}{\lambda_t} \frac{P_t}{P_{t+1}} p_{t+1}^{(n-1)}\} \tag{18}$$

Prices are fixed $P_t = P$, for simplicity and model tractability. The price of a n-period bond at time t is given by:

$$p_t^{(n)} = E_t\{m_{t+1} p_{t+1}^{(n-1)}\} \tag{19}$$

where the stochastic discount factor

$$E_t m_{t+1} = E_t\{\beta \frac{\lambda_{t+1}}{\lambda_t}\}$$

After methmetical substitution and manipulation, the bond price and risk-neutral bond price are:

$$log(p_t^{(n)}) = -[E_t \sum_{i=0}^{n-1} r_{t+i} + \frac{1}{2} VAR_t \sum_{i=0}^{n-1} r_{t+i} - COV_t c_{t+n} \sum_{i=0}^{n-1} r_{t+i}] \tag{20}$$

$$log(q_t^{(n)}) = -[E_t \sum_{i=0}^{n-1} r_{t+i} - \frac{1}{2} VAR_t \sum_{i=0}^{n-1} r_{t+i}] \tag{21}$$

where r_{t+i} and c_{t+n} are the logarithms of gross interest rate and consumption. The second moment of expected future short rates represents the compounded loss due to fluctuations in the expected short rate path.

So how the volatiltiy surprise affects the term premium? As shown in Equation (22), the term primium is equal to the difference between the bond yield and the yield of its risk-neutral counterpart. When n increases, c_{t+n} approaches permanent income, which is unlikely to vary with the path of rates. Therefore, the covariance term $COV_t c_{t+n} \sum_{i=0}^{n-1} r_{t+i}$ should be small.

$$TP_t^{(n)} = -\frac{1}{n}(p_t^{(n)} - q_t^{(n)}) = \frac{1}{n}[VAR_t \sum_{i=0}^{n-1} r_{t+i} - COV_t c_{t+n} \sum_{i=0}^{n-1} r_{t+i}] \tag{22}$$

Based on the expression of bond price in Equation (20), variance of the price of a n-period bond at time t is calculated as follow if we retain the first and second moments.

$$\begin{aligned} VAR_t(p_t^{(n)}) &= E_t(p_t^{(n)})^2 - (E_t p_t^{(n)})^2 \\ &= VAR_t \sum_{i=0}^{n-1} r_{t+i} \end{aligned} \tag{23}$$

Note that the uncertainty of the interest rate path dominates the variation in bond price. Combining Equations (22) and (23), the volatility surprise, which measures the impact of FOMC announcements on the volatility of the long-term bond price, should have direct influence on the term premium of long-term interest rates. The empirical evidence supports this argument.

We evaluate that to what extend the term premium reacts to the volatility surprise (shown in Table 5). The accumulated daily changes within the 30 days after a FOMC announcement is of our concern. To control for the influence of policy rate targeting and forward guidance, we include first differences of the spot month and three month federal funds future rates in the regression. We

Table 5: Impact of the volatility surprise on term premiums (Event study, Daily)

$$\Delta^M TP_i = \alpha + \beta VOL_i + \gamma_1 \Delta^M FFR_i + \gamma_2 \Delta^M FFR_{i+2} + e_i$$

i denotes the i^{th} FOMC announcement since 2003:01. $\Delta^M FFR_{i+2}$ represent 30-day changes in the three-month (approx. two scheduled meetings) ahead funds futures.

	Δ^MACM Term Premium					
	5 year			10 year		
Δ^MMP1	-0.47^{***}	-0.48^{***}	-0.50^{***}	-0.51^{**}	-0.54^{***}	-0.57^{**}
	[-3.62]	[-4.23]	[-3.98]	[-2.26]	[-2.76]	[-2.50]
Δ^MFF4	0.11	0.15	0.17	-0.07	-0.01	0.02
	[0.95]	[1.35]	[1.49]	[-0.35]	[-0.04]	[0.10]
VOL		0.08^{**}			0.15^{**}	
		[2.46]			[2.49]	
VOL_1d			0.08			0.12
			[1.21]			[1.04]
R2	0.178	0.240	0.207	0.155	0.233	0.181
	Δ^MKW Term Premium					
	5 year			10 year		
Δ^MMP1	-0.53^{***}	-0.53^{***}	-0.54^{***}	-0.67^{***}	-0.69^{***}	-0.74^{***}
	[-6.75]	[-7.09]	[-6.77]	[-5.38]	[-6.27]	[- 6.39]
Δ^MFF4	0.48^{***}	0.50^{***}	0.51^{***}	0.52^{***}	0.56^{***}	0.62^{***}
	[6.88]	[6.82]	[6.34]	[4.75]	[5.33]	[5.56]
VOL		0.05^{**}			0.10^{***}	
		[2.06]			[2.78]	
VOL_1d			0.04			0.14^{***}
			[1.06]			[3.35]
R^2	0.216	0.252	0.230	0.166	0.241	0.242

Note: Robust t-statistics in parentheses.
ACM and KM term premium are respectively estimated according to Adrian et al. (2013) and Kim and Wright (2005).
Δ^M indicates the 30-day change after event announcements. MP1 and FF4 are spot month and three month ahead federal funds futures.
VOL (or VOL_1d) is the volatility surprise captured by the four-day (or one-day) time window.
Sample excludes the period from July 2007 to June 2009 containing the Global Financial Crisis.(Bauer et al., 2019)

consider two estimates of the term premium and two long-term maturities to show the robustness.

Three points in Table 5 worth noting. First, adding the volatility surprise to the regression improves the explanatory power (R^2). Second, the volatility surprise captured by the four-day window demonstrates more significant impact on the term premium than that captured by the one-day window, with the only exception that the Kim and Wright (2005) term premium of the ten-year Treasury is considered. Lastly, the information content in the volatility surprise is irreplaceable by measures of policy rate changes or forward guidance.

In conclusion, the volatility surprise is constructed based on real-time and high-frequency financial data. It shows relevance to monetary policy actions and exerts influence to the term premia of longer-term rates. We will utilize those properties of the volatility surprise to identify monetary policy shocks in the risk-taking channel.

4 Data in the SVAR Model

Our sample ranges from January 2003 to January 2020. It includes 158 FOMC meetings, both scheduled and unscheduled. The sample covers the entire ZLB period as well as two periods at the beginning and the end with the normalized federal funds rate.

In the SVAR model, we include four endogenous variables, such as the PCE chain-type price index, the industrial production, a monetary policy indicator, and a measure of financial frictions.

The PCE chain-type price index is a measure of final good prices of all domestic personal consumption[4]. The Federal Reserve emphasizes its role in

[4]A detailed comparison between CPI and PCE price index is provided by McCully, C. P., et

measuring price inflation as it "covers a wide range of household spending"[5]. The industrial production is a sensitive indicator of real production activities, and is released in monthly frequency. We follow the practice of Gertler and Karadi (2015) and use the excess bond premium (Gilchrist and Zakrajšek, 2012) as a measure of financial frictions. The excess bond premium captures the difference in yields between the corporate and Treasury bonds with identical maturities after statistically purging the impact of firm-specific indicators of default and bond characteristics. Empirically, it is a viable indicator of the credit market sentiment and the degree of financial friction in financial markets.

The policy indicator that we select is a long-term real interest rate, i.e., the 10-year Treasury inflation-protected securities (TIPS) yield. Hanson and Stein (2015) and Nakamura and Steinsson (2018) suggest that TIPS yields reflect virtually all the responses of nominal interest rates to monetary policy surprises on FOMC dates. Furthermore, a real yield is theoretically connected with the real activities and the policy transmission to the real economy.

We generate two event-study monetary policy surprises as the policy instruments. The first monetary policy surprise, the policy rate surprise, is used in Gürkaynak et al. (2005) and Gertler and Karadi (2015). It captures changes in the three month Federal Funds futures (FF4) on FOMC announcement days. Fluctuation of Fed Funds futures, as they claim, captures impacts produced by policy rate changes and forward guidance. It is a common practice that assesses exogenous monetary policy actions in light of the Taylor rule. The other monetary policy surprise that we innovate for the risk-taking channel is the volatility surprise. We generate the volatility surprise by capturing the unexpected change of near-term expectation in long-term rate volatility (i.e.,

al. (2007). "Comparing the consumer price index and the personal consumption expenditures price index." Survey of Current Business 87(11): 2633.

[5]See the official website of the Federal Reserve: https://www.federalreserve.gov/faqs/economy_14419.htm

the TYVIXBP index) around each FOMC meeting announcement. We select the interest rate volatility of 10-year Treasury yield in order to match with the maturity of our policy indicator. Both surprises are converted into monthly time series to fit into the monthly SVAR model. The conversion procedure is summarized in Appendix B.

When considering the volatility surprise as the policy instrument, we are not intended to presume that the Federal Reserve attempts to control or manipulate the expected volatility of an interest rate. Instead, we strive to recognize the fact that the Federal Reserve's unconventional policy tools and innovations in communication may contribute to the exogenous impact of monetary policy on financial markets. In the SVAR model, the communication and other unintended consequences of FOMC announcements may have an impact on the real economy that originates from the monetary authority. This impact may thus constitute a portion of exogenous monetary policy shocks to the SVAR system. The two monetary policy surprises demonstrate two distinctive and orthogonal dimensions of the impact of monetary policy announcements, such as its influence on short rate level versus its influence on long rate volatility. The policy rate surprise narrow focus to changes in the policy rate, while the volatility surprise comprehensively evaluates monetary policy announcements in terms of its impact on the risk perception. We simulate monetary policy shocks with the policy rate surprise in the the interest rate channel, which is characterized by a Taylor rule type of monetary policy reaction function. The risk-taking channel instead accepts a broader definition of monetary policy and emphasizes the influence on interest rate volatility. Therefore, the volatility surprise is ideal for motivating the monetary policy shocks in the risk-taking channel so that we can investigate the risk-side of monetary policy transmission.

4.1 First-stage regression and the relevance of external instruments

A common issue of the estimations with instrumental variables is the weak instrument. If the covariance between an endogenous regressor and its instrumental variable is low, the IV estimator is severely biased toward the OLS estimator. In this case, the instrumental variable is considered as a weak instrument. We adopt Stock and Yogo (2005) criteria (an F-statistics larger than 10) to determine the relevance of instrumental variables. In various specifications, the policy indicator is either the one-year Treasury yield or 10-year TIPS yield. And the policy instrument is either the volatility surprise or policy rate surprise. In the first-stage regression, we regress the reduced form VAR residual of either policy indicator on each monetary policy surprise. Table 6 shows the results. The F-statistic is computed with heteroskedasticity and autocorrelation consistent (HAC) standard deviation.

Table 6: Results of the first-stage regression (Monthly)

Channels	Risk-taking	Interest-rate	Credit	
Policy Indicator	10Y TIPS(1)	10Y TIPS(1)	1Y	1Y
VOL	0.077^{***}			0.019^{*}
	(0.014)			(0.011)
PRATE		1.425^{***}	0.659^{***}	
		(0.299)	(0.169)	
Obs.	203	203	203	203
Robust F-Stat.	26.97	22.73	15.3	3.04

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Robust standard errors in parentheses.
The dependent variable is the reduced form VAR residual of the policy indicator specified in the second row. VOL and PRATE are the volatility surprise and policy rate surprise converted into monthly time series.

In models similar to Gertler and Karadi (2015), which consider the one-year Treasury yield as the policy indicator, the coefficient of policy rate surprise is highly significant. This indicates that unexpected policy rate changes constitute a strong instrumental variable for the monetary policy as projected by short-term rates. In contrast, the volatility surprise is barely correlated with shifts in the short-term rate. As to the timing, the reactions of the one-year yield to both monetary policy surprises are instantaneous.

When considering the 10-year real rate as the policy indicator, the volatility surprise and policy rate surprise are both strong instruments with higher than 10 F-statistics. the volatility surprise is more significant as an instrumental variable for the long-term real rate than the policy rate surprise is. The explanation power is higher as well. This evidence reveals the difficulty of utilizing variation in the funds rate or other short-term rates to explain the more volatile fluctuations in long-term rates.

However, the strong correlation only exists between the lagged VAR residual of 10-year TIPS yield and the two monetary policy surprises. Our evidence in Table 7 and 8 suggest that this mismatch may be because these monetary policy surprises have a more persistent impact on the long-term real rate than what they do on the short-term rate. This lagged matching can also be attributed to the conversion of monetary policy surprises from daily to monthly time series, a process that unavoidably extend the persistence of surprises. Matching the lagged residual of policy indicator with current monetary policy surprises may better reconcile monetary policy actions with reactions of financial markets.

One concern about the non-contemporaneous matching is that historical values of the policy indicator seem predictive for volatility surprises. Thus, identified monetary policy shocks might reflect a systematic component of the impact of monetary policy. However, we find no evidence to support this argument in the daily date analysis and Granger causality test.

Table 7 shows that volatility surprises do not predict 10-year TIPS yield movements within one week before 4-day time windows. In contrast, volatility surprises motivate significant fluctuations in long-term TIPS yield and the impact is relatively persistent.

Table 7: Real yield effects of volatility surprises (Event study, Daily, 2003-2020)

Week	1-w before	1-week			2-week		
Maturity	10Y	2Y	5Y	10Y	2Y	5Y	10Y
VOL	-1.231	0.051	0.043^{**}	0.041^{***}	0.137^{***}	0.074^{***}	0.057^{***}
	[-0.882]	[1.448]	[1.898]	[2.717]	[2.068]	[2.630]	[2.308]
R2	0.014	0.066	0.088	0.116	0.156	0.133	0.112

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Robust t-statistic in parentheses.
Cumulative changes of Treasury real yields in the weeks before announcements as well as those changes in one week (or two weeks) after announcements.
The standard deviation of volatility surprise is normalized to 1.
The volatility surprise is the dependent variable in the second colume, while it is the explaining variable for the remaining columns.

Table 8 exhibits the Granger causality between volatility surprises and the reduced-form VAR residual in the policy indicator equation at monthly frequency. Importantly, we pair volatility surprises with contemporaneous policy indicator residuals. It is shown that the monetary-policy-induced volatility surprise can help in predicting innovations in the 10-year TIPS yield but historical and current innovations in this yield render limited explanatory power to the volatility surprise. The result strongly supports the unidirectional impact of volatility surprises on policy indicator residuals.

Table 8: Pairwise Granger causality test (Monthly)

Null Hypothesis	Obs.	F-statistic	Prob.
VOL does not GC Policy Indicator Residual	200	6.001	0.001
Policy Indicator Residual does not GC VOL		0.308	0.820

The VAR model used to generate the policy indicator residual includes four variables, such as industrial production, the PCE price index, the 10-year TIPS yield (policy indicator) and the excess bond premium.
Three lags are included in the test. VAR residuals of the policy indicator are contemporaneous with volatility surprises.

Consequently, we attribute the mismatching to the conversion procedure from daily to monthly times series and the persistent impact of volatility surprises on the long-term real yield.

In summary, we construct a four-variable SVAR model with a financial variable that measures financial frictions. Departing from the literature's stylized short-term rates, we adopt a long-term real rate to indicate the monetary policy impact on the whole yield curve. To properly identify the monetary policy shocks in the risk-taking channel, we generate a new high-frequency, event-study measure of perceived risk in long-term rates. Thus, we can analyze how monetary policy influence the economy through the risk perception in the financial sector. In adherence with the literature, we retain the policy rate surprise that is theoretically consistent with the discretionary policy actions under a Taylor rule. In the next section, we correspond the two policy instruments with two monetary policy transmission channels and evaluate their effects on the economy.

5 Empirical Results

This section present the impulse responses of economic variables to monetary policy shocks respectively identified in the interest rate channel and the risk-taking channel.

5.1 Transmission in the interest rate channel

The Keynesian-type interest rate channel is the textbook view of the monetary policy transmission mechanism in which long-term rates play a role.

This channel may be partitioned into two stages of propagation, such as the transmissions to the yield curve and to the economy. The former, in general, characterizes three suppositions. First, the monetary policy is measured by changes in the policy rate. Second, changes in short-term rates pass through to long-term rates given to expectations theory of the term structure. Third, nominal and real rates move synchronously due to the sticky price setting in Keynesian-type models. Statistically, we test the validity of those three hypotheses jointly by observing whether policy rate surprises can stimulate fluctuations in a long-term real rate.

In terms of the transmission to economic activities, the interest rate channel works through a cost-of-capital effect typically discussed as the neoclassical theory of investment. Accordingly, changes in the cost of capital affect real activities through their impact on consumption of durable goods and fixed investment.

To examine the monetary transmission in the interest rate channel, we consider the 10-year TIPS yield as the policy indicator and adopt the policy rate surprise to identify monetary policy shocks.

In the first stage regression, if the transmission to the yield curve is valid, the coefficient in the first stage regression should be positive and statistically significant, which is confirmed by our results in Table 6. Furthermore, the F-statistics is significantly higher than 10. In the second stage, we estimate the mapping vector between the monetary policy shocks and reduced form residuals of endogenous variables under the restriction that monetary policy affects long-term rates primarily through unexpected variation in the policy rate (i.e., the policy rate surprise).

Figure 5 plots impulse responses of endogenous variables to the monetary policy shocks identified in the interest rate channel. In comparison, we also show the impulse responses from the conventional Cholesky identification scheme in the right column. Both columns show impulse responses to a one standard deviation structural monetary policy shock. In the right column, the reactions in the VAR model with the conventional Cholesky identification are insignificant for all variables. In the left column, monetary policy shocks are identified as the systematic movements of a long-term real rate in responses to unexpected policy

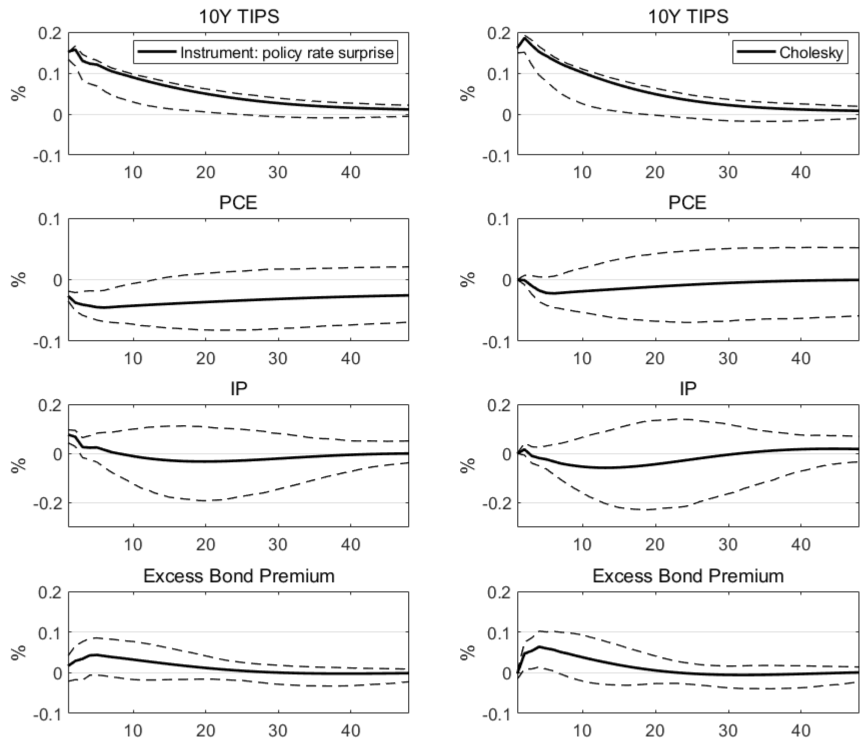

Figure 5: The impulse responses to the monetary policy shocks identified in the interest rate channel

rate changes on FOMC announcement dates. Influenced by a contractionary policy shock, the price level gradually slides for roughly eight months and remains at a low level for an extended period. The reaction of output is silent to this shock and the confidence band is wide. The muted response in production provides opposing evidence to the cost-of-capital effect and implies the failure of the interest rate channel in transmitting to the economy. Furthermore, the typically countercyclical excess bond premium reacts ,but only mildly, to the shock.

5.2 Transmission in the risk-taking channel

Risk is a critical factor for asset pricing in finance studies, but it is less explored at the aggregate level, especially in the studies of monetary policy transmission (related work includes Bekaert et al. (2013), Baker et al. (2016), Husted et al. (2020)). Borio and Zhu (2012) first shed light on the role of risk percieved by financial markets in monetary policy transmission and officially propose the risk-taking channel. Specifically, the monetary policy may affect risk perceptions or risk tolerance of financial intermediaries and then have a first-order impact on economic activity. This paper is the first empirical attempt to identify the monetary policy shocks through influence of monetary policy on the aggregate risk perception in bond markets, which monetary policy primarily exert impact on.

We consider the 10-year TIPS yield to indicate the monetary policy actions and the volatility surprise to instrument the identification of monetary policy shocks. The volatility surprise incorporates the impact of all the components of monetary policy, notably including effects of unconventional monetary policy tools. Monetary policy shocks in the risk-taking channel are identified as variation in a long-term real rate driven by monetary-policy-induced changes in perceived fluctuations of monetary policy shocks in the long run. For instance, if financial markets expect less volatility of monetary policy shocks in the future ten years due to an FOMC announcement, we consider this monetary policy as expansionary.

The Figure 6 shows the impulse responses to monetary policy shocks identified in the risk-taking channel. A one-standard-deviation contractionary monetary policy shock leads to a significant and persistent drop in price level, a similar result as the "interest rate channel" SVAR model. What interests us is the strong reactions of the excess bond premium and output. Under a tightening shock transmitting through the perceived risk, the credit environment immediately

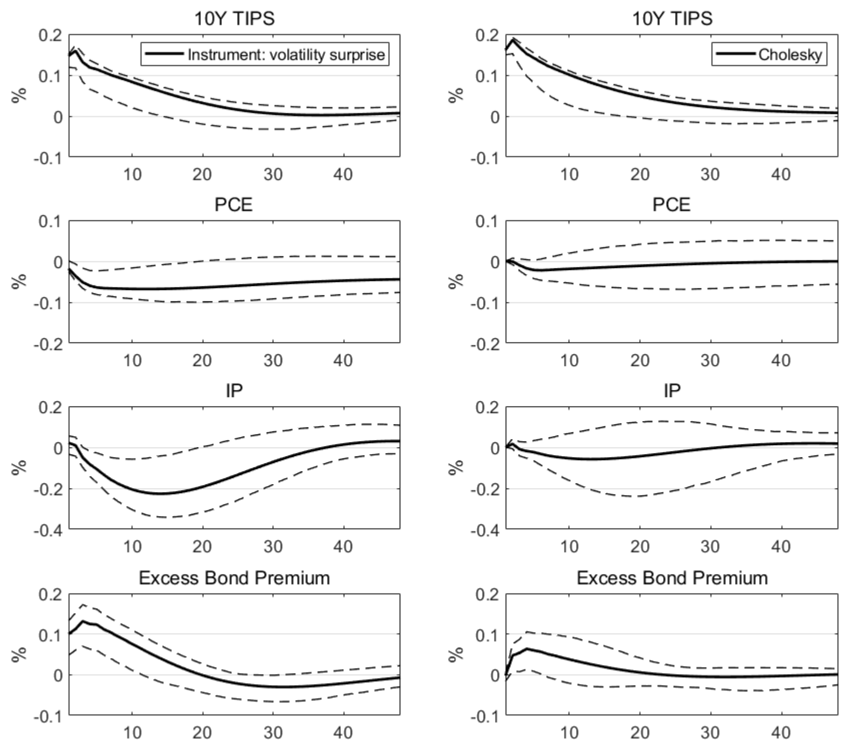

Figure 6: The impulse responses to monetary policy shocks identified in risk-taking channel

aggravates, and excess credit costs hike up for ten basis point for approximately a year. The same shock also leads to 50 basis point decline in output. Additionally, we observe close interaction between financial frictions and industrial production. The trough of production coincides with the time point as the soaring excess bond premium recovers from the peak.

The impulse responses of aggregate variables suggest the viability of the risk-taking channel. FOMC statements somehow influence the expected volatility of future interest rate path in the long run. This aspect of monetary policy shows strong implication for long-term real rates, financial frictions, and real activity.

6 Discussion

In this section, we compare the empirical results among those three monetary transmission channels and provide preliminary explanations based on existing findings in the literature.

6.1 Quiescent financial markets and illusive cost-of-capital effect

When considering a long-term rate as a node of monetary policy transmission, the linkage between the policy rate and long-term rates seems marginally drive economic activity. We delve into the literature in search of theoretical or institutional clues for the muted responses of the excess bond premium and real output in the interest rate channel model.

The reaction of real output is consistent with Blinder and Maccini (1991), Chirinko (1993), among others, which find the difficulty in identifying a quantitatively significant effect of the cost-of-capital variable in "interest-rate sensitive" components of aggregate spending.

Whereas, due to the multidimensionality of monetary policy, it should be premature to conclude the disfunction of monetary policy. The FOMC statements may include some components of monetary policy other than the policy rate targeting that influence both long-term rates and economic activity. As a complement, by identifying the risk-taking channel via the volatility surprise, we suggest a more comprehensive identification strategy of monetary policy shocks.

The unresponsiveness of the excess bond premium may attribute to two explanations, respectively center around the two components of a long-term yield, such as the expected path of future short-term rates and the term premium.

One possible avenue is that financial intermediaries may passively adjust their expectations in future short-term rates and their baseline long-term lending rates when encountering exogenous policy rate changes. That is to say a policy rate movement may be unexpected, but the adjustment of long-term real rates to a policy rate change could be systematic. An increase in the banks' cost of capital due to a policy rate change may thus pass through to borrowers. In a competitive market, a bank may have no incentive to augment excess credit premium on baseline long-term rates as long as the information of the expected path of future short rates is publicly available in financial markets. In fact, the Federal Reserve periodically releases the estimated expected yield and term premium data of Treasury bonds with a full spectrum of maturities based on approaches of Kim and Wright (2005) and Adrian et al. (2013). This information offers limited arbitrage space for a bank to implement a heterogeneous premium on baseline rates from other banks.

Another potential explanation is a story of yield-searching investors proposed by Hanson and Stein (2015), among others. This story aims to justify their finding that unexpected policy rate changes are highly associated with significant changes in term premia on distant real forward rates. This short-lived variation in term premia due to demand shocks in the bond market is well observed not only by empirical research but also in the institutional behaviors of commercial banks (Stein, 1989). The response of the excess bond premium in the interest rate channel indicates that these demand shocks in financial tradings may be too trivial and transitory to affect banks' lending decisions and the credit premium. In combination, the muted reaction of the excess bond premium may be justified from the perspectives of interest rate pass-through and short-lived drifts in term premia. However, our results may be insufficient to distinguish between those explanations.

Lastly, the flat impulse responses of financial frictions and output to policy shocks in the interest rate channel motive us to explore the content of monetary policy beyond policy rate changes.

6.2 Comprehensive identification and role of credit supply

We notice that systematic changes of a long-term rate responding to policy rate decisions do not trigger sways of the excess bond premium and output. Whereas, changes in the long-term real rate caused by shifts in perceived interest rate risk do.

The synchronization of the responses of excess bond premium and real output corroborate financial accelerator models first proposed by Bernanke et al. (1999). They feature amplifier effects of credit market frictions on monetary policy transmission. Their claim is in accordance with our results. The increase in excess credit costs demonstrates the aggravation in information asymmetry and the increase of agency costs in the credit generating process, leading to widespread real effects. Meanwhile, our evidence opposes the Modigliani and Miller (1958) Theorem, which implies that financial structure is irrelevant to real economic outcomes.

The Fed's private information may also play a role in the transmission. Campbell et al. (2012) and Nakamura and Steinsson (2018) demonstrate that market participants may update their expectations about economic fundamentals in response to Federal Reserve's announcements. The Federal Reserve also signals information about the state of the economy to the public (Romer and Romer, 2000; Melosi, 2016). These effects may be sourced from the private information held by the Federal Reserve and exogenous to financial markets. In order to evaluate the exogenous impact of entire information content in FOMC announcements, we do not specially tease out these effects in the volatility surprise and instead incorporate them in the monetary policy shock identification. Therefore, facing a policy shock stimulated by a volatility surprise, financial intermediaries' update of economic prospects may influence their perception in future monetary policy actions. Thus lead to variation in the excess bond premium.

Furthermore, we shed light on the monetary policy impact on the supply of long-term capital than the demand. The cost-of-capital effect focuses on the demand side in credit markets and seems pale in explaining how monetary policy pull out the economy from mud of recessions. The risk-taking channel shift our attention to the supply side of long-term capital. Financial intermediaries may keep an eye on the uncertainty of future monetary policy path. An unexpected soar of the volatility may aggravate information asymmetry, boost monitor costs of borrowers' balance sheets, and require additional loss provision for future deterioration. These real costs may render banks with incentives to charge an excess credit premium and, more likely, to reduce risk-taking lending behaviors. Our finding call for further exploration and theoretical development related to the banks' reaction to second-moment movements in interest rates.

7 Conclusion

Monetary policy is multi-dimensional, and it contains more information than what may be explicit by policy rate movements. The introduction of unconventional monetary policy tools shifts our attention to policy influences in longer-term interest rates. To incorporate the entire policy impact on the whole yield curve, we introduce a long-term interest rate as the policy indicator into an otherwise standard monetary SVAR. In order to distinguish monetary policy shocks from endogenous long-term rate fluctuations, we consider an instrumental variable identification strategy. Our innovation is to construct an event-study monetary policy surprise from the variation of interest rate volatility around each FOMC announcement and utilize it as an external instrument for identification.

We estimate an empirical SVAR model to evaluate the validity of the conventional Keynesian interest rate channel and the less-explored risk-taking channel within a single framework.

We gather evidences that the interest rate volatility is a critical ingredient in identifying monetary policy shocks from movements in the long-term real interest rate. While the transmission through the conventional Keynesian interest rate channel is insignificant, we empirically witness the transmission through the risk-taking channel.

Admittedly, our analysis does not constitute a call for a different new instrument of monetary policy, especially given the difficulty of accurately targeting the public's perception of interest rate volatility. Instead, we provide a tool for market participants including the Fed to analyze the potential impact of policy on long-term rates from a bank's risk-taking channel perspective. This paper underscores the need for further exploration on the role that long-term interest rates and their volatility play in the transmission mechanism of monetary policy.

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A Algorithm for Identification

Considering partitioning the mapping matrix between reduced-form residuals and structural shocks as

$$S = \begin{bmatrix} s & S_q \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} \tag{24}$$

and the reduced-form variance-covariance matrix as

$$\Sigma = \begin{bmatrix} \Sigma_{11} & \Sigma_{12} \\ \Sigma_{21} & \Sigma_{22} \end{bmatrix} \tag{25}$$

Since structural shocks are normalized, $E[u_t u_t'] = E[SS'] = \Sigma$ and Σ is symmetric. Therefore,

$$\left(\Sigma_{21} - \frac{s_{21}}{s_1 1}\Sigma_{11}\right)' \left(\Sigma_{21} - \frac{s_{21}}{s_1 1}\Sigma_{11}\right) = s_{12} Q s_{12}' \tag{26}$$

with

$$Q = \frac{s_{21}}{s_1 1}\Sigma_{11}\left(\frac{s_{21}}{s_1 1}\right)' - \left(\Sigma_{21}\left(\frac{s_{21}}{s_1 1}\right)' + \frac{s_{21}}{s_1 1}\Sigma_{21}'\right) + \Sigma_{22} \tag{27}$$

The contemporaneous response of the policy indicator to a unit increase of monetary policy shocks s^p is derived from the underlying closed form solution.

$$(s^p)^2 = s_{11}^2 = \Sigma_{11} - s_{12}s_{12}', \tag{28}$$

where the portion of reduced-form variance of the policy indicator attributed to other structural shocks

$$s_{12}s_{12}' = \left(\Sigma_{21} - \frac{s_{21}}{s_1 1}\Sigma_{11}\right)' Q^{-1} \left(\Sigma_{21} - \frac{s_{21}}{s_1 1}\Sigma_{11}\right) \tag{29}$$

With the estimated $\frac{s_{21}}{s_{11}}$ in the second-stage regression and Σ in reduced form VAR, we obtain the estimate of s vector.

B Conversion of the Event-study Series to Monthly Time Series

Most macro-economic variables are measured in monthly or lower frequencies. In order to infer with macroeconomic variables in our monthly SVAR model, we convert the event-study time series into a monthly series in three steps. First, we arrange all event-study volatility surprises on a daily time axis according to their respective announcement dates. As the TYVIX index measures the 30-day implied volatility of the long rate, a volatility surprise shows the difference of investors' expectation of long rate volatility measured for the future 30 days due to an FOMC announcement. Thus, we set the impact horizon of a volatility surprise as 30 days to match the time length of the expectation. Second, in case of the 30-day impacts of two volatility surprises partially overlapped, we integrate the two surprises based on their respective FOMC announcement dates and sum up the overlapped portion. This circumstance may incurs between an unscheduled and a scheduled FOMC meetings, or between two unscheduled meetings. Third, we add up the impacts of volatility surprises on each day of a month and divide the sum with number of days in a month (i.e. 30 days).

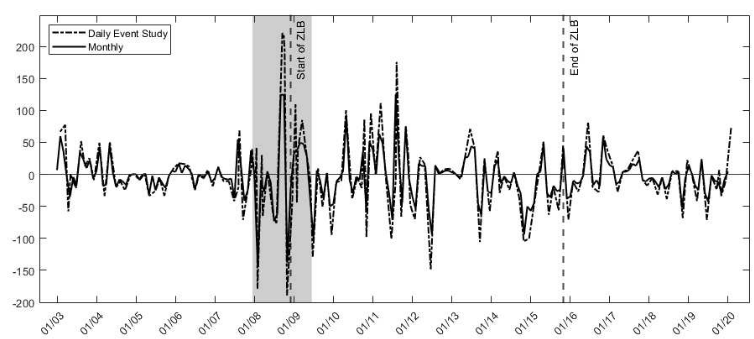

Figure 7: The volatility surprise (monthly & event study)

Overall, the monthly volatility surprise retains the features of the event-study time series, such as the timing of peaks and troughs, the mean reverting property, etc. However, in monthly series, we notice that one positive spike on October 2008, which amounts to more than 8 times of sample standard deviation, is more prominent than its counterpart in event-study series. As shown in Figure 7, we truncate the data on October 2008 to the same level as that on September 2008 to diminish the distortion. The distinctive spike is due to the different ways of recording volatility surprise impacts in the two series. Near the October 2008, two emergent unscheduled FOMC meetings were held on September 29th and October 7th. Both meetings induce large positive volatility surprises, indicating the policy actions announced after those meetings aggravate the long-term perceived risk in interest rates. Those meetings are less-than-30-day apart. In the event-study series, the impacts of those meetings are parallelly registered on their respective dates and do not intervene with each other. In contrast, the monthly time series lengthen the impacts of volatility surprises to 30 days and adds up the overlapped impacts of two meetings with less than 30-day interval. Therefore, if two or more FOMC meetings are closely adjoined and generate volatility surprises in an identical sign, the monthly time series may be distorted by the resulting extremely large spike. This phenomenon is prominent in October 2008 and a truncation is applied to restore the distortion.

Admittedly, this conversion approach may fall short in identifying the timing of events. For example, if an FOMC announcement is made at the end of month t. In event-study time series, this volatility surprise is in the month t. However, in monthly conversion, since the 30 days after the meeting majorly locate in month $t + 1$, the principle volatility surprise is recorded in month $t + 1$, rather than in the month when it actually happens. This shortcoming partially explains why the monthly volatility surprise matches better with the lagged VAR residual of the policy indicator.

C Institutional Explanation for the Four-day Window

We further investigate the institutional mechanism of this pre-FOMC-event drift in the volatility that roughly starts from 4 days prior to an FOMC announcement. We find its association with the timing of an FOMC announcement in a week. In Table 9, we list the weekday distribution of FOMC announcement dates. In the whole sample from 2003 to 2018, the majority of FOMC decisions (92%) are announced on Tuesday, Wednesday, and Thursday. Four days before those weekdays are respectively Friday, Saturday and Sunday. As weekends are non-trading days for major exchanges, the data on Saturdays and Sundays are identical with closing quotes on the nearest precedent Fridays. Therefore, the TYVIX data in four days before the 93% of FOMC announcements points to closing quotes on Fridays in preceding weeks. In other words, the 4-day time window essentially takes the difference of the ending quote on Friday preceding one announcement and the ending quote on the announcement date.

Table 9: Weekday Convention of FOMC Announcements

	Mon	Tue	Wed	thu	Fri, Sat, Sun	Total
Sample Counts	5	40	97	11	5	158
Percent	3%	25%	61%	7%	4%	100%

However, why do Fridays before announcement weeks become turning points of the TYVIX index? Chordia et al. (2001) among others investigate weekday effects of trading activities and indicate that Fridays often feature a significant decrease in trading volume and liquidity. Chen and Singal (2003) and Jones and Shemesh (2010) address a "Friday effect" with the reduction in demand and price of call and put options due to the downside risk of holding securities during weekends. The TYVIX index is calculated with the Treasury note options prices via Black-Sholes non-arbitrage formula. Therefore, decline in demand for call and put options leads to a lower figure of the TYVIX index on Fridays.

For our purpose, we attempt to capture the exogenous impact of monetary policy rather than the effects of upcoming FOMC meetings. Therefore, we strive to minimize the noise introduced by the event-driven, pre-FOMC-announcement drift. The utilization of this Friday effect facilitates this practice.

In detail, the trading positions of options established after a weekend are more or less related to two types of short-term trading activities. First is the short-term hedge for the interest rate volatility caused by an FOMC event. An approaching FOMC meeting induces short-term uncertainty in interest rates. Risk-avoiding bond investors may enhance appetite for hedging, leading to the bid-up of options prices. The other activity is the short-term speculation on an FOMC decision. Speculation on possible interest rate changes may heat up before an FOMC announcement. Both activities can temporarily drive up the demand for the 10-year T-note options and the TYVIX index. The common characteristic of those tradings is a near-zero expected return that may not be adequate to compensate for the downside risk during the weekend. Therefore, those investors in aggregation should have limited gain from their expectation for monetary policy. Thus trade for or against the soaring volatility before an FOMC meeting. We attempt to diminish the impact of these trading activities.

In contrast, if other investors establish their options positions before or on the preceding Friday and hold during the weekend, their expectation for the upcoming FOMC decision is so strong that their expected returns on those positions overweight downside risk in the weekend. In other words, they gain from their expectation of monetary policy and their positions contribute to the expected component of monetary-policy-induced interest rate volatility. Consequently, only the positions established before, and held through, the weekend owns a tight relationship with the expectation of monetary policy.

To focus on changes in the expectation of monetary policy due to the information content of FOMC announcements, we determine both ends of the time window in light of the Friday effect. In terms of the leading end, the Friday preceding a policy decision has the least FOMC-event-driven trading positions of the 10-year T-note options, in avoidance of the downside risk during the weekend. More importantly, the ending quote on Friday captures the volatility attributed to the expectation of monetary policy. It is because the corresponding options positions have adequately high expected return to tolerate the risk in the weekend. For the trailing end, the short-term hedging and speculation may halt right after an FOMC announcement because the short-term uncertainty on interest rates may be principally resolved by the public statement of an interest rate decision.

Consequently, we take the difference of the TYVIX index between the closing quotes on Fridays before announcements and the closing quotes on the announcement dates. The two ends of this time window thus are, in the highest degree, unaffected by FOMC-event-driven, short-term trading activities. Captured changes of expected volatility in the long rate may solely attribute to the difference between expected and actual monetary policy.

D The connection between volatility surprise and conventional monetary policy

One critical question here is how the transmissions of monetary policy through the two ends of the yield curve relate to each other. If they are relatively independent of each other, it would be appropriate to adopt different mechanisms for stimulating policy-induced movements in short- and long-term rates. Otherwise, policy rate changes may be sufficient to measure monetary policy in all transmission channels, supporting a policy reaction function akin to Taylor rules. We run the following regression to investigate whether a policy rate surprise can explain the contemporaneous volatility surprise. Thus, we may infer whether the impact of monetary policy on short- and long-term rates are interrelated.

$$VOL_t = \alpha + \beta Prate_t^- + \gamma Prate_t^+ + \epsilon_t \tag{30}$$

To investigate the one-to-one relationship between two monetary policy surprises, we select the daily event study time series, which are only consisted of FOMC events.

VOL_t is the volatility surprise and $Prate_t$ is a policy rate surprise. $Prate_t^-$ records unexpected policy rate drops and notes zero for FOMC meetings with sudden policy rate hikes. As the opposite case, $Prate_t^+$ records unexpected positive changes of the policy rate and takes zero when an opposite change incurs. We show the results that respectively consider the current month and three month ahead Fed Funds futures (FF1 and FF4) as the policy rate surprise. We assume a unidirectional causality from a policy rate surprise to the contemporaneous volatility surprise. This design is because an FOMC announcement takes precedence over the reaction of the financial market. The monetary authority must wait until the next FOMC meeting to change the policy rate target in order to address the current period volatility surprise.

Table 10 shows a non-linear relationship between a policy rate surprise and a volatility surprise. An unexpected policy rate cut is associated with a negative volatility surprise, indicating that an expansionary policy rate change is likely to be effective in reducing the perceived risk in long-term interest rates. On the contrary, an unexpected increase in the policy rate is uncorrelated with volatility surprises. This asymmetric relationship alone is worthwhile for further exploration. This finding may be associated with the insurance effect of monetary policy. If the primary goal of monetary policy is to cope with the downside economic risk, an expansionary monetary policy may curtail the public's negative economic outlook more than an identical-magnitude contractionary policy would aggravate the pessimistic prospect (Borio and Zhu, 2012). Overall, the impact of a policy rate movement on its corresponding volatility surprise is trivial since the R squared is unessential.

The low explanatory power of policy rate surprises on volatility surprises suggests the weak connection between monetary policy transmission mechanisms through the short and long ends of the yield curve to the economy.

In brief, we notice that monetary policy affects short-term rates through operations and guidance on the policy rate, while influences long-term rates via altering the perceived risk of long-term interest rates. Both channels induce variation in financial frictions and, in turn, lagged adjustment of the real output. In contrast, the systematic component of long-term rates in response to policy rate changes is significant but does

Table 10: Responses of volatility surprises to policy rate surprises

Dep. VOL	Indep. MP1	Indep. FF4
$PRATE^-$	12.78***	6.26***
	[2.75]	[3.26]
$PRATE^+$	-0.19	0.01
	[0.15]	[0.00]
Observations	138	138
R^2	0.024	0.085

Note: * $p < 0.05$, ** $p < 0.01$. HAC Robust T-statistics in parentheses.
The volatility surprise is the dependent variable. Two versions of policy rate surprises are captured respectively from variations in spot month and 3 month ahead Fed funds futures. Sample only includes scheduled meetings.

not contribute to the dynamics of economic activity.