ESSAYS ON MONETARY POLICY:

MEASUREMENT AND TRANSMISSION

by

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This dissertation

is dedicated to my wife Jingyu Wang

and my parents Yuehong Qi and Weijun Chen,

who supported me unconditionally

until the present time.

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The federal funds rate became uninformative about the stance of monetary policy from December 2008 to November 2015. During the same period, unconventional monetary policy actions, like forward guidance and large-scale asset purchases, show the Federal Reserve's intention to depress longer-term interest rates. My research question is whether, after the 2007-2009 financial crisis, monetary policy still effectively influences or adjusts the real economy. The critical challenges are to indicate the impacts of increasingly diversified monetary policy actions and empirically identify monetary policy shocks more comprehensively than exclusively focusing on variation in the policy rate.

Chapter 2 considers a long-term real interest rate as an alternative monetary policy indicator in a structural VAR framework. Based on an event study of FOMC announcements, I advance a novel measure of long-term interest rate volatility with important implications for monetary policy identification. I find that monetary policy shocks identified with this volatility measure drive significant swings in credit market sentiments and real output. In contrast, monetary policy shocks identified by otherwise standard unexpected policy rate changes lead to muted responses of financial frictions and production. These finding supports the validity of the risk-taking channel and suggests an indispensable role of financial markets in monetary policy transmission.

Chapter 3 documents the pass-through of the short-term interest rate onto the components of Divisia monetary aggregates. The information factors extracted from real balances of monetary assets alleviate the price puzzle, which is commonly seen in conventional monetary VAR analysis of the transmission mechanism. We also show that financial and monetary markets reacted strongly to the Federal Reserve policy after 2007. The strong monetary response varies not only quantitatively over time, but qualitatively across asset classes. Although far from a one-to-one relationship, balances of assets more closely associated with household demand, such as currency and savings, tend to move in the opposite direction of short-term rates—indicative of a liquidity effect. Whereas balances more closely associated with firms returns are mixed, where institutional money markets also show a liquidity effect, large time deposits or commercial paper exhibit a strong Fisher effect post 2007.

In summary, this dissertation sets the foundation for future research in the measurement of monetary policy and the investigation of monetary policy transmission to the real economy post the financial crisis.

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CHAPTER 1

INTRODUCTION

From December 2008 to November 2015, the Federal Reserve lowered the federal funds rate essentially to zero. This zero lower bound restriction imposed two challenges on the measurement of the Fed's monetary policy stance. First, The federal funds rate becomes uninformative. Second, The "unconventional monetary policy tools" affect not only short-term but also longer-term interest rates. In January 2020, the federal funds rate returned to zero lower bound in light of the outbreak of coronavirus pandemic. The critical question to discuss in this dissertation is how monetary policy affects economic activities when the zero short-term interest rate becomes the new norm, and unconventional policy tools are routinized. The quest starts from searching for new measures of monetary policy actions.

In the second chapter, I consider a structural framework to identify monetary policy transmission through the risk-taking channel. An increasing amount of evidence indicates that monetary policy affects not only the short-term interest rate but also the risk perception and risk tolerance of financial intermediaries. I evaluate the risk implication of monetary policy announcements on the long-term real interest rates and subsequent influence on the financial market and aggregate economic activities. To my knowledge, this is the only study that identifies in a structural VAR model the changes in risk perception as an integral component of monetary policy shocks.

The third chapter investigates the information content of monetary assets that is not readily available in the movement of short-term interest rates. This chapter leads the exploration of monetary policy transmission through various components of Divisia monetary aggregates, which measure the monetary services provided by monetary assets. By adopting a Factor-Augmented Bayesian VAR model with the Time-Varying-Parameter feature, we visualize the impulse responses of economic variables as well as various components of monetary aggregates to the federal funds rate shocks.

CHAPTER 2

THE LONG-TERM RATE AND INTEREST RATE VOLATILITY IN MONETARY POLICY TRANSMISSION

Abstract: The federal funds rate became uninformative about the stance of monetary policy from December 2008 to November 2015. During the same period, unconventional monetary policy actions, like large-scale asset purchases, show the Federal Reserve's intention to depress longer-term interest rates. This chapter considers a long-term real interest rate as an alternative monetary policy indicator in a structural VAR framework. Based on an event study of FOMC announcements, I advance a novel measure of long-term interest rate volatility with important implication for monetary policy identification. I find that monetary policy shocks identified with this volatility measure drive significant swings in credit market sentiments and real output. In contrast, monetary policy shocks identified by otherwise standard unexpected policy rate changes lead to muted responses of financial frictions and production. Our results support the validity of the risk-taking channel and suggest an indispensable role of financial markets in monetary policy transmission.

2.1 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 essentially collapsed to its zero lower bound (ZLB), the measurement of monetary policy experienced two challenges, such as an uninformative short-term rate and the quantification of unconventional monetary policy tools. 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 a Monetary Conditions Index, which is derived from a linear combination of short-term interest rates and exchange rates, to infer monetary policy actions. However, without a proper identification scheme, this measure has some shortcomings as the exchange rate is subjected to influences other than monetary policy decisions. Some economists revisit monetary aggregates and supply evidence that a superlative measure of money (i.e., Divisia monetary index) can properly reflect the stance of monetary policy in structural VAR (SVAR) models, especially in the aftermath of the 2007 financial crisis (Keating et al., 2014, 2019).

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 that the Federal Reserve conducted. 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 was to depress longer-term interest rates. An increasing amount of researches demonstrate the significant impact of LSAPs on long-term Treasury yields[1]. 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)

We suggest a medium- to long-term interest rate as an alternative monetary policy indicator with three main considerations. First, we want this measure to be sensitive to variation in short-term rates. Second, this measure should be unrestricted by the ZLB. Third, it should reflect the non-negligible impact of unconventional monetary policy tools with particular attention for the long 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. Swanson and Williams (2014), Hanson and Stein (2015) and others argue that Treasury yields with more than two-year

[1] Please refer to Gagnon (2010), Gagnon et al. (2011), d'Amico et al. (2012), Rosa (2012), Swanson (2015) and more.

maturities may properly reflect the impact of forward guidance. 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 LSAPs as the only one that affects long-term interest rates. DSGE models on monetary transmission are still preliminary in depicting the role of longer-term rates in transmitting monetary policy to the economy (please refer to the Christiano et al. (2010) review). To our knowledge, this is the first attempt that explicitly considers a long-term rate as the policy indicator in an SVAR model.

The critical challenge in considering a long-term interest rate—such as the 10-year real yield—as the policy indicator lies in the identification of exogenous monetary policy actions from fluctuations in long-term rates.

Our approach stems from an event study of FOMC announcements and a high-frequency identification approach in SVAR models. Kuttner (2001) constitute an event study from shifts of the spot-month federal funds future rate in each FOMC announcement date. This is done in order to gauge unexpected monetary policy actions (see also Gürkaynak et al. (2005), Hamilton (2008) and Campbell et al. (2012)). More recently, Gertler and Karadi (2015) advance a VAR identification strategy in which unexpected changes in the federal funds futures rate, captured by an event-study approach, facilitates 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 2.1 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 investigate other institutional and theoretical perspectives of monetary policy transmission that extend beyond traditional short-term offer rates.

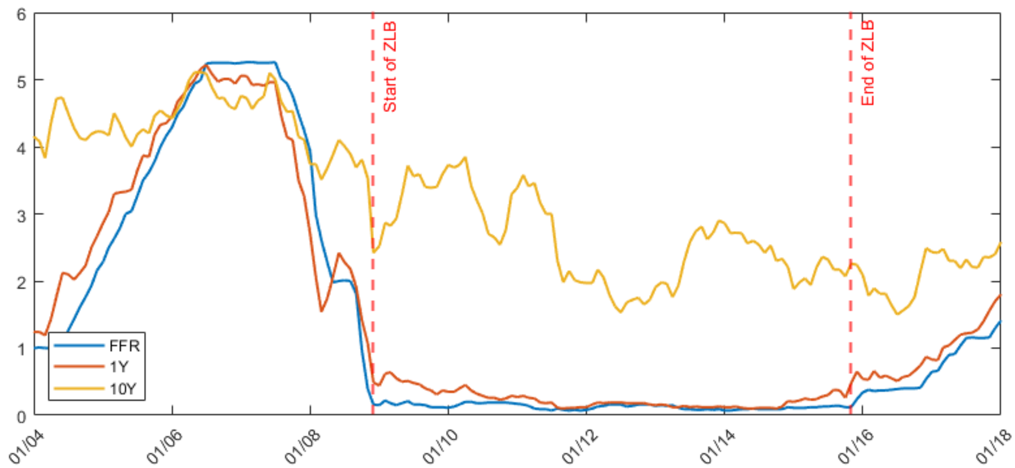


Figure 2.1: Federal Funds Rate, 1yr and 10yr Treasury Yields

Institutionally, the Federal Reserve seems to maintain different degrees of intention on the two ends of the yield curve. Interest rate volatility is frequently under-explored in the context of monetary policy.

For 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 is 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 [2].

The Federal Reserve does not explicitly express and maintain a target for any long-term rates. After an FOMC press release, the statement may induce heteroskedastic variation in long-term rate fluctuations around ex-post steady states. In other words, when analyzing the influence of an FOMC decision, the investigation should not be restricted to changes in the expected levels of long rates, but also shed light on shifts in expected volatility. Several market-based measures of interest rate uncertainty – such as the MOVE index, the TIV index of Choi et al. (2017) and TYVIX index of the Chicago Mercantile Exchange – are all focus on long-term interest rates.

Recent theoretical developments in the topic of monetary transmission reconfirm our focus on the critical but less explored role of interest rate volatility. Rajan (2006) and Adrian and Shin (2008) discuss the impact of monetary policy on the risk-taking behavior of financial intermediaries. Risk perception and risk tolerance of financial intermediaries contribute to their varying risk-taking behavior and thus affect economic activity. 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). It is relatively common in the literature to utilize the volatility implied by option prices to gauge the perceived risk in a given market[3].

Given these sparse but interrelated studies, we hypothesize that interest rate volatility plays a role in the monetary policy transmission, especially in the risk-taking channel.

[2] Bundick et al. (2017) and Lakdawala et al. (2019) both construct implied volatility indexes about short-term interest rates via VIX methodology. They argue that even volatility of short rates conceives important information for asset pricing.

[3] Please refer to Fleming et al. (1995), Fleming (1998) and Christensen and Prabhala (1998) for perceived risk in stock market, and Carlson et al. (2005), Emmons et al. (2006) and Swanson (2006) for perceived uncertainty in policy rates

However, to my knowledge, at the time of this writing, there is no existing event study measure that quantifies the impact of monetary policy announcements on expectations of the volatility of long-term rates. Furthermore, little effort has been dedicated to investigating the potential role of movements in the second moment of a long-term rate in motivating monetary policy shocks and driving innovations in the long-term rate.

Overall, we center attention on how monetary policy transmits to the yield curve, especially to long-term rates, and, in turn, how it propagates to aggregate economic activities. We introduce a long-term real rate and an event study measure with the implied volatility of a long-term nominal rate into an otherwise standard SVAR model.

In our econometric technique, selecting a long-term real rate as a policy indicator affords us some versatility to include more comprehensive information content from FOMC statements. We identify monetary policy shocks with the assistance of high-frequency external instruments. We construct event studies respectively from movements of the spot-month funds future rate and variation in the implied volatility of 10-year rate around each FOMC announcement. From this construct, we generate two policy instruments which are time series of policy rate surprises and time series of volatility surprises. The SVAR impulse responses show that both policy rate surprises and volatility surprises can significantly stimulate fluctuations in the long-term real rate and the price level without incurring the price puzzle put forth by Eichenbaum (1992), in which the price level abnormally increases in response to a contractionary monetary policy shock in many monetary VAR analysis, but only the latter drives swings of financial frictions and output. These findings support the financial accelerator models (Bernanke et al., 1999) in which financial intermediations amplify the policy impact on economic activity. Our results also question the cost-of-capital effect in Neoclassical theory of investment since production seems muted to the policy-rate-induced change in the long-term real rate. In terms of monetary transmission channels, we obtain evidence in support of the risk-taking channel but fail to observe the validity of the conventional Keynesian interest rate channel.

This study extends an SVAR model to examine the validity of different mainstream monetary transmission channels within a comparable framework. Furthermore, we generate the first measure of monetary-policy-induced changes in the expected volatility of monetary policy shocks in the long run. This single measure is capable of characterizing the variety of monetary policy tools through their impacts on the interest rate risk in the financial market. Lastly, we observe relatively independent monetary policy transmission mechanisms through the two ends of the yield curve. This finding may open a window for refined monetary policy identifications respectively for short- and long-term interest rates.

This research also connects with a growing topic focusing on the linkage between short- and long-term rates surrounding FOMC announcements, such as Cochrane and Piazzesi (2002), Gürkaynak et al. (2005) among others. Hanson and Stein (2015) suggest a story of yield-searching investors to explain how a change in the short-term rate induced by a policy rate movement contributes to the instant shift of the term premia of long-term real rates. However, they make an assumption to simplify the transmission from monetary policy to long-term rates; that changes of short-term rates can properly assess the full information content of FOMC announcements. We relaxes this assumption and further asks a more structural question: which components of monetary policy propagate to the economy through long-term rates. Our results are consistent with previous findings that an unexpected policy rate change affects long-term nominal and real rates, but additionally, it reveals that the interest rate volatility, rather than the policy rate, plays the primary role in transmitting the effect of monetary policy to economic activity through long-term rates.

The rest of the chapter proceeds as follow. Section 2.2 presents our econometric framework of structural VAR model and identification strategy. Section 2.3 introduces the data and sample, especially the policy indicator and policy instruments. Section 2.4 lays out the empirical results, and Section 2.5 discusses their implications on the monetary policy transmission. Section 2.6 offers a detailed procedure of the construction of the volatility surprise for readers' reference, and Section 2.7 concludes.

2.2 Econometric Framework

In this section, we overview the econometric model and the identification strategy. Our econometric analysis is based on an SVAR model with an intention to investigate the monetary policy transmission mechanism. We select a high-frequency identification (HFI) scheme to identify monetary policy shocks.

The HFI approach is developed 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 spot-month federal funds future rate 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 approach measure the unexpected impact of monetary policy caused by FOMC announcements and carry relevance to monetary policy shocks. Furthermore, 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 a lower-frequency VAR. It bears the capacity to reflect the impact of monetary policy actions or monetary policy stances. 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 policy effects and identify monetary policy shocks, we utilize policy instruments as instrumental variables for the policy indicator to estimate the unbiased contemporaneous responses of the policy indicator to structural monetary policy shocks. This method combines the features of event studies with structural identification in SVAR models.

2.2.1 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

$$AY_t = \Sigma_{j=1}^{p} C_j Y_{t-j} + \epsilon_t \tag{2.1}$$

The straightforward 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

$$Y_t = \Sigma_{j=1}^{p} B_j Y_{t-j} + u_t \tag{2.2}$$

where $B_j = A^{-1}C_j$ and 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

$$u_t = S\epsilon_t \tag{2.3}$$

with $S = A^{-1}$. 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

$$E_t[u_t u_t^{'}] = SS^{'} = \Sigma \tag{2.4}$$

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.

$$Y_t = \Sigma_{j=1}^p B_j Y_{t-j} + s\epsilon_t^p \tag{2.5}$$

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).

$$E[Z_t \epsilon_t^{p\prime}] = 0 \tag{2.6}$$

$$E[Z_t \epsilon_t^{q\prime}] \neq 0 \tag{2.7}$$

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.

$$`u_t^p = \gamma Z_t + \epsilon_t \tag{2.8}$$

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 $\frac{s^q}{s^p}$.

$$u_t^q = \frac{s^q}{s^p}\hat{u_t^p} + e_t \tag{2.9}$$

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.[4]

Importantly, this econometric framework imposes no restrictions that the policy indicator must be a short-term rate, and that policy instrument should be a variable describing behavior in the policy rate.

2.2.2 Identify monetary policy shocks in the risk-taking channel

Previous studies like Gertler and Karadi (2015) limit the potential of this econometric framework by implicitly making two relatively strict assumptions; that monetary policy takes effect through short-term rates, and that the measure of monetary policy is confined to policy rate changes. We relax those restrictions by proposing a long-term interest rate as a policy indicator and constructing a policy instrument concerning the risk-side implication of each entire FOMC announcement.

[4] See Appendix 2.8.1 for more details about the algorithm for identification.

On the one hand, there is an increasing amount of evidence suggesting that the monetary policy affects long-term rates in complex manners. At least four avenues are discussed in the literature. First, the conventional Keynesian interest rate channel suggests that the policy rate changes should pass through to long-term nominal rates based on the expectations theory of term structure, and may further affect long-term real rates because of the sticky price setting in Keynesian models. Second, unexpected changes in the policy rate lead to variation in the term premia of distant forward rates according to Jorda (2005), Hanson and Stein (2015), and others. Third, unconventional monetary policy tools, such as forward guidance and LSAPs, affect longer-term rates through communication and open market operations. Lastly, according to the risk-taking channel (Borio and Zhu, 2012), monetary policy and Federal Reserve's communication with the public may influence the risk perception of financial intermediaries and affect long-term real rates via variation in risk-taking behavior such as long-term lending. Although long-term rates, in the aforementioned four avenues, seem to be an unavoidable node in the policy transmission, they are not included in the state-of-art monetary VAR models, such as those in Christiano et al. (1999). We possess minimal knowledge of the role of long-term rates in the "black box" between monetary policy and economic activity. We attempt to shed light on this black box by taking a long-term real rate as a potential policy indicator. It may reflect the full spectrum of the aforementioned impact of monetary policy on long-term rates.

On the other hand, studies on the risk-taking channel attract increasing attention but this channel is seldom identified in a VAR model. There are extensive empirical studies on the linkage of monetary policy and bank's risk-taking behavior[5]. However, without a structural model, it is unpractical to investigate the endogenous interactions among monetary policy, the risk perception in financial markets, and real economic activities. This chapter generates

[5] Please refer to Altunbas et al. (2009), Gambacorta (2009), Delis et al. (2012), Bruno and Shin (2015) and Dell'Ariccia et al. (2017).

a monetary policy surprise, that captures how each FOMC meeting announcement, instead of each policy rate change, shifts the near-term expectation of long-term interest rate volatility. Then, we utilize this surprise in interest rate volatility to identify monetary policy shocks in the risk-taking channel.

In general, our identification of monetary policy shocks in the risk-taking channel not only allows for influences of monetary policy on the long end of the yield curve but also consider the entire impact of each FOMC statement on the risk perception in bond markets.

In the risk-taking channel, monetary policy shocks motivate adjustments of financial intermediaries' risk perception. Unlike the default risk, which bears more relationship with the operation in the private sector, the risk specified here is the interest rate risk, akin to the anticipated volatility of interest rate in the extended horizon. Based on individuals' risk interpretations of monetary policy announcements, those financial intermediaries shall decide the volume of their lending (risk-taking) activities and term/credit premium on their baseline long-term lending rates. For instance, a foreseeable high interest rate volatility may introduce additional uncertainty in banks' investment decisions, affecting lending activities and credit premiums. Unexpected changes in the policy rate may fall short in identifying monetary policy shocks in the risk-taking channel due to its lack of risk implication and the loss of richer information content in FOMC statements besides policy rate movements.

The identification includes two steps. First, find an appropriate policy instrument. Second, identify the exogenous impact of monetary policy.

We consider three criteria under relevance and exogeneity conditions for a policy instrument to be qualified in identifying policy shocks in the risk-taking channel. In terms of relevance to monetary policy shocks, it should be adequately comprehensive to include the entire information content of FOMC announcements and be confined to bonds markets as the Federal Reserve primarily exerts impact on interest rates. On the point of exogeneity, it should be exogenous to stances of the public who has no access to the Federal Reserve's private information. Thus, the captured movements are only sourced from the Federal Reserve's private information set. With an event study approach, we generate the time series of volatility surprises that capture the risk-side implication of FOMC announcements for a representative long-term bond market. Section 2.6 provides a detailed road map of generating this risk-related policy instrument, the volatility surprise.

The equations (10) and (11) show in detail how to apply event study method to identify the exogenous movements in perceived risk in daily data.

$$VOL_t = d_t^{FOMC}[E_{1,t}\sigma^p_{t+30} - E_{0,t}\sigma^p_{t+30}] \tag{2.10}$$

$$where\ [\sigma^p_{t+30}]^2 = \sigma_{t+30}(s^p\epsilon^p_t)^2 + \sigma_{t+30}(s^q\epsilon^q_t)^2 \tag{2.11}$$

On the left-hand side of equation (10), a volatility surprise, VOL_t, captures variation in the 30-day expectation in volatility of the policy indicator induced by monetary policy and unexpected by financial markets. The right-hand side of the equation demonstrates the event study approach. The expectation operator E_1 (and E_0) denote the expectation based on the information set before (and after) the release of an FOMC statement. The volatility of policy indicator in the ensuring 30 days after the FOMC announcement is noted as σ^p_{t+30}. It is partitioned into two components respectively ascribed to different structural shocks, i.e. monetary policy shocks and non-policy shocks. Given that the measuring scope are principally identical for the two 30-day implied volatility shortly before and after an announcement, We consider the 30 days in the volatility measurement unchanged. Let d_t^{FOMC} be the time dummy for FOMC announcements; which equals 1 when there is an FOMC announcement and, otherwise, equals zero.

We follow the assumption in Wright (2012) that the information content of monetary policy statements is the source of the higher volatility of monetary policy shocks $\sigma(\epsilon^p_t)$ on FOMC announcement days. This implies that the non-policy structural shocks ϵ^p_t are randomly distributed on the timeline and their contributions to the volatility of policy indicator are stable shortly before and after one announcement. As the impact of non-policy structural shocks is essentially canceled out when taking the difference in an event study approach, we retain changes in the volatility of monetary policy shocks in volatility surprises (s^p is treated as a constant parameter). As shown in equation (12), volatility surprises indicate variation, due to FOMC announcements, in the expected volatility of monetary policy shocks. If the policy indicator is a long-term rate, then volatility surprises monitor changes in the expected volatility of monetary policy shocks in the long run.

$$VOL_t = s^p d_t^{FOMC} E_t(\Delta\sigma_{t+30}(\epsilon_t^p)|\Omega_1 - \Omega_0) \tag{2.12}$$

For the identification of the exogenous impact of monetary policy, we combine the identification by external instruments with identification by heteroskedasticity. The volatility surprise is the crucial element in the process. Prior to introducing how we identify, we first explicit why we combine those two approaches.

Identification by heteroskedasticity is introduced by Rigobon (2003) and further applied by Rigobon and Sack (2003), Rigobon and Sack (2004) and others. One strategy proposed by Wright (2012) relies on the observation that, on the dates with FOMC announcements, the variance of monetary policy shocks is different from that on the dates without announcements.

Let σ_1 and σ_0 be the volatility of monetary policy shocks respectively in FOMC announcement and non-announcement dates. And Σ_1 and Σ_0 are the variance-covariance matrices of reduced form errors estimated separately for those two circumstances. Vector s represents how reduced form residuals react to a unit increase in structural monetary policy shocks ϵ_t^p. The assumption can be expressed by

$$\Sigma_1 - \Sigma_0 = ss'\sigma_1^2 - ss'\sigma_0^2 = ss'(\sigma_1^2 - \sigma_0^2) \tag{2.13}$$

As Σ_1 and Σ_0 can be estimated via equation-by-equation OLS regressions and $\sigma_1^2 - \sigma_0^2$ is assumed to be a constant, the vector s is estimable by a distance minimization function.

This identification is advantageous over the identification by external instruments in two points. First, this approach is associated with the measurement of risk if considering changes in the volatility or variance of monetary policy shocks in the context of interest rate risk. This may be a probable approach to incorporate the risk factor into the identification of monetary policy shocks. Second, it enables us to identify the impact of entire monetary policy rather than only account for policy rate changes. This approach does not require full knowledge of how each component of monetary policy affects the volatility before analyzing the influence of monetary policy in integral.

However, this heteroskedasticity approach falls short to our needs in three aspects. First, since the identification is achieved in daily data, the resulting monetary policy shocks are unable to interfere with macroeconomic variables, which are usually in monthly or even lower frequency. Second, the varying volatility or variance on announcement days may not only show the influence of monetary policy but also reflects the pre-FOMC-announcement drift in the volatility driven by the occurrence of FOMC events[6]. Monetary policy shocks identified by the variance on announcement dates may not precisely reflect monetary policy stances. Third, the realized volatility may not be a good measure of perceived risk since the realized volatility is settled and no longer risky for market participants.

To deal with those shortcomings, we combine the heteroskedasticity approach with the external instrument method by three modifications to the former.

First, we allow heteroskedasticity among all FOMC announcement dates. Specifically, instead of identifying the mapping vector s in a lump sum, we identify s^p, the impact of a one-unit monetary policy shock ϵ_t^p on the policy indicator with the volatility surprise being the instrumental variable. More accurate identification is achieved because volatility surprises update changes in the volatility for each FOMC announcement relative to an adjacent non-announcement date. In comparison, Wright (2012) draw attention to the different variances

[6]Please see the detail of pre-FOMC-announcement drift in Section Six.

for FOMC announcement and non-announcement dates. Furthermore, by converting the event-study time series of volatility surprises into the monthly one, we overcome the gap of data frequency between event study time series and monthly VAR model.

Second, as to the policy instrument, we apply a 4-day time window in order to exclude the impact of the event-driven, pre-FOMC-announcement drift of interest rate volatility and retain the relevance of volatility surprises to monetary policy actions (please refer to Section Six for detail).

Third, we select changes of near-term (i.e., 30-day) expectation in volatility, rather than swings of actual volatility, to capture the heteroskedasticity. On the one hand, the realized volatility contains no uncertainty to market participants and may deviate from the definition of risk. On the other hand, changes in the expectation reflect more information in FOMC statements than changes in actual volatility. The majority of dates for measuring volatility before and after an announcement are overlapped. Changes in the expectation of volatility take into account variations in expected returns in all days within the measuring scope. Whereas, differences in actual volatility essentially compares the return of the last day with that of the first day in the measuring range.

In practice, we identify monetary policy shocks through the varying expected volatility of the policy indicator (i.e., the volatility surprise), given its implication for fluctuations in future monetary policy shocks.

We follow the identical procedure as the aforementioned 2-stage regressions. We consider the volatility surprise identified via the event study method as the policy instrument and run the first-stage regression as follows.

$$Monthly : u_t^p = \gamma VOL_t + \epsilon_t \tag{2.14}$$

Then in the second stage, we estimate $\frac{s^q}{s^p}$, the reactions of u_t^q relative to u_t^p in response of a unit increase of monetary policy shocks. The fitted value $\hat{u_t^p}$ is the component of u_t^p

responding to monetary policy shocks and is driven by varying expected volatility of future monetary policy shocks in long term. The second-stage regressions in equation (14) show that unexpected variation in the volatility expectation drives contemporaneous exogenous movements of other endogenous variables. From an economics perspective, if a monetary policy announcement drives up the interest rate risk perceived in the bond market, investors may reduce holding of long-term assets and push up long-term nominal as well as real rates. I identify this increase of long-term real rate as the consequence of a contractionary monetary policy shock.

$$Monthly : u_t^q = \frac{s^q}{s^p} \hat{u_t^p} + e_t \; where \; \hat{u_t^p} = \gamma VOL_t \tag{2.15}$$

Overall, monetary policy shocks in the risk-taking channel are identified through the second-moment movement of a representative long-term rate and the entire information content of FOMC statements. We make no redundant restrictions on other structural parameters.

2.3 Data and Sample

Our sample ranges from January 2003 to January 2018. It includes 140 FOMC meetings, both scheduled and unscheduled. The sample also covers the entire ZLB period as well as two periods with normalized federal funds rate.

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

The PCE chain-type price index is a measure of prices of all domestic personal consumption of final goods[7]. The Federal Reserve emphasizes its role in measuring price inflation

[7] A detailed comparison between CPI and PCE price index is provided by McCully, C. P., et al. (2007). "Comparing the consumer price index and the personal consumption expenditures price index." Survey of Current Business 87(11): 2633.

since it ”covers a wide range of household spending”[8]. The industrial production is a sensitive indicator of real production activities, and its data is available in monthly frequency. We follow the practice of Gertler and Karadi (2015) and retain the measure of financial frictions, the Gilchrist and Zakrajšek (2012) excess bond premium. The excess bond premium captures the difference in yields between the corporate and Treasury bonds with identical maturity 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 frictions in financial markets.

We propose a long-term real interest rate, i.e., the 10-year Treasury inflation-protected securities (TIPS) yield, as an alternative policy indicator. Hanson and Stein (2015) and Nakamura and Steinsson (2018) suggest that TIPS yields reflect virtually all the responses of nominal interest rates on FOMC dates to monetary policy surprises. Furthermore, a TIPS yield is less susceptible to the price shock and more responsive to monetary policy actions, measured by various monetary policy surprises, than the correspondent nominal rate. Table 2.1 shows the contemporary changes of 10-year real and nominal rates in response to monetary policy surprises and reduced form VAR residuals of non-policy variables. RES_IP and RES_PCE are the VAR residuals of industrial production and PCE price index in our baseline 4-variable VAR model with the 10-year nominal or real rates being the policy indicator, respectively. The statistics illustrate that changes in the 10-year nominal rate are highly subjected to price fluctuations. Whereas, changes of the 10-year TIPS yield are responsive to monetary policy surprises and innovations in output but are relatively inactive to fluctuations in the price level. This property of the TIPS yield helps us focus on the effect of monetary policy, rather than on the reaction to the noisy price fluctuation. We adopt the 10-year TIPS yield in the interest rate channel and the risk-taking channel in which

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

long-term rates are theoretically relevant. In comparison, to investigate the credit channel, the policy indicator used in Gertler and Karadi (2015) is the one-year Treasury yield.

Table 2.1: The Contemporary Responses of 10-year Real or Nominal rates to Shocks

	(1) $\Delta 10Y\ TIPS$	(2) $\Delta 10Y$
VOL	0.071***	0.026
	(0.023)	(0.020)
PRATE	1.080**	0.992**
	(0.470)	(0.436)
RES_PCE	10.400	25.429**
	(6.990)	(11.258)
RES_IP	−6.830*	2.046
	(3.850)	(2.102)
Observations	177	177
R^2	0.173	0.080

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: HAC Robust standard errors in parentheses

We generate two event-study monetary policy surprises as the policy instruments. The first monetary policy surprise, the policy rate surprise, is directly borrowed from Kuttner (2001). It captures the changes of the spot-month federal funds future rate on the FOMC announcement dates. It is a common practice that assesses exogenous monetary policy actions in light of the Taylor rule. The only modification we make is to adjust the sample period according to ours. 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 around each FOMC meeting announcement. We select the interest rate volatility of 10-year Treasury yield in order to match with the maturity of policy indicator. The volatility surprise demonstrates monetary-policy-induced changes in the expected volatility of future monetary policy shocks in the long run perceived by financial markets. In Section 2.6, we provide a detailed procedure for producing the volatility surprise, including the selection of a time window and the conversion to monthly time series. Both surprises are converted into monthly time series to fit into the monthly SVAR model[9].

When setting 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 may not ignore that the Federal Reserve's communication, such as communication styles, languages in the summary of economic projections, and more, may contribute to the exogenous impact of monetary policy on financial markets. In the SVAR model, the influences of communication and other unintended consequences of FOMC announcements may be a source of impact on the real economy originated from the monetary authority. And thus, they constitute a portion of exogenous monetary policy shocks to the VAR system. The two monetary policy surprises demonstrate two distinctive and orthogonal dimensions of the impact of monetary policy announcements, such as the influence on short rates level versus the effects on long rate volatility. Another critical difference between the two monetary policy surprises is the measuring objects. The policy rate surprise lasers the focus on changes in the policy rate, while the volatility surprise comprehensively evaluates monetary policy announcements in terms of the risk implication. In our models, we stimulate monetary policy shocks with the policy rate surprise in the credit channel and the interest rate channel. Both channels are characterized by a Taylor rule type of monetary policy reaction function. On the contrary, the risk-taking channel accepts a broader definition of monetary policy and emphasizes the influence on interest rate volatility. Therefore, the volatility surprise is ideal for initiating the monetary policy shocks in the risk-taking channel in order to investigate the risk-side monetary policy transmission.

[9] For conversion procedure, please refer to Appendix 2.8.3

2.3.1 First-stage regression and the relevance of external instruments

A common issue of the estimations with instrumental variables is the weak instrument. Specifically, 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 (a larger than 10 F-statistics) to determine the relevance of instrumental variables. In various settings, 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 2.2 shows the results. The F-statistics is based on heteroskedasticity and autocorrelation consistent (HAC) standard deviation.

Table 2.2: The Results of the First-stage Regression

	Risk−taking 10Y TIPS(1)	Interest Rate 10Y TIPS(1)	Credit 1Y	 1Y
VOL	0.058^{***} (0.012)			0.033 (0.016)
PRATE		0.983^{***} (0.271)	0.803^{***} (0.146)	
Obs.	178	178	178	178
Robust F-Stat.	23.96	13.12	30.17	4.17

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 the models which consider the one-year Treasury yield as the policy indicator, the coefficient of policy rate surprise is significant at a high multitude. This indicates that unexpected policy rate changes are a strong instrumental variable for the monetary policy projected on short-term rates. In contrast, volatility surprises are barely relevant with shifts in short-term rates. Overall, the reaction of the one-year yield to monetary policy surprises is 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. However, the strong relevance is significant between the lagged VAR residual of 10-year TIPS yield and the two monetary policy surprises. It may be because these monetary policy surprises have a more persistent impact on long-term real rate than what they do on short-term rates. This lagged matching can also be attributed to the conversion of monetary policy surprises from daily to monthly time series, a process in which unavoidably extend the persistence of surprises. Matching the lagged residual of policy indicator with current monetary policy surprises may shorten the time interval between monetary policy actions and reactions of financial markets.

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 monetary policy. However, we find no evidence to bolster this argument in the daily date analysis and Granger causality test (please refer to Appendix 2.8.2).

We also report that 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 suggests the difficulty of merely applying the policy rate or short-term rates to explain the more volatile fluctuations in long-term rates.

In summary, we construct a 4-variable SVAR model with a financial variable indicating financial frictions. Departing from the 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, we generate a new high-frequency, event-study measure of perceived risk in the long-term rate. As a result, we take the risk-side impact of FOMC statements on long-term rates into the account of the measurement of monetary policy. To be comparable with the literature, we retain the policy rate surprise to denote the monetary policy stance consistent with the Taylor rule. In the next section, we correspond the first three significant combinations of policy instruments and indicators with three mainstream monetary policy transmission channels and evaluate their effectiveness in transmitting to the economy.

2.4 Empirical Results

At the beginning of this section, we review the empirical results in Gertler and Karadi (2015) and illustrate how their work supports the validity of the credit channel. Afterward, we examine the impulse responses of economic variables to monetary policy shocks respectively identified in the interest rate channel and the risk-taking channel.

2.4.1 Review of the empirical evidence for credit channel

Gertler and Karadi (2015) propose the SVAR model with identification through external instrument for the study of monetary policy transmission. They follow the convention in the monetary transmission literature and make two assumptions. First, monetary policy only directly affects the short end of the yield curve. Second, monetary policy is measured by the federal funds rate or its close alternatives, like Eurodollar rates. In practice, they consider the 1-year Treasury yield as the policy indicator to reflect current policy rate changes and forward guidance. To capture the exogenous monetary policy actions, they regard the policy rate surprise as the policy instrument.

Their finding illustrates that a change in the short-term market rate motivated by a shift in policy rate drives fluctuation of the excess bond premium and, in turn, the lagged movements of output. They argue that a frictional financial market is crucial to the propagation of monetary policy, corresponding to the central role of external financing premium in the credit channel proposed by Bernanke and Gertler (1995). In the credit channel, a contractionary change of policy rate, as claimed by Bernanke and Gertler (1995), affects both borrowers' balance sheet quality and lenders' capital availability. The changes in both avenues eventually influence the spread between the costs of external and internal financing. Bernanke et al. (1999) further develop this channel into a financial accelerator mechanism by incorporating general equilibrium modeling and contract theories in a business cycle framework. The impulse responses of the excess bond premium and real output support the effective transmission through the credit channel. In short, the theoretical and empirical work leads to the same argument that the policy rate change propagates to the economy through, though may not exclusively through, a financial accelerator mechanism.

The unsolved question for this model is whether long-term interest rates play a role in the transmission. Exhaustively, there are three hypotheses given the validity of Gertler and Karadi (2015) finding. First, monetary policy only affects short-term rates, and long-term rates are unresponsive. Second, monetary policy only influences movements of short-term rates, which in turn drives sways of long-term rates. Third, monetary policy affects short- and long-term rates individually in different mechanisms. The abundant empirical evidence of the significant impact of monetary policy on long-term rates rejects the first hypothesis (Gürkaynak et al., 2005; Wright, 2012; Hanson and Stein, 2015). However, no empirical proof has been found for the second and third hypotheses from the monetary policy transmission perspective. We test them by introducing a long-term real rate as the policy indicator into our VAR model. Furthermore, if any of the two latter hypotheses are true, we test whether they are blind alleys in transmission. In other words, we monitor whether the impact of monetary policy on the yield curve can eventually influence economic aggregates.

2.4.2 Transmission in the interest rate channel

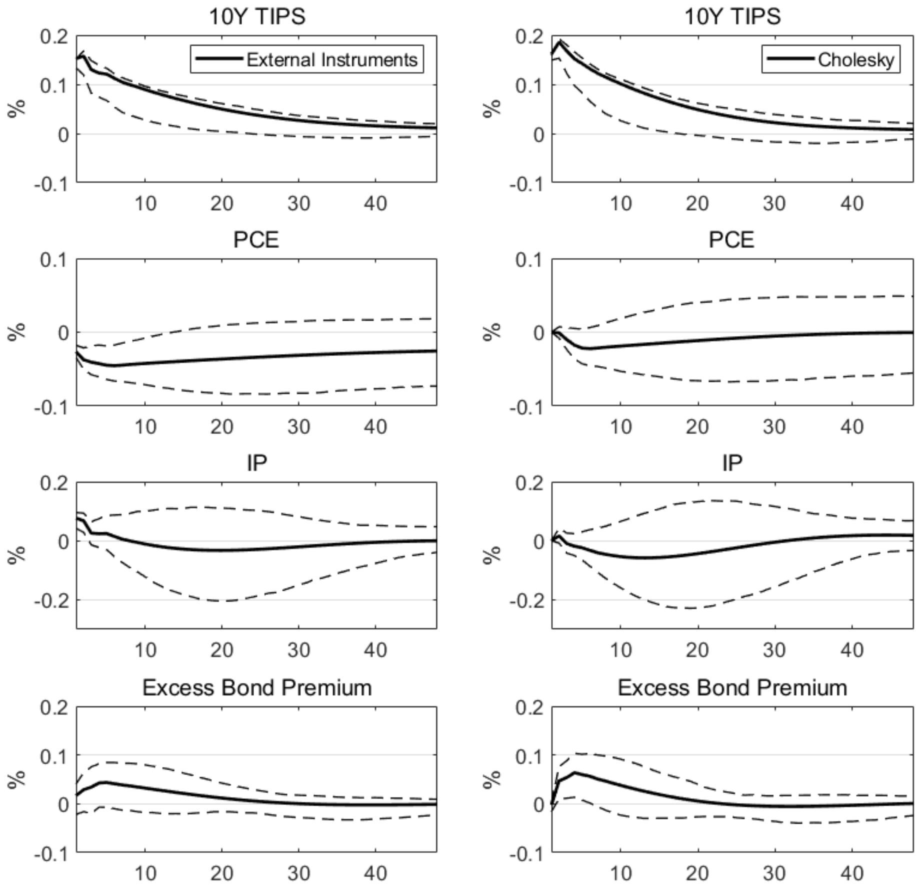
The Keynesian interest rate channel, corresponding to the aforementioned second hypothesis, is almost the textbook view of the monetary policy transmission mechanism in which long-term rates play a role. This channel may be partitioned into two steps, such as the transmissions to the yield curve and 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. 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 second proposition, the literature mentions two avenues regarding transmission from short to long rates. On the one hand, a shift in the short rate leads the market to adjust the expected path of future short rates according to the expectations hypothesis of term structure. On the other hand, more recent researches, e.g., Hanson and Stein (2015), indicate that unexpected changes in the policy rate affect term premia on distant forward rates. Since we focus on attesting whether the pass-through from short to long rates is effective, we integrate the effects in both avenues.

In terms of the transmission to economic activity, the interest rate channel assumes a cost-of-capital effect typically discussed in the neoclassical theory of investment. Accordingly, changes in the cost of capital affect real activities through their impact on spendings on 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. It is confirmed by our results in Table 2.2. Furthermore, the F-statistics is significantly higher than 10. In the second stage, we estimate the mapping vector between monetary policy shocks and reduced form residuals of endogenous variables under the restriction that monetary policy affects long-term rates primarily through variation in the policy rate.



Note: The left column shows impulse responses in the SVAR model identifying the interest rate channel, and the right one displays those in the model applying Cholesky ordering. Black line in each box indicates the averaged impulse response of one endogenous variable over 48 months. Dash lines contain the 90% confidence interval.

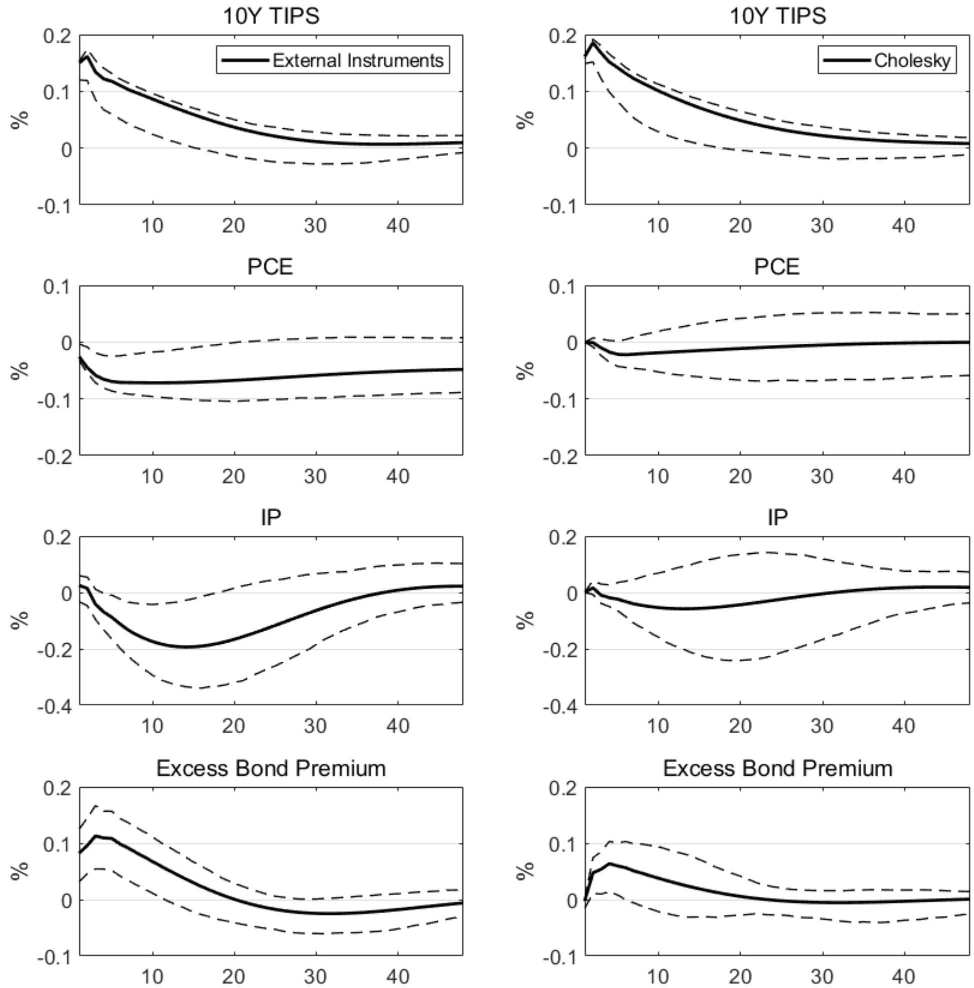
Figure 2.2: The impulse responses to the monetary policy shocks identified in the interest rate channel

Figure 2.2 shows 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 impulse responses 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 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. The confidence band is wide. The muted response in production provides opposing evidence to the cost-of-capital effect in the neoclassical theory of investment and implies the failure in transmitting to the economy in the interest rate channel. Furthermore, the typically countercyclical excess bond premium behaves abnormally. It declines right after a tightening policy shock but quickly recovers to zero. It may be interpreted by a lagged pass-through from the cost of capital to lending rates. Banks may take in the long-term rate spike, leading to an instantaneous reduction of the excess bond premium. Within a quarter, banks seem eventually pass through the exogenous increase of cost of capital to borrowers, and thus the excess bond premium return to a flat response.

2.4.3 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 (related work includes Bekaert et al. (2013), Baker et al. (2016), Husted et al. (2017)). Borio and Zhu (2012) first proposed the risk-taking channel in monetary policy transmission. Specifically, the monetary policy may affect risk perceptions or risk tolerance of financial intermediaries and then have a first-order impact on economic activity. Empirically, this chapter is the first attempt to find an appropriate measure that specifically accounts for influences of monetary policy on aggregate risk perception, especially the risk attitude in the bond market where 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. Importantly,



Note: The left column shows impulse responses in the model identifying the risk-taking channel, and the right one displays those in the model applying Cholesky ordering. Black line in each box indicate the averaged impulse response of one endogenous variable to a 1 std. monetary policy shock over 48 months. Dash lines contain the 90% confidence interval.

Figure 2.3: The impulse responses to monetary policy shocks identified in risk-taking channel

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 2.3 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" model. What interests us is the strong hump-shape reactions of the excess bond premium and output. Under a tightening shock transmitting through perceived risk, the credit environment immediately 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 when the response of excess bond premium is indistinguishable from zero.

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

2.5 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.

2.5.1 The credit and interest rate channels: The financial accelerator or cost-of-capital effect

We compare our results in the interest rate channel model with those in Gertler and Karadi (2015), whose distinction from the former centers on the selection of policy indicators. They select the one-year Treasury yield as the policy indicator and generate sensible impulse responses of the excess bond premium and real output to monetary policy shocks. When considering the 10-year real yield as the policy indicator, we find that those responses are muted.

The multidimensionality of the monetary policy may contribute to the distinctive impulse responses. Monetary policy consists of the headline figure and the FOMC statement. The headline figure, in most cases, is the policy rate target and is communicated with the public by an unambiguous, narrow target range of the federal funds rate. It may dominate the impact of monetary policy on short rates, but it could be reluctant to represent the whole influence on longer-term rates. Meanwhile, an FOMC announcement incorporates more diversified information, such as the FOMC's Summary of Economic Projections (SEP), forward guidance, LSAPs, and other details of open market operations. Those information contents and associated operations influence short rates as well as long rates. Since those new policies affect the slope of the term structure of interest rates, Eberly et al. (2019) refer to those new elements in the current monetary policy framework as slope policies. Slope policies are thus differentiated from the traditional level policy that sets the current level of the Federal funds rate. For instance, Gagnon et al. (2011),Rosa (2012), Swanson (2015) and others indicate that LSAPs have a much greater influence on long-term Treasury yields than to short-term yields.

Gertler and Karadi (2015) identify the impact of policy rate changes on a short-term rate as the exogenous (monetary policy) shocks and focus on the transmission via short-term rates. It is a proper identification scheme if we consider that impacts of Federal Reserve's operations on short-term rates are through adjusting the funds rate. Whereas, the policy impacts on long-term rates are unrevealed in the black box of transmission. Their results may suggest that the effects of unexpected policy rate hikes on the short end of the yield curve are adequate to result in credit crunch and shrinkage of production. Nevertheless, this model has no access to the question of whether, and how, a long-term interest rate plays a role in this transmission.

When considering long-term rates 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 unresponsiveness of the excess bond premium may attribute to two explanations. 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. In other words, a policy rate movement may be unexpected, but the adjustment of long-term real rates to the 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 in 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 may confirm that these demand shocks in financial securities trading are too trivial and transitory to affect banks' lending decisions. 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 too preliminary to support preference in those explanations.

As to the reaction of real output, our evidence shows that fluctuation in a long-term real rate induced by policy rate changes does not lead to variation in output, contradicting to the cost of capital effect in the neoclassical theory of investment. This finding is consistent with Blinder and Maccini (1991), Chirinko (1993), among others, which find the difficulty in identifying a quantitatively significant effect of the neoclassical 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 that monetary policy fails to transmit to the economy.

Additionally, the quiet response of output in the interest rate channel reconfirms the necessity to consider not only policy rate movements but also the entire information content of FOMC statements. 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. Thus, by identifying the risk-taking channel via the volatility surprise, we suggest a more comprehensive identification strategy of monetary policy shocks.

Another noteworthy observation is that the responses of excess bond premium and real output are synchronized. In fact, it is the case for all three channels. For example, in Gertler and Karadi (2015) model, a hike of excess credit costs accompanies a decline in output. In the interest rate channel model, the unchanged excess bond premium is followed by a flat response of production. It seems that the financial frictions, rather than the cost of capital, are a critical driving factor of economic activity. This finding strongly supports 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.

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

2.5.2 The interest rate and risk-taking channels: A more comprehensive identification strategy

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. Instead, changes in the long-term real rate caused by shifts in perceived interest rate risk does.

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 conjecture that monetary policy may have a more significant impact on the supply of long-term capital than the demand. The cost-of-capital effect focuses on the demand side in credit markets. For firms' long-term investment decisions, fluctuations in the cost of capital may be too transitory to be considered. Moreover, capital adjustment costs may take an additional toll on firms' frequent adjustment of capital stocks if they adopt a cost-oriented investment strategy. As a result, firms may not be cost-efficient in closely tracking borrowing costs and adjusting long-term investments accordingly. The investigation of the risk-taking channel provides us with crucial insight into the supply side of long-term capital. Financial intermediaries may be aware of variation in the expected volatility of monetary policy shocks. An unexpected soar of the volatility may indicate the increasing difficulty in interest rate forecasting and the additional provision for potential interest losses. These real costs may render banks with incentives to add an excess premium on baseline lending rates and reduce risk-taking behavior. Our results suggest further exploration and theoretical development in the real impact of second-moment movements in interest rates.

Another noteworthy finding is that, in both models, the price level (i.e. the PCE chain-type price index) is well behaved without demonstrating the price puzzle. These similar price reactions suggest that movements in the price level bear closer relationship with changes in interest rates than with the particular policy tools driving those interest rate changes. In both models, it seems that innovation in long-term real rate stimulates variation in the price level, regardless of the components of monetary policy that trigger this innovation. Comparing with the price responses in the Gertler and Karadi (2015) "credit channel" model, the price level responds more rapidly to innovations in long-term rates than those in short-term rates. It takes approximately two years for the price to distinguishably react to the policy shocks identified in the movement of a short-term rate. In contrast, it takes much less time for the price level responding to shocks identified in the long rate. This finding has two implications. From one perspective, it seems that the policy transmission from short- to long-term rates is not as instant as suggested by the expectations hypothesis. Otherwise, the price level should behave the same in two models without the difference in lagged effects. From another aspect, our results may demonstrate a conflict for the Fed using a short-term interest rate to target the long-run inflation. Inflation targeting denotes that monetary policy is conducted with a long-run target of inflation (detailed discussed by Svensson (1999a,b)). Supposed a monetary authority adopts a short-term rate, such as the funds rate, as the main instrument for inflation targeting, but inflation is more responsive to changes in long-term rates, then the effectiveness of monetary policy may be discounted.

2.5.3 The credit and risk-taking channels: All roads lead to Rome

Monetary policy shocks identified in the credit channel and the risk-taking channel both invoke the hump-shape reactions of the excess bond premium and output. However, the transmission mechanisms are different. The credit channel identifies the monetary policy shocks as variation in a short-term rate caused by unexpected policy rate changes. In contrast, the risk-taking channel defines monetary policy shocks as movements in a long-term real rate induced by the FOMC-statement-driven changes in risk perceived for long-term interest rates.

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.

$$VOL_t = \alpha + \beta Prate_t^- + \gamma Prate_t^+ + \epsilon_t \tag{2.16}$$

We select monthly time series rather than the event study time series, which are only consisted of FOMC events, to include all the data points on the time axis, and avoid the data selection bias. It is necessary because the intervals between any two FOMC meetings are irregular, especially when some unscheduled meetings are taken into account. VOL_t is the monthly volatility surprise and $Prate_t$ is the monthly 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. As to the endogeneity issue, 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 2.3 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. It 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 less than 0.03. Furthermore, policy rate changes are far from being a determinant of volatility surprises as the F-statistics (2.64) is much less than the criteria of 10.

Table 2.3: The Explanatory Power of a Policy Rate Surprise on a contemporaneous Volatility Surprise

	VOL
C	0.010
	(0.029)
NEG_PRATE	2.341***
	(0.843)
POS_PRATE	0.155
	(3.320)
Observations	188
R^2	0.029

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Note: HAC Robust standard errors in parentheses

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 not contribute to the dynamics of economic activity.

2.6 Construction of the Volatility Surprise

The generating procedure of the volatility surprise is crucial to our identification of the monetary policy shocks in the risk-taking channel. However, technical details of the process may divert readers from our empirical results in monetary policy transmission. Thus, after presenting our findings, we set up the following section to discuss our practice in the event study of the risk-side impact of monetary policy in high-frequency data.

2.6.1 Event study of monetary policy impact on interest rate volatility

The methodology of generating the volatility surprise should be consistent with the theoretical model in the risk-taking channel. The risk-taking channel implies three required properties for the volatility surprise that are associated with the exogeneity and relevance conditions for policy instruments. First is exogeneity. It should be exogenous from the perspective of financial markets which have no access to the private information set of the Federal Reserve. Thus, the volatility surprise may not be obtained from the Federal Reserve; instead, it could be collected through massive data in financial markets. Second is inclusiveness. It may reflect the integrated risk-side impact of entire information content in FOMC statements, instead of merely concerning influences of policy rate changes. The third is relevance. It should bear a close relationship with interest rate/ bond markets since monetary policy primarily intends to affect these markets. In short, the goal is to identify the impact of the entire information content in FOMC announcements on the interest rate risk perceived by bond markets.

Our event study approach stems from Kuttner (2001). He applies a 30-minute or one-day time window around each FOMC announcement on near-term federal funds rate futures to capture exogenous monetary policy actions. This method is widely employed for studying the effects of discrete events or news releases, such as Gürkaynak et al. (2005), Campbell et al. (2012) and more. In general, the event-study approach captures market price changes of financial assets and their derivatives, like futures and options, within a small time window around FOMC meetings to quantify the influence of information content of FOMC announcements.

Event study methods fit in our purpose in three aspects. First, it considers an FOMC announcement as a whole and enable us to evaluate the impact of various tools or components of monetary policy within one measure like policy rate changes or variation in interest rate volatility. Meanwhile, this convenience also constitutes a challenge to the identification of monetary policy shocks. It is essential to impose structural assumption on why an event study time series captures, entire or a dimension of, monetary policy. Second, it incurs no model uncertainty, as it is not nested to an economic model. Third, it is compatible with the irregularity of FOMC meeting dates. In each year, FOMC meetings are not held on the same dates. With the event study applied on high frequency (daily) data, we accurately match the timing of each monetary policy announcement with its correspondent second-moment movement of the interest rate.

The main differences between the event study constructed for the volatility surprise and Kuttner (2001) approach are that we consider the expected volatility of a long rate as the event study object, and that we utilize a wider (i.e. 4-day) time window to capture exogenous movements.

2.6.2 The implied volatility of 10-year Treasury

We extract the risk of long-term interest rates perceived by bond markets from the daily time series of 30-day option-implied volatility of the 10-year Treasury-Note futures price (short for "TYVIX index") obtained from Cboe Options Exchange (Cboe). The TYVIX index measures the annualized expectation in the 30-day standard deviation of the 10-year T-note 30-day futures price implied by market-traded futures and options prices. This implied volatility is model-free and alleviates the the problems of measurement errors and model misspecification. It requires only the assumption of absence of arbitrage, and can be calculated directly from observed option prices. The TYVIX index indicates the implied volatility of the 10-year Treasury yield, as Treasury bond prices are inversely mapped to Treasury yields ceteris paribus.

Given the TYVIX index is denoted as a percentage of the futures price, it is influenced by changes in the futures price of 10-year Treasury note. To exclude the impact of Treasury notes price on the percentage representation, we multiply the TYVIX index with the spot-month futures price of 10-year T-note. Thus we obtain the TYVIX index in basis points of spot-month 10-year T-note futures price (Swanson, 2006). As a result, the varying T-note futures price level does not affect our measure.

Given that the 10-year Treasury yield is the representative long-term interest rate received most extensive attention in financial markets, we set it as the long-term rate, following the practice of Wright (2012), Hanson and Stein (2015) and others. From another perspective, we select implied volatility of the 10-year nominal rate to represent our measure of the volatility of long-term rates with an intention to match the maturity of the policy indicator of our choice.

The TYVIX index admittedly not the only measure of volatility of long-term rates. Merrill Lynch provides an options volatility estimate index, the MOVE index. It is the yield curve weighted index of the 30-day options-implied volatility of 2-, 5-, 10- and 30-year bond prices. It is based on relatively illiquid options written on actual Treasury securities. Another reason for adopting TYVIX index instead is that it only measures fluctuations in the 10-year Treasury bond futures market and enable us to focus on the role of long-term rates in monetary transmission. A related measure is the TIV index (Choi et al., 2017). It is derived by replicate a variance swap in the fixed income market and is virtually identical to the TYVIX index.

Figure 2.4 shows the TYVIX in basis point. It soars to a peak during the onset of the financial crisis and experiences a gradual decline during the ZLB period. There are some turbulences in the aftermath of the period. Notably, the two peaks of TYVIX index are respectively coincided with two local troughs of the federal funds rate in August 2003 and at the outset of the ZLB period in December 2008. This phenomenon indicates the cease

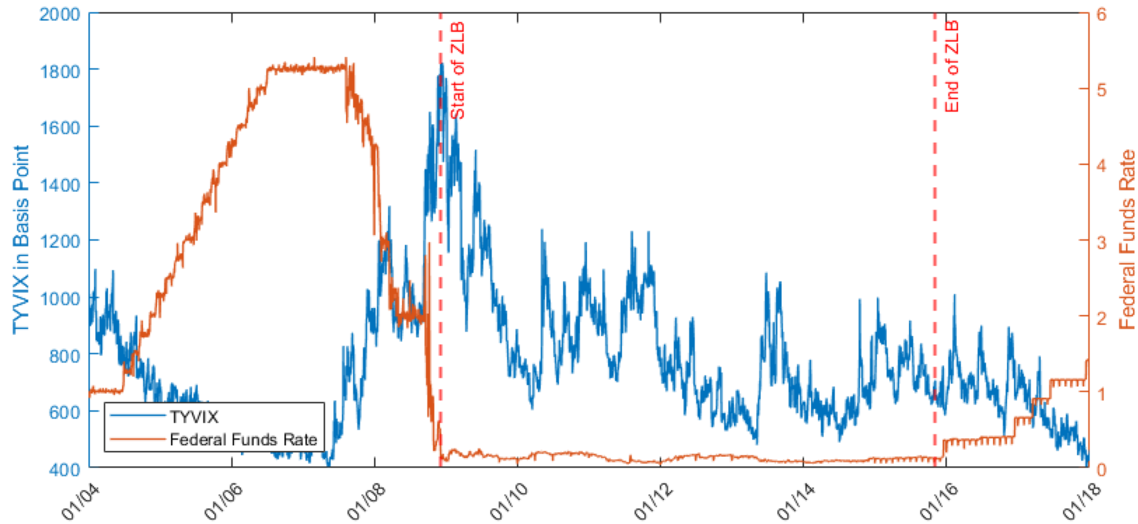


Figure 2.4: The Option-implied 30-day Volatility of 10-year T-note Future (Basis Point)

of expansionary monetary policy paths may stimulate the implied volatility of long-term interest rate.

The 30-day measuring horizon of the TYVIX index facilitates the event study on FOMC announcements. We seek to isolate each monetary policy announcement from policy announcements in ensuing meetings, although the impacts of policy announcements may intertwine to each other[10]. A too wide measuring horizon may extend across several FOMC meetings and complicate the measurement by considering future policy actions and their expected impacts simultaneously. The 30-day measuring window on TYVIX index pragmatically enables the isolation for most FOMC meetings. In other words, it enables us focus on one FOMC announcement at a time and evaluate its impact on the volatiilty of an interest rate with a long maturity.

The FOMC of the Federal Reserve holds eight scheduled meetings per year and publicly announces new actions from deliberation at the end of each meeting. Time intervals between

[10]Some monetary policy tools may have extended implications on future policy decisions, such as forward guidance. We evaluate this forward-looking impact through investigating movements in a long-term rate and its volatility, rather than extending the measuring horizon of the volatility.

any two contiguous scheduled FOMC meetings range from one to two months. We select the 30-day length for calculating the volatility so that the effect of one event is shielded from being polluted by the expectation of monetary policy actions in the next FOMC announcement, which is more than 30-day apart. This property facilitate us to capture its impact independently.

An exception of this separation is for unscheduled FOMC meetings. The FOMC "may also hold unscheduled meetings as necessary to review economic and financial developments"[11]. In our sample, 20 out of 140 FOMC meetings were unscheduled. Admittedly, intervals between some scheduled and unscheduled meetings are shorter than 30 days. However, they may not seriously detriment to the isolation aforementioned. On the one hand, as those meetings are unscheduled, the scheduled FOMC meetings preceding them shall not expect them ex-ante. Thus, an unscheduled FOMC meeting may not pollute the volatility surprise generated in its preceding scheduled meeting. On the other hand, an unscheduled meeting aims to "review" the announced monetary policy in its precedent scheduled meeting and does not officially provide forward-looking information such as summary of economic projections and forward guidance. We attribute changes of the TYVIX index around an unscheduled meeting to its newly announced statement, rather than to changes in the expectation of future monetary policy actions in an ensuing FOMC meeting less than 30 days apart.

In all, the 30-day measuring horizon, to the maximum extent, enables us to focus on the impact of one FOMC statement in each volatility surprise.

2.6.3 The 4-day time window

The state-of-art identification assumption for event studies is that variation in a target financial variable within an adequately narrow time window around each FOMC announcement

[11]Cited from the website of Board of Governors of the Federal Reserve System. https://www.federalreserve.gov/faqs/about_12844.htm

may not be contaminated by noisy economic news. Therefore, it is solely attributed to the exogenous impact of monetary policy. However, we depart from this popular Kuttner (2001) approach and consider a 4-day time window instead to control for the pre-FOMC-announcement drift in volatility. Specifically, we notice a prominent pre-FOMC-event drift of the TYVIX index in basis points, which mainly due to the short-term trading activities before each FOMC event, rather than due to monetary policy actions[12]. We find that this drift introduces more noise to the measurement than the inclusion of economic news in a relatively wide window. The 4-day time window is a feasible way to preclude this volatility drift.

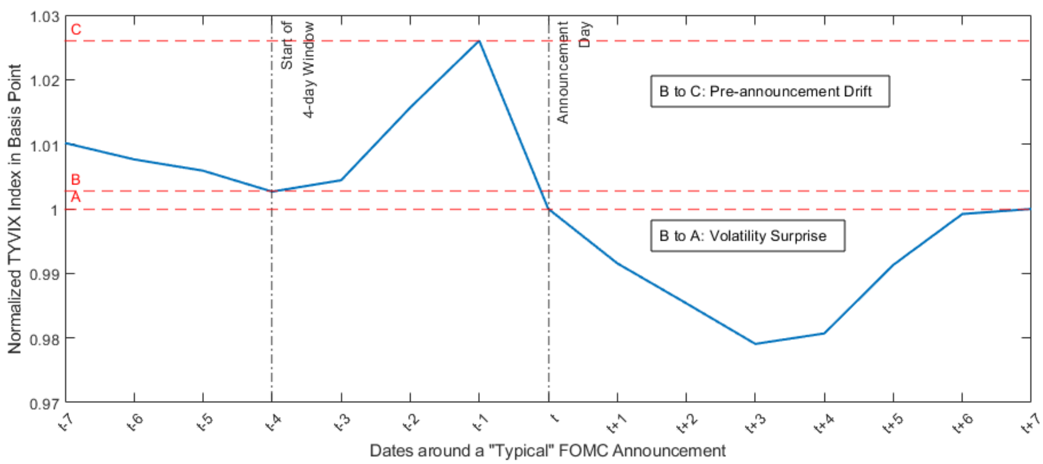


Figure 2.5: Averaged TYVIX Index from -7D to +7D of FOMC Decisions (Basis Point).

In Figure 2.5, we plot the TYVIX in basis point on 15 days around a "typical" FOMC announcement, averaging data around all FOMC meetings from 2003:1 to 2018:1. The 15 days are seven days before, the announcement date, and seven days after an announcement).[13]

[12]Lucca and Moench (2015) first introduce this concept for financial assets yields.

[13]We adopt actual dates rather than trading dates in Figure 2.5, but our data is recorded only on trading days. Therefore, our data source fills the empty data points of weekends and holidays with the nearest precedent trading day data. For example, the data input for Saturday and Sunday is the same as the input for Friday.

Before an FOMC meeting, the TYVIX in basis point, on average, accumulates consecutively since four days before the announcement and then quickly ease back on the announcement date. This drift may be analogous to the fixed effect of FOMC events. It might not be relevant to the information content of monetary policy as this drift happens before a "typical" FOMC announcement.

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 2.4, 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 92% 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 2.4: Weekday Convention of FOMC Announcements

	Mon	Tue	Wed	thu	Fri	Sat	Sun	Total
Sample Counts	5	40	81	10	3	1	1	140
Percent	4%	28%	57%	7%	2%	1%	0%	100%

Note: The sample ranges from 2003:1 to 2018:1.
FOMC events include scheduled and unscheduled meetings with official statements.
If one FOMC event takes more than one day, the last day is considered as the announcement date.

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.

To verify the relationship between the pre-FOMC-announcement drift in the volatility and the Friday effect, in Figure 2.6, we further show time-averaged fluctuations in the TYVIX index in basis point for announcements on different weekdays. No matter which day (a Tuesday, Wednesday or Thursday) an FOMC statement is released, the TYVIX index reaches the trough in the preceding Friday. In the announcement week, trading volume and liquidity in options markets resume from the low point. This pattern suggests that the pre-FOMC-announcement drift is due to the Friday effect. Another interesting finding is that, on average, the interest rate volatility amplifies at a higher speed when approaching an FOMC event. This may be due to more unofficial market rumors and trading on interest rate uncertainty before official news release. In short, the pre-FOMC-announcement drift seems to commence at the beginning of an announcement week and gain momentum when approaching the FOMC press conference.

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. We take advantage of the Friday effect to facilitate 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

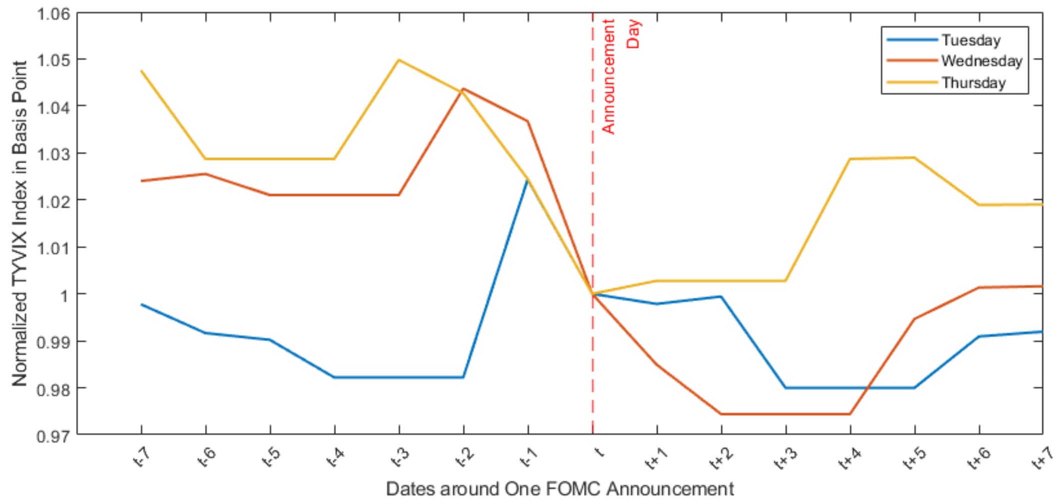


Figure 2.6: Averaged TYVIX Index for Announcements on Different Weekdays

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.

Pragmatically, instead of frequently adjusting time windows, we measure monetary-policy-driven changes in the interest rate volatility with a unified 4-day time window. In detail, for each FOMC meeting, we subtract the closing quote of TYVIX index in basis point on the fourth day prior to the FOMC announcement from the closing quote on the announcement date. Then we record this difference on the FOMC announcement date. Using this 4-day time window can accurately capture the impact of 92% of FOMC decisions in our sample (i.e., the FOMC announcements made on Tuesday, Wednesday and Thursday) because the four days before those weekdays all point to ending quotes on preceding Fridays.

We measure the unexpected change of the TYVIX index for each FOMC announcement (shown in Figure 2.7) and generate the event-study volatility surprise. Data points in the volatility surprise represent changes in the TYVIX index in basis point during the unified

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 2.8.3 (The monthly series is also shown in Figure 2.7).

Furthermore, we make minor adjustments to the time windows for FOMC announcements released on weekdays other than Tuesday, Wednesday and Thursday. For the decisions on Mondays, we narrow time windows into three days to set the leading end of time windows to be Friday. As to the FOMC announcements made during the weekend, we extend the trailing end of time windows to the ensuing Mondays in order to let financial markets to price in those announcements. In total, we adjust the time windows for 6 out of 140 FOMC meetings in our sample. [14]

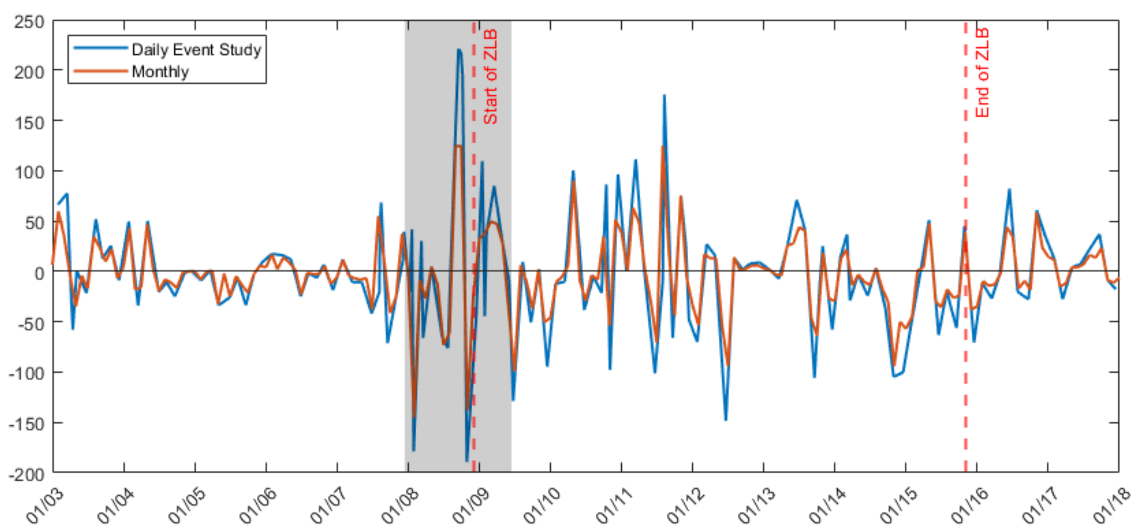


Figure 2.7: The Volatility Surprise (Basis Point; Event Study and Monthly)

Admittedly, a potential drawback of a relatively wide time window is that it may include the impact of economic news other than monetary policy decisions. However, event studies

[14] The results are robust without adjustments.

for interest rate volatility are different from those for level data. Unlike the scholars applying tight time window, such as 30 minutes or shorter, We are unnecessary to completely rule out the impact of economic news. Instead, we make a less restrictive assumption on the frequency of economics news. If economic news is frequently released and has the same occurrence probability on dates approximating to a time window, the contribution of economics news to interest rate volatility is relatively stable around this time window and can be canceled out when taking the difference. As a result, if the TYVIX index in basis point is different at the two ends of a time window, the difference should be ascribed to the varying expectation after an FOMC announcement. This assumption renders us a potentially wider time window, i.e., the 4-day window, because we maybe not obliged to purge all noises from economic news.

In Table 2.5, we look at the relationship between volatility surprises captured by various time windows and unconventional monetary tools. Specifically, 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). Since almost all FOMC announcements contain sentences regarding forward guidance, we only include those announcements that change the communication styles in the forward guidance dummy, for instance, the change from a calendar threshold to an outcome-based threshold. Since the Federal Reserve only implements those unconventional tools during the ZLB period, we truncate the sample to that period. As to the exogeneity issue, we consider a volatility surprise is a reaction of the bond market to an FOMC announcement, which includes information of those unconventional tools. Thus, we assume a contemporaneous unidirectional impact from announcements regarding unconventional tools to volatility surprises.

Table 2.5 shows the superiority of the four-day time window, as volatility surprises captured by the 4-day time window has the highest correlation with announcements of unconventional monetary policy tools than those measured in tighter or wider time windows.

Table 2.5: Comparison of the Time Windows for Volatility Surprises

	1D	2D	3D	4D	5D
FG	27.073	54.644	68.639**	73.915**	73.915**
	(22.395)	(37.302)	(34.062)	(34.174)	(34.174)
LASP	−68.657***	−72.656***	−74.980***	−71.463***	−71.463***
	(16.598)	(22.758)	(22.155)	(22.271)	(22.271)
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

It confirms our hypothesis that the pre-FOMC-announcement drift in the volatility produces more noise, rather than reflects more information of monetary policy, in producing the volatility surprise.

Interpretation of those coefficients provides us additional insight in properties of the volatility surprise. In Appendix 2.8.4, we further provide details on the connection between volatility surprises and unconventional monetary policy tools.

LSAPs are associated with negative volatility surprises, indicating that an expansionary policy announcement reduces the perceived risk of long-term rate. Noteworthily, we may not attribute the cause of negative volatility surprises to policy rate changes that may be happened simultaneously with unconventional policy actions. During the ZLB period, the policy rate is essentially zero and changes of the policy rate, either expected or unexpected, are minimal comparing with its fluctuation during normalized interest rate periods. In contrast, volatility surprises are larger in magnitude during the ZLB period. Thus, negative volatility surprises are more attributable to LSAPs, rather than to possible unexpected changes in the policy rate that coincide with those expansionary assets purchases. Our finding that LSAPs and policy rate cuts similarly lead to negative volatility surprises is consistent with the results in a working paper Mallick et al. (2017). They apply a VAR model with Cholesky identification as well as sign restrictions to find that a conventional policy rate cut and an LSAP both lead to the negative response of bond yield volatility.

As to forward guidance, a change in communication styles is generally correlated with a positive volatility surprise. Lakdawala (2016) and Kim (2017) both find that forward guidance shocks are contractionary. The public may perceive more variation in future monetary policy shocks due to shifts in communication approaches. A forward guidance that confirms a previously set threshold tends to relate with a negative volatility surprise. Shown in Appendix 2.8.4, the attempts at forward guidance prior to outcome-based threshold approach seems failed to clarify the path of monetary policy so they may have lead to increased volatility. What's interesting is the fact that forward guidance appears to be more effective when it is outcome-based (more effective at reducing volatility) except at the time of adoption. Maybe at the time of adoption the positive change in volatility simply reflects the fact that investors did not fully believe the commitment given the failed attempts at forward guidance earlier but then came around to the conclusion that this commitment was indeed credible.

Through an event study featuring the 4-day time window and the utilization of TYVIX index, We obtain the event-study volatility surprise. Eventually, we convert it into a monthly series and identify monetary policy shocks from a risk-taking channel perspective.

2.7 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 identify monetary policy shocks from long-term rate fluctuations, we construct an event study from the variation of interest rate volatility around each FOMC announcement and utilize the resulting time series as an external instrument.

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 find merits in the external instrument and heteroskedasticity identification approaches. Thus, we combine elements from both in our analysis. Furthermore, we introduce a first attempt to quantify the monetary-policy-induced variation in the perceived interest rate risk in financial markets supported by an event study.

Two relatively independent transmission mechanisms are identified through the two ends of the yield curve. Both avenues converge in the similar responses of financial frictions and output. We conclude 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 unobservable, we obtain evidence consistent with the risk-taking channel and review the viability of the credit channel.

Our analysis does not constitute a call for a different instrument of monetary policy, given the difficulty of accurately targeting the public's perception of interest rate volatility, particularly on the long end of the yield curve. Instead, we provide a tool for market participants to analyze the potential impact of policy on long-term rates from a risk-taking channel perspective. This study underscores the need for further exploration in the role of long-term interest rates in the transmission mechanism of monetary policy.

2.8 Appendix for Chapter 2

2.8.1 Algorithm for identification

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

$$S = \begin{bmatrix} s & S_q \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} \tag{2.17}$$

and the reduced-form variance-covariance matrix as

$$\Sigma = \begin{bmatrix} \Sigma_{11} & \Sigma_{12} \\ \Sigma_{21} & \Sigma_{22} \end{bmatrix} \tag{2.18}$$

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

$$\left(\Sigma_{21} - \frac{s_{21}}{s_1 1}\Sigma_{11}\right)' \left(\Sigma_{21} - \frac{s_{21}}{s_1 1}\Sigma_{11}\right) = s_{12} Q s_{12}' \tag{2.19}$$

with

$$Q = \frac{s_{21}}{s_1 1}\Sigma_{11}\left(\frac{s_{21}}{s_1 1}\right)' - \left(\Sigma_{21}\left(\frac{s_{21}}{s_1 1}\right)' + \frac{s_{21}}{s_1 1}\Sigma_{21}'\right) + \Sigma_{22} \tag{2.20}$$

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.

$$(s^p)^2 = s_{11}^2 = \Sigma_{11} - s_{12}s_{12}', \tag{2.21}$$

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

$$s_{12}s_{12}' = \left(\Sigma_{21} - \frac{s_{21}}{s_1 1}\Sigma_{11}\right)' Q^{-1} \left(\Sigma_{21} - \frac{s_{21}}{s_1 1}\Sigma_{11}\right) \tag{2.22}$$

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.

2.8.2 Supporting material for matching volatility surprises with lagged VAR residuals in the equation of policy indicator

A concern about the non-contemporaneous matching in SVAR identification is that historical values of the policy indicator seem predictive for volatility surprises so that identified monetary policy shocks might reflect systematic component of monetary policy. However, we find no evidence to bolster this arguement in the daily date analysis and Granger causality test.

Table 2.6 shows that volatility surprises are not predictable by 10-year TIPS yield movements within one week before 4-day time windows. Whereas, volatility surprises motivate significant fluctuations in long-term TIPS yield and the impact is relatively persistent.

Table 2.6: Real yield effects of volatility surprises (daily event study, 2003-2018)

	Week 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)	(2.63)	(2.308)
R^2	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 (and two weeks) after announcements.
The standard deviation of volatility surprise is normalized to 1.
In the second colume, the volatility surprise is the dependent variable.

Table 2.7 indicates the Granger causality between volatility surprises and reduced-form VAR residual in the policy indicator equation. Importantly, we pair volatility surprises with contemporaneous policy indicator residuals. It is shown that the monetary-policy-induced volatility surprise can help in predicting innovation in the 10-year TIPS yield but historical and current innovations in this yield supply limited explanatory power to the volatility surprise. The result strongly support the unidirectional impact of volatility surprises on policy indicator residuals.

Table 2.7: Pairwise Granger Causality Test

Null Hypothesis:	Obs.	F-statistic	Prob.
VOL does not Granger Cause Policy Indicator Residual	176	5.642	0.001
Policy Indicator Residual does not Granger Cause VOL		0.344	0.793

Note: The policy indicator is the 10-year TIPS yield. VAR residuals of the policy indicator are contemporaneous with volatility surprises in the test.

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.

2.8.3 Conversion of the event-study volatility surprise 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). Consequently, we derive the monthly volatility surprise as shown in Figure 2.8.

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

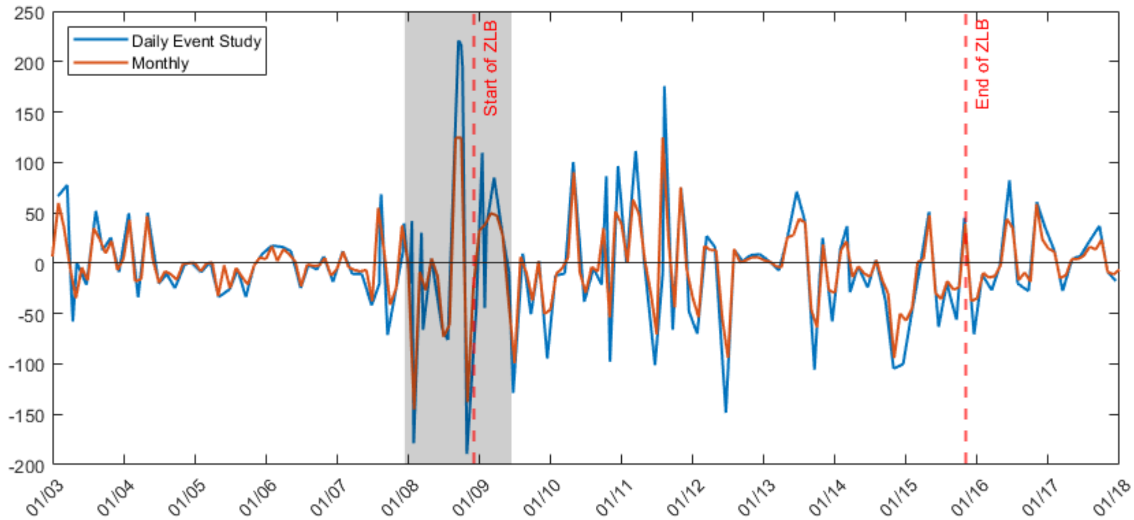


Figure 2.8: The Volatility Surprise (Monthly & Daily; Basis Point)

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 2.8, 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.

2.8.4 The volatility surprise and unconventional monetary policy tools

The volatility surprise provides us insight in the risk-side impact of unconventional monetary policy tools. Table 2.8 shows that changing forward guidance communication style is often associated with a positive volatility surprise. The public may perceive more variation in future monetary policy shocks due to shifts in communication approach.

In general, announcements of balance sheet policies (BSPs) lead to negative voaltility surprises as they reconfirm the goal of monetary policy, which is to curtail the downside economic risk. More interestingly, the gradual exit of balance sheet approaches also causes negative volatility surprises. However, these may not contribute to the reduction in monetary easing; instead, they may be attributed to the improvement of economic prospect.

Table 2.8: Reactions of the Volatility Surprise to Important Policy Changes (Event Study)

Dates	Communication	Volatility Surpirse
	Forward Guidance	
2009/03/18	ZLB for an extended period	1.397
2011/08/09	Adopt calendar threshold	2.890
2012/01/25	Extend calendar threshold	-1.153
2012/09/13	Extend calendar threshold	0.032
2012/12/12	Adopt outcome-based threshold	0.146
2013/12/18	Confirm outcome-based threshold	-0.951
2014/03/19	Confirm outcome-based threshold	-0.476
2014/12/17	Confirm outcome-based threshold	-1.649
	Balance Sheet Policys (BSPs)	
2008/10/29	Announce LSAP1	-3.114
2010/09/21	Clarify reinvestment policies	-0.352
2010/11/03	Announce LSAP2	-0.352
2011/09/21	Announce Maturity Extension Program (MEP)	-1.087
2012/09/13	Announce LSAP3	0.032
2013/12/18	Slowing purchases	-0.951
2014/09/17	Balance sheet normalization	-0.601

Note: Volatility surprises are normalized to unit standard deviation.

CHAPTER 3

MONETARY TRANSMISSION IN MONEY MARKETS: A DIVISIA COMPONENT INVESTIGATION

Abstract: Recent work in the monetary literature has amply demonstrated the superior information content of Divisia monetary aggregates. Most of the work focuses exclusively on monetary assets at high degrees of aggregation. In a first, we document pass-through of the short-term interest rate onto the components of these Divisia indices. We show that financial and monetary markets reacted strongly to Federal Reserve policy post 2007. The strong monetary response varies not only quantitatively over time, but qualitatively across asset classes. Although far from a one-to-one relationship, balances of assets more closely associated with household demand, such as currency and savings, tend to move in the opposite direction of short-term rates—indicative of a liquidity effect. Whereas balances more closely associated with firms returns are mixed, where institutional money markets also show a liquidity effect, large time deposits or commercial paper exhibit a strong Fisher effect post 2007.[1]

[1]Authors - Zhengyang Chen and Victor Valcarcel

3.1 Introduction

Important macroeconomic work in the 1960s by Brunner (1961), Brunner and Meltzer (1963), Friedman (1961), Friedman and Schwartz (1963), among others, changed economists' views regarding the efficacy of monetary policy and the importance of monetary aggregates (see Nelson (2003)).

In the years that followed, however, a New Keynesian "consensus" emerged that centered on de-emphasizing money in favor of a single nominal interest rate in order to link monetary policy and aggregate demand. While a host of factors to explain this dates back to the Keynesian-Monetarist debates of the 1960s and early 1970s, two are particularly salient. First, standard textbook IS equations do not include a monetary aggregate, but a single representative short-term real rate. Second, a once strong empirical relationship between the monetary aggregates, which the Federal Reserve produces, and economic activity began to break down in the 1980s. This erosion in the predictability of these monetary aggregates can be attributed primarily to an explosion of financial innovations and the mass adoption of money markets, mutual funds, and other assets. Furthermore, changes in banking rules during the 1980s allowed banks to begin offering interest-earning demand deposits. Thus, in a data-rich monetary environment replete with a multitude of monetary instruments, a single relatively narrow measure of money balances, such as M2, loses its appeal.

Even prior to the Taylor (1993) landmark paper, monetary economists had long recognized that central banks in practice treated the nominal interest rate—rather than the monetary aggregates—as their instrument of choice for the conduct of monetary policy. Interest-rate rules that responded to nominal variables in an appropriate manner could deliver low and stable inflation, even if these rules did not respond directly to movements in the stock of money.

Even as central bankers moved to systematically expunge money out of monetary economics, Taylor clarified his own views on this issue at a conference in July 1992. While noting that "interest rates are likely to remain the preferred operating instrument of monetary policy," Taylor (1992, p. 12) writes:

> *"The evidence that the large swings in inflation are related to money growth indicates, however, that money should continue to play an important role in monetary policy formulation in the future."* (Taylor, 1992)

In itself, the use of a Taylor rule for monetary policy analysis is neutral on the issue of the importance of monetary aggregates. Nelson (2003) points out that the fact that actual policy is well-characterized by a short-term interest rule (the federal funds rate) with no explicit money term, does not preclude a role for monetary aggregates in the transmission of monetary policy.

The 2007 Financial Crisis and the following protracted zero-lower-bound (ZLB) period highlighted some shortcomings of the information content that the federal funds rate alone provides about monetary transmission. This opened the door to revisit the use of information from monetary aggregates in monetary models within the New Keynesian framework (see examples in Belongia and Ireland (2015), Belongia and Ireland (2018), and Keating et al. (2019) among others).

A popular role for money in economic theories of the past was in the provision of a wealth effect. With exogenous increases in real money balances, the ensuing stimulative effect of raised real financial wealth should affect consumption or aggregate demand. However, compelling work by Ireland (2001) shows empirically the role for money in the IS equation that arises from non-separable utility is quantitatively negligible. Theory and evidence does not provide support for the inclusion of a real balances term in the IS function. However, a real balance effect is not the only operating mechanism at work. The importance of the money stock may not be through a direct real balance effect. Instead, money may act as an index of the gamut of (market and non-market) rates that are relevant for aggregate demand. "Real money balances capture the many channels of monetary transmission." (Meltzer, 125)

Friedman (1956) specified a money demand function, where a spectrum of yields enters the money demand function. This is in contrast to the standard LM specification, in which the return on short-term nominal securities is the sole opportunity cost variable. A Friedman-style money demand function suggests that information content of money summarizes monetary conditions not contained in short-term interest rates. Friedman's view of money demand was comprehensive, including yields of financial instruments as well as returns on physical assets. The more direct observability of monetary aggregates presents an advantage.

Friedman's was a disaggregated approach featuring the desirable property of heightened information content of money. The role for money arises from its ability to serve as an index of substitution effects, rather than wealth effects of monetary policy. In this chapter, we take both of these notions seriously. We set out to investigate substitution effects on a disaggregated approach to money balances.

A complicating issue is that the standard monetary aggregates (e.g. M1 and M2) produced by the Federal Reserve—which are typically referred to in the literature as simple-sum aggregates—suffer from serious measurement error. Instead, we take the following quote to heart and investigate other monetary aggregates known as Divisia created by William Barnett in the 1980s (see Barnett (1978) and Barnett (1980)).

> *"Indeed, if pressed on this issue, virtually all monetary economists today would no doubt concede that the Divisia aggregates proposed by Barnett are both theoretically and empirically superior to their simple-sum counterparts."* (Belongia and Ireland, 2014)

Friedman and Kuttner (1992) show evidence that the strong association between M2 and aggregate economic activity in the 1960s and 1970s all but disappeared in the 1980s. Many researchers since have concluded that money demand in the US has been inherently unstable, thereby dooming any attempt to pin down money demand shocks.[2] However, Belongia (1996) and Hendrickson (2014) replicate portions of the Friedman and Kuttner (1992) model and conclude these allegations of a breakdown in the relationship are the consequence of measurement error in the monetary aggregate. In an investigation of the long-run relationship between nominal and real macroeconomic variables, Serletis and Gogas (2014) find persuasive evidence that Divisia monetary aggregates play an important role in money demand theory. Finally, in a recent paper, with a comprehensive investigation of Divisia aggregates, Belongia and Ireland (2019) show convincingly that money demand in the US is far more stable than previously thought.

As a preview of results we outline three main findings. First, estimated monetary service factors (MSF) from Divisia aggregates show more volatility at higher levels of aggregation and seem to more closely mirror the shape of short-term interest rates at lower levels of aggregation. Second, output and the price level move in opposite directions to an expansionary monetary policy shock even when including information from both commodity prices and monetary services. However, the magnitude of the puzzle is ameliorated with the inclusion of our MSF estimates as we climb up the Divisia component composition from narrower to broader aggregates. Third, we show that financial and monetary markets reacted strongly to Federal Reserve policy post 2007. The strong monetary response not only varied quantitatively over time, but qualitatively across asset classes. Although far from a one-to-one relationship, balances of assets more closely associated with household demand, such as currency and savings, tend to move in the opposite direction of short-term rates—indicative of a liquidity effect. On the other hand, balances more closely associated with firms returns are mixed, where institutional money markets also show a liquidity effect while large time deposits or commercial paper exhibit a strong Fisher effect post 2007.

[2]Many ascribe this as the last nail in the coffin for any consideration of monetary quantities in monetary models.

The rest of the chapter is organized as follows. Section 3.2 provides background on Divisia money. Section 3.3 describes the econometric framework for the estimation of a single factor-augmented VAR (FAVAR). Section 3.4 outlines the methodology to estimate a monetary service factor (MSF) with dynamic model averaging (DMA) techniques from iteration of various FAVARs specified in the previous section. Section 3.5 briefly describes the data. Section 3.6 explains results of the MSF estimates. Section 3.7 presents results from a FAVAR of monetary policy augmented with the MSF estimates. Section 3.8 describes results from a disaggregated specification of substitution effects of monetary transmission. Section 3.9 concludes.

3.2 Divisia Monetary Aggregates

Seminal work in Barnett (1978) and Barnett (1980) demonstrated how economic aggregation theory can be used to construct appropriate measures of money balances, where liquidity services are provided through an entire gamut of assets that include various types of interest-bearing deposits and non-interest-bearing assets. By comparison, the simple-sum measures of money balances the Federal Reserve reports are problematic. This is because traditional measures of M1 and M2 simply add up the nominal value of all monetary assets in circulation while ignoring the fact that their components yield different flows of liquidity services and, in equilibrium, also differ in the opportunity (or user) costs that households and firms incur when they include them in their portfolios.

Chrystal and MacDonald (1994) dubbed the essential message of Barnett's work—that simply summing monetary assets imposes, unrealistically, that they are perfect substitutes for each other even when they render different yields—as the "Barnett Critique." Belongia and Ireland (2014) emphasize the Barnett Critique is *"...as relevant today as it was 30 years ago."*

Index-number theory has been used to generate official government aggregate data since the 1920s. In general, the data construction and measurement techniques should rely on the theory that is used to rationalize the procedure. The assumptions implicit in the data construction procedures should be consistent with the assumptions used to generate the models in which the data are nested. Lacking coherence between the structure of an aggregator function and the econometric models in which aggregates are embedded leads to measurement error. Simple-sum M1 and M2 aggregates lack this coherence.

Aggregation of micro-founded theory depends on unknown aggregator functions, such as utility, cost, and distance functions. Monetary aggregation would, therefore, require estimating the functions that link each type of monetary asset, such as currency, checking account, certified deposits, etc, with their respective monetary services. It is generally costly and troublesome for governments to collect adequate data for the estimation of aggregator functions.

Conversely, statistical index-number theory provides non-parametric indexes derived directly from quantity and price data. It involves decomposing the value ratio between two time periods of a well-defined set of transactions into a component that measures the overall price change and another component that evaluates the aggregate change in quantity in the two periods of time. Importantly, this aggregation approach relies on actual price and quantity data, rather than on estimations of unknown parameters in functional form of an aggregator function that is assumed ex-ante.

A more direct connection between index number theory and microeconomic aggregation theory was established by Diewert (1976) who proposed a series of second-order 'superlative' index numbers. These index numbers are functions of prices and quantities that track an unknown aggregator function up to the second order and do not require parametric estimation of the hyperparameters. Barnett's Divisia monetary aggregates are examples of these superlative index numbers. Divisia methodology uses information from the user costs of monetary services as well as quantities of monetary assets to trace the aggregator function and, in turn, construct actual monetary aggregates.

The derivation of Divisia monetary aggregates is firmly embedded in microeconomic theory. Consider a decision problem over monetary assets. Let m_t' be the vector of real balances of monetary assets in time period t and r_t denote the vector of holding-period yield for those assets. The one-period holding yield of a benchmark asset is denoted as R_t. The monetary service this benchmark asset provides is strictly due to investment returns and otherwise generates negligible liquidity services. R_t is typically referred to as the benchmark rate which corresponds to a notional maximum holding yield available to households and firms during time period t. The decision problem features the maximization of utility from monetary assets subject to a restriction of total planned expenditure in monetary services y_t.

$$\text{Max } u(m_t)$$
$$\text{subject to } \pi_t' m_t = y_t$$

Barnett (1978) shows how the real user cost for each weakly separable group of monetary assets π_{it} is calculated by

$$\pi_{it} = \frac{R_t - r_{it}}{1 + R_t} \tag{3.1}$$

The solution to this microeconomic problem shows that the exact monetary aggregate (M_t) should equal the utility generated from an optimal allocation of monetary assets m_t^* to a representative agent. The real user cost in (3.1) and the quantity of a given monetary asset jointly determine the expenditure share of the asset relative to the total expenditure of monetary services. The growth rate of the monetary aggregate (and its price dual) is determined by the growth in its underlying monetary assets (and their own real user costs) weighted by their respective expenditure shares, which are themselves functions of real user costs of the form described in (3.1). The following describes the aggregate quantity index and its associated aggregate user cost:

$$\frac{d\log M_t}{dt} = \Sigma_i s_{it} \frac{d\log m^*_{it}}{dt} \tag{3.2}$$

$$\frac{d\log \Pi_t}{dt} = \Sigma_i s_{it} \frac{d\log \pi_{it}}{dt} \tag{3.3}$$

where s_{it} is the expenditure share of each monetary asset in the total expenditure.

$$s_{it} = \frac{\pi_{it} m^*_{it}}{y_t} \tag{3.4}$$

The real user cost dual satisfies Fisher's factor reversal in continuous time

$$\Pi_t M_t = \pi'_t m_t \tag{3.5}$$

The Divisia index is a discrete-time approximation of equation (3.2) described as

$$\log M_t - \log M_{t-1} = \Sigma_i \bar{s}_{it}(\log m^*_{it} - \log m^*_{i,t-1}) \tag{3.6}$$

where

$$\bar{s}_{it} = \frac{1}{2}(s_{it} + s_{i,t-1}) \tag{3.7}$$

describes the expenditure shares associated with each underlying monetary asset i.

The Center for Financial Stability (CFS) provides data for aggregate Divisia quantity indexes at various levels of aggregation as well as their components. Divisia M1 (henceforth, DM1) includes currency (c), demand deposits (DD), other checkable deposits (OCDs) at commercial banks, and OCDs at thrift institutions. Divisia M2 (henceforth, DM2) adds the following components to DM1: savings deposits (SDs) at commercial banks, SDs at thrift institutions, retail money-market funds (RMMFs), small time deposits (STDs) at commercial banks, and STDs at thrifts. At 15 components, Divisia M4 (henceforth, DM4) is the broadest monetary aggregate currently available in the US. It adds the following five monetary instruments to DM2: institutional money-market funds (IMMFs), large time deposits (LTDs), repurchase agreements (REPOs), commercial paper (CP), and 3-month T-bills. Figure 3.1 shows annualized growth rates of DM1, DM2, and DM4 from the CFS.

Much of the empirical Divisia literature referenced in previous sections focuses on dynamics of various aggregates (DM1 through DM4) with DM2 receiving the most attention. However, Jadidzadeh and Serletis (2019) find support for the recommendation that empirical analysis be conducted with broadest aggregate available (DM4). Keating et al. (2019) also center attention on DM4, although their findings are generally robust to replacing it with DM2. While the optimal aggregation level remains debatable, to date most of the empirical Divisia literature has focused on monetary aggregates. As far as we know, this work constitutes the first empirical analysis that centers on the components of Divisia, rather than the Divisia aggregates themselves.[3] Two central thrusts of our contribution involve: (i) augmenting a popular VAR identification scheme of monetary policy with information extracted from various components of Divisia money and (ii) estimating substitution effects of monetary policy shocks on underlying Divisia components.

3.3 Econometric framework

Most of our analysis stems from a factor-augmented VAR (FAVAR) that follows closely Koop and Korobilis (2014) where a system of the usual suspect macroeconomic variables typically included in investigations of monetary transmission, such as Christiano et al. (1999), is augmented with monetary information from Divisia M4. This section outlines the methodology employed for estimating the system.

Let y_t be an n_1 x 1 vector of macroeconomic series and x_t be an n_2 x 1 vector of monetary variables of interest. The variables in x_t presumably provide information content about

[3] Valcarcel (2018) also conducts a disaggregated analysis but he focuses on user costs of components rather than the quantities.

monetary flows that a central bank may find useful. Similar set ups where monetary variables were included in the information block of a standard VAR were advanced by Christiano et al. (1999) for simple-sum and Keating et al. (2019) for Divisia. If variables in x_t share a common feature, then we assume it can be captured by a latent factor f_t that we then use to augment the VAR of order p for y_t as follows:

$$\begin{bmatrix} y_t \\ f_t \end{bmatrix} = c_t + A_{t,1} \begin{bmatrix} y_{t-1} \\ f_{t-1} \end{bmatrix} + ... + A_{t,p} \begin{bmatrix} y_{t-p} \\ f_{t-p} \end{bmatrix} + \omega_t \tag{3.8}$$

where c_t is an intercept, $[A_{t,1}, ..A_{t,p}]$ are time-varying VAR coefficients and ω_t is a mean-zero Gaussian disturbance term with time-varying covariance Q_t. The vector f_t contains information common to monetary variables and relates y_t and x_t as follows

$$x_t = \lambda_t^y y_t + \lambda_t^f f_t + u_t \tag{3.9}$$

where λ_t^y and λ_t^f are regression coefficients, and u_t is a vector of idiosyncratic shocks with diagonal time-varying covariance matrix V_t.

Thus, we follow the seminal work by Bernanke et al. (2005) where equation (3.9) allows us to extract a latent factor, which we interpret as a monetary services factor (MSF) from Divisia components included in x_t, and equation (3.8) models the dynamic interactions of the latent factor (MSF) with macroeconomic variables included in y_t.

Banerjee et al. (2006) show there is substantial time variation in the loadings and covariances of factor models that use both financial and macroeconomic data. This highlights the importance of allowing for time variation in Bernanke et al. (2005)-type FAVARs. Thus, the specification (3.8) - (3.9) provides for a flexible model as it allows every parameter to take on a different value each period t.

However, this specification requires a stance on the evolution of the parameters over time. The loading vectors $\lambda_t = \left((\lambda_t^y)', (\lambda_t^f)'\right)'$ and VAR coefficients $\beta_t = (c_t', vec(A_{t,1})', ..., vec(A_{t,p})')'$ evolve according to the following multivariate laws of motion

$$\lambda_t = \lambda_{t-1} + \nu_t$$
$$\beta_t = \beta_{t-1} + \eta_t \tag{3.10}$$

where $\nu_t \sim N(0, W_t)$ and $\eta_t \sim N(0, R_t)$ and $\omega_t \perp u_t \perp \nu_t \perp \eta_t$.

Bayesian estimation of FAVARs with time-varying parameters is typically implemented using Markov Chain Monte Carlo (MCMC) methods. Primiceri (2005), Del Negro and Otrok (2008) and Carriero et al. (2018), among others, provide methods based on MCMC to sample from the nonlinear multivariate joint posterior density of f_t and the remaining model parameters. Implementation is typically computationally intensive.

Additionally, given that both f_t and β_t are unobserved, a standard Kalman Filter recursion for state space models is not possible. Thus, nonlinear extensions, such as the unscented Kalman Filter (UKF) and the extended Kalman Filter (EKF) are required. However, given our time series are relatively short, we follow Koop and Korobilis (2014) dual conditionally linear filtering/smoothing algorithm.

Their method involves two steps: first, update the parameters $\theta_t \equiv (\lambda_t, \beta_t)$ given an estimate of f_t; second, update f_t conditioned on an estimate of θ_t. This conditioning allows the use of two separate linear Kalman filters/smoothers, one for θ_t and one for f_t where estimation of θ_t involves extracting $\tilde{f}_t$, the principal components estimate of f_t, based on $x_{1:t}$.

We use simulation-free variance matrix discounting methods (e.g. Quintana and West (1988)) to estimate covariances of the system.

We estimate the covariance matrices associated with the measurement equations (Q_t, V_t) using exponentially weighted moving average (EWMA) estimators, which depend on decay factors κ_1 and κ_2. Lower values of the decay factors imply that the more recent observation $t-1$, and its squared residual, take higher weight than older observations in estimating (Q_t, V_t). The EWMA method implies that an effective window of $(\kappa_1/2 - 1(\kappa_2/2 - 1))$ is used for the estimation. Primiceri (2005) and Cogley and Sargent (2005) estimate time-varying covariances of integrated stochastic volatility models in the context of macroeconomic VARs, and both highlight how their methods provide an alternative to GARCH models. The EWMA estimators we employ here are more trivial to compute while remaining an accurate approximation to an integrated GARCH approach.

Covariance matrices associated with the state equations (W_t, R_t) are estimated using the forgetting factors κ_3 and κ_4, respectively, which, according to Koop and Korobilis (2014), have a similar interpretation to the EWMA decay factors. Their forgetting factor approach suggests that an effective window of $(1/(1-\kappa_3)(1/(1-\kappa_4)))$ observations is sufficient to estimate W_t and R_t. The choice of the forgetting/decay factors can be made based on the expected amount of time variation in the parameters.[4]

The main algorithm proceeds in five steps: First, all parameters are initialized β_0, λ_0, f_0, V_0, Q_0. Second, obtain the principal component estimates of the factors $\tilde{f}_t$. Third, estimate the time-varying parameters θ_t given $\tilde{f}_t$. Fourth, estimate V_t, Q_t, R_t, and W_t using variance discounting (VD). Fifth, estimate β_t, λ_t given V_t, Q_t, R_t, and W_t using a Kalman filter smoother (KFS). Sixth, estimate the factors f_t given θ_t using a KFS.

Identification in the FAVAR is achieved in a straightforward fashion by restricting the FAVAR covariance matrix V_t to be a diagonal. This restriction ensures that the factors f_t capture movements that are common to monetary variables in x_t after removing the effect of current macroeconomic conditions through the inclusion of $\lambda_t^y y_t$ term in (3.9).

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[4]Koop and Korobilis (2014) argue that the choice of forgetting factors is similar in spirit to the choice of priors. Empirical macroeconomists frequently impose subjective priors on the degree of time variation in their parameters; see for instance the informative priors used in the TVP-VARs of Primiceri (2005) and Cogley and Sargent (2005).

3.4 Dynamic model averaging (DMA) for the estimation of a single monetary services factor (MSF)

An extraction of a latent MSF from Divisia components included in DM1, DM2, and DM4 can be achieved with a single TVP-FAVAR model contingent on a particular set of components included in x_t, all of which receive equal weight. However, if we want to allow the importance in the contribution of those components toward a single MSF indicator to vary, then iterating the TVP-FAVAR over a permutation of variables included in x_t is required. This generates multiple model specifications. With multiple models, it is common to use model selection or model averaging techniques. We follow Koop and Korobilis (2014) in allowing for the selected model to change over time, thus doing dynamic model averaging (DMA) where the weights used in the averaging process are allowed to change over time.

Let there be M_j for $j = 1, ...J$ models, each with different Divisia components that enter the MSF. This implies a different x_t for each model where a different combination of columns of x_t is set to zero. A given model M_j can be written as

$$\begin{bmatrix} y_t \\ f_t^{(j)} \end{bmatrix} = c_t + A_{t,1} \begin{bmatrix} y_{t-1} \\ f_{t-1}^{(j)} \end{bmatrix} + ... + A_{t,p} \begin{bmatrix} y_{t-p} \\ f_{t-p}^{(j)} \end{bmatrix} + \omega_t \tag{3.11}$$

$$x_t^{(j)} = \lambda_t^y y_t + \lambda_t^f f_t^{(j)} + u_t \tag{3.12}$$

where $x_t^{(j)}$ is a subset of x_t and the $f_t^{(j)}$ is the MSF implied by M_j. Given that x_t is of length n_2, there are $2^{n_2} - 1$ possible combinations of monetary variables that can be used to extract the MSF. This involves estimating many TVP regression models as described in detail by Raftery et al. (2010).

The objective is to calculate ($\pi_{t|t-1,j}$) the probability that, given available information through time $t - 1$, model j applies at time t. Once $\pi_{t|t-1,j}$ for $j = 1, ...J$ are obtained following Raftery et al. (2010) fast recursive algorithm, they can be used as weights for DMA.

Given an initialization $\pi_{0|0,j}$ for $j = 1, ...J$, the model prediction equation described in Raftery et al. (2010) is:

$$\pi_{t|t-1,j} = \frac{\pi^{\alpha}_{t|t-1,j}}{\sum_{l=1}^{J} \pi^{\alpha}_{t-1|t-1,l}} \tag{3.13}$$

where $0 < \alpha \leq 1$ is a forgetting factor that calibrates how fast should model switching occur. Lower values of α allow for an increasing switching number of Divisia components that enter the MSF each period t. For example, if $\alpha = 99$, forecast performance 20 quarters ago receives 80% as much weight as forecast performance on the previous period $t-1$. Whereas a value of $\alpha = 1$ is consistent with conventional Bayesian model averaging implemented one period at a time on an expanding window of data.

The model prediction equation (3.13) is complemented with the following model updating equation:

$$\pi_{t|t,j} = \frac{\pi_{t|t-1,j} f_j(Data_t|Data_{1:t-1})}{\sum_{l=1}^{J} \pi_{t|t-1,l} f_j(Data_t|Data_{1:t-1})} \tag{3.14}$$

where $f_j(Data_t|Data_{1:t-1})$ is a measure of fit for model j.

3.5 Data

Our quarterly sample spans 1967:Q1 to 2018:Q3. All monetary data is obtained from the CFS, which makes available the Divisia monetary aggregates as well their components. Divisia M1 (DM1) includes currency (c), demand deposits (DD), other checkable deposits (OCDs) at commercial banks, and OCDs at thrift institutions. Divisia M2 (DM2) adds the following components to DM1: savings deposits (SDs) at commercial banks, SDs at thrift institutions, retail money-market funds (RMMFs), small time deposits (STDs) at commercial banks, and STDs at thrifts. At 15 components, Divisia M4 (DM4) is the broadest monetary aggregate currently available in the US. It adds the following five monetary instruments to DM2: institutional money-market funds (IMMFs), large time deposits (LTDs), repurchase agreements (REPOs), commercial paper (CP), and 3-month T-bills.

The macroeconomic variables included are real GDP, the GDP deflator, total reserves, the federal funds rate, the monetary base, and Reuters Commodity Research Bureau (CRB) spot price index—all obtained from HAVER. We select the GDP deflator as our price index to be consistent with Christiano et al. (1999), which once constituted the standard monetary SVAR (see Ramey (2016)), as well as Keating (1992) whose baseline model we augment here. Our results were qualitatively robust to price index alternatives such as the consumer price index (CPI) and the personal consumption expenditure (PCE) index, both of which have received more attention, particularly post 1985 (see Ramey (2016)). All variables are log transformed except the interest rates. We employ the Wu and Xia (2016) shadow federal funds rate to substitute for the federal funds rate during the ZLB period. We obtain that rate from the Federal Reserve Bank of Atlanta. Using the shadow rate allows us to extend our analysis through the aftermath of the US financial crisis. However, the benefits of shadow rates are far from settled. For example, Keating et al. (2019) show that the incidence of price puzzles are exacerbated in SVARS that include various shadow prices for a modern sample. And Krippner (2019) highlights that inflation outcomes post 2008 may be sensitive to shadow rate selection.

3.6 Estimates of a monetary services factor (MSF)

A popular set of variables in parsimonious monetary VAR specifications typically include the price level, output, and a short-term interest rate. We take as an example a specification similar to Keating (1992) with these first three variables in y_t for the VAR construct in equation (3.11). Two important distinctions in our specification are worth highlighting. First, ours is a time-varying parameter approach, whereas Keating (1992) is a standard VAR. Second, Keating (1992) includes a fourth (monetary) variable—simple-sum aggregate M2—in the VAR. In our view, including simple-sum aggregates is misguided. Therefore, rather than adding a monetary variable in fourth place in the VAR, we leave the main VAR component "as is" with price, output, and interest rates, and augment it with a factor (x_t) component in equation (3.11) that includes components of Divisia aggregates DM1, DM2, or DM4 and from which we extract a common MSF.

Given that there are $2^{n_2} - 1$ possible combinations of monetary variables that can be used to extract the MSF—while we want to distinguish between different DIVISIA aggregates—we estimate a total of 93 TVP-FAVAR specifications.

First, we extract a MSF from a DMA, that follows equation (3.12), from 31 different TVP-FAVARs that rotate over permutations of the five components—currency (c), demand deposits (DD), other checkable deposits (OCDs) at commercial banks, and OCDs at thrift institutions—included in DM1. This estimate is shown in panel (a) of Figure 3.2.

We then extract a second MSF estimate based on the five components that are included in DM2 (but excluded from DM1), namely: savings deposits (SDs) at commercial banks, SDs at thrift institutions, retail money-market funds (RMMFs), small time deposits (STDs) at commercial banks, and STDs at thrifts. Panel (b) of Figure 3.2 shows this estimate.

Finally, we consider components that are exclusive to DM4: institutional money-market funds (IMMFs), large time deposits (LTDs), repurchase agreements (REPOs), commercial paper (CP), and 3-month T-bills (TB3) in producing the MSF denoted in Panel (c) of Figure 3.2. Inspection of Figure 3.2 reveals some sensible features of these MSFs. First, the MSF based on components from the narrower aggregate (DM1) seems to correlate more closely with the behavior of short-term interest rates. The high interest rate period of the late 1970s to early 1980s renders higher degrees of monetary services. In a high interest rate environment, the opportunity cost of holding liquid assets increases and, with it, the monetary services that interest-bearing deposits yield. Second, the estimate of the MSF based on the components exclusive to the broader aggregate (DM4) exhibit a substantially higher degree of volatility. Components in DM4, such as repurchase agreements, commercial paper, and T-bills have traditionally rendered higher and more volatile yields than bank deposits. This would seem to justify the higher volatility of the DM4-based MSF factor over the DM1-based MSF factor. Finally, Valcarcel (2018) shows higher degree of correlation between the federal funds rate and prices (or more precisely user costs) of components of DM1 than those of DM4. Therefore, it seems sensible for a MSF that is extracted from the narrower DM1 to bear a closer resemblance to short-term rates than one extracted from broader aggregates, such as DM4.

3.7 The aggregate effects of MSF-augmented monetary policy shocks

This section outlines results from the FAVAR in (3.8) where $y_t = [GDP_t, P_t, PCom_t, R_t]'$ is augmented with an estimated single factor (f_t), which we interpret as the MSF, and is extracted from components in DM1, DM2, or DM4 as described in the previous section. Figure 3.3 shows responses for each horizon averaged over all t to an expansionary monetary policy shock. Output responds in the expected direction to a surprise reduction in the federal funds rate. However, it shows a modest but not significant liquidity puzzle and, importantly, it shows a strong price puzzle—despite inclusion of a commodity price variable, which was advocated by Christiano et al. (1999) as an *ad hoc* solution to the price puzzle. This puzzle is quite prevalent in the VAR literature. The MSF extracted from DM1 responds negatively and significantly to an expansionary monetary policy shock. Figures 3.4 and 3.5 replace the MSF estimated from DM1 components with ones estimated from DM2 and DM4, respectively. Conclusions are not sensitive to the choice of MSF.

However, averaging the time-varying responses for each horizon aggregates away possibly important structural changes in the transmission and propagation of shocks. Therefore, we report time-varying responses of the macroeconomic variables to an unexpected shock in the short-term interest rate over the sample. In addition, we include the responses of the MSF estimate when the MSF is extracted from DM1 components, DM2 components, or DM4 components.

Figure 3.6 shows the first-year responses (quarter 1 through quarter 4 post shock) to an exogenous reduction in the short-term policy rate. Panel (a) of this figure shows the responses of output, the price level, commodity prices, the federal funds rate, total reserves, and the MSF extracted from components in DM1. Panels (b) and (c) replace the DM1-MSF with an MSF extracted from DM2 or DM4 components, respectively. The federal funds rate response to its own shock exhibits a monotonic reduction over time, except for two periods associated with active monetary policy reactions—the Volcker disinflation period and the ensuing recession of 1980-1982, and the Bernanke ZLB period following the US Financial Crisis of 2007. The higher magnitude response peaks prior to the onset of the Great Moderation in the US (often identified as beginning in 1984). The gradual reduction on the importance of this shock between 1984 and 2008 is also consistent with a gradual monetary policy stance from a more forward-looking central bank in the moderated environment of the 1990s and early 2000s. Then, a second local peak, in the magnitude of the response, is estimated to occur around 2008, consistent with an active monetary policy reaction to deteriorating economic conditions in the US. It is worth mentioning that we impose an exogenous decrease in the federal funds rate throughout our sample, yet the first peak is identified to occur following an active Federal Reserve contraction of the early 1980s and the second peak is identified following an active expansion in 2008. Both of these instances arguably constitute the most active periods of Federal Reserve policy post WWII.

Unsurprisingly, the output response is relatively muted within the first year post shock, consistent with the standard New Keynesian prediction. The commodity price index response experiences qualitative variation over time, which is to be expected given inherent volatility in commodity prices. These have been typically included (with mixed results as it is highlighted by Keating et al. (2014)) in VAR modeling in order to address puzzling responses of the price level that tend to recur.

Importantly, a substantial price puzzle emerges even at this short horizon and despite inclusion of the aforementioned commodity price index. Interestingly, in the early part of the sample, the magnitude of the perverse increase in the price level following an increase in the short-term rate is reduced isomorphically as we replace MSF-DM1 with MSF-DM2 or MSF-DM4. However, the magnitude of the price level response at the end of the sample is not sensitive to which factor is included.[5]

Finally, the last graph on the southeast quadrant of each panel shows the MSF response to the monetary policy shock. Overall, monetary services decrease following reductions in the federal funds rate. This is sensible if co-movement in interest rates bind. If drops in the short-term rate lead to an expectation of decreasing returns in other money markets, this may lead to reductions in the demand for assets that render monetary services. However, these responses exhibit considerable time variation. The responses are consistently larger (in absolute value) earlier in the sample, when interest rates were typically higher, and are substantially lower since 2008—a low-interest rate period.

Figure 3.7 shows time-varying responses of the same three FAVAR specifications for the medium term (five through 12 quarters post shock). At this longer horizon, the output response is now sensibly negative. The response of total reserves is also sensible as it follows the massive expansion of reserves from the Fed large scale asset purchases (LSAPs) and quantitative easing (QE) programs. The price puzzle persists and the rest of the responses remain similar to their shorter horizon counterparts.

[5]The post-2008 period is one of compression in interest rates associated with the components of DM4 (see Mattson and Valcarcel (2016)). If compression in interest rates portends compression in the different information contents of various Divisia aggregates, this could also reduce the pass-through.

Figure 3.8 shows the overall time-varying responses over all horizons. These responses highlight that output and the price level move in opposite directions to an expansionary monetary policy shock even when including information from both commodity prices and monetary services. The ensuing strong price puzzle is consistent with modern findings by others (see Haan et al. (2009) and Keating et al. (2019), among others.) Interestingly, the magnitude of the puzzle is ameliorated with the inclusion of the MSF as we climb up the Divisia component composition from narrower to broader aggregates.

3.8 Substitution in the monetary transmission of Divisia components

The FAVAR specification estimates a single unobservable MSF factor f_t from observable Divisia components. In this section, we estimate impulse responses directly from the multiple components included in the MSF. An advantage of this approach is that linking the factor block to observables directly renders more straightforward interpretation of the effects of monetary transmission. It is also worth mentioning that all Divisia component responses are completely unrestricted.

Figure 3.9 shows responses of the components in DM1 for each horizon averaged over all t to an expansionary monetary policy shock. An exogenous federal funds rate decrease looks to have little effect, on average, on the largest components of DM1: currency and demand deposits. There is a modest short-run effect on traveler's checks. While checkable deposits at commercial banks do not seem responsive, there is, however, a large negative response of other checkable deposits at thrifts. This suggests that rates in the smaller, more segmented, thrift and credit union markets might be slower to adjust generating a lower demand for these deposits than in the much larger, more competitive, faster-moving commercial bank sector.

Figure 3.10 shows responses of components that are excluded from DM1 and included in DM2. Generally, these components seem more responsive to monetary policy shocks. These components are associated with typically higher yields rendering higher monetary services and lower degrees of liquidity. If reductions in the short-term rate were expected to pass through to rates that some of these components yield, then a liquidity effect would explain a positive response of these monetary balances. On the other hand, if interest rates of some of these components are less sensitive to federal funds rate fluctuations, then spreads across these components would generate substitution effects. Ensuing increases in demand for some monetary assets following monetary policy shocks may lead to opposite effects in others.

Savings, both in commercial banks and thrifts, increase following a monetary policy expansion, whereas retail money market funds and small time deposits respond negatively. As the latter may be more tightly associated with financial investment, perhaps the reduction in the short-term rate lowers expected returns in money markets, leading to a substitution effect away from money markets and into household savings.

Figure 3.11 shows responses of components that are excluded from DM2 and included in DM4. Qualitatively, institutional money markets, T-bills, and repurchase agreements respond similarly to savings following an expansionary monetary policy shock. Conversely, large time deposits respond in the same direction as small time deposits and retail money markets to monetary easing. The response of commercial paper is positive but not statistically significant for the sample.

A fervent subscriber to *both* the expectations hypothesis of the term structure of interest rates and the principle of the liquidity effect of monetary policy would ascribe to the following mechanism: First, co-movement in interest rates leads a given federal funds rate reduction to pass-through to rates of other monetary assets. Second, lower rates in other asset classes would lead to higher demand for those assets. If the interest rate pass-through is complete and uniform across asset classes, then absent other shocks we would expect an increase in demand of all monetary assets across the board. This would be a wholesale liquidity effect in money markets. The Federal Reserve enacts expansionary monetary policy, thereby increasing liquidity in money markets.

Furthermore, if pass-through were asymmetric so that interest rates of some monetary assets increased following a reduction in the federal funds rate, then differential responses of these monetary assets could still be congruent with a liquidity effect mechanism. Thus, monetary assets whose interest rate experienced a decrease following monetary policy easing would respond positively to the policy shock, whereas a monetary asset whose interest rate increased following a federal funds rate drop would respond negatively to the policy shock. Nevertheless, asymmetric pass-through runs counter to the positive interest rate comovement typically found in the data, and violates term structure of interest rate theories, such as the expectation hypothesis and liquidity preference framework.

However, asymmetric interest rate pass-through is not requisite for the differential effect of monetary policy shocks on these assets. So long as the degree of pass-through is not uniform over the asset classes, then the generation of interest rate spreads could lead to differential responses.

Overall, we document qualitatively different responses of these monetary assets to federal funds rate reductions, which suggests that some degree of substitution across these assets takes place following monetary policy shocks. For example, the negative response of STDs at thrifts and OCDs at thrifts, to a federal funds rate drop could ensue even absent quantitatively similar decreases in their own yields. If, say, the yields in both STDs and OCDs decreased by less than the federal funds rate drop *and* the yield reduction in STDs was of a lower magnitude than the yield in OCDs, then investors might substitute away from the latter and into the former.

We next document the extent to which these differential responses across the monetary assets included in DM1, DM2, and DM4 vary over time. Figure 3.12 shows the first year response (quarter one through four) of various monetary assets to an exogenous increase in the federal funds rate (the red line at the bottom right of each panel). Panel (a) shows the responses of the assets included in DM1, panel (b) includes those assets included in DM2 and not DM1, and panel (c) includes assets in DM4 not included in DM2.

While Figure 3.9 showed negligible responses of most DM1 components to monetary policy shocks on average, the corresponding time-varying responses in Panel (a) of Figure 3.12 uncover some changing dynamics. Both currency and demand deposits show substantial increases to monetary policy shocks following the 2007 Financial Crisis. Furthermore, the magnitudes of these responses at the end of the sample suggest a reduction in the currency-to-deposit ratio of households following the 2008 Recession. This is consistent with evidence of a reduction in this ratio occurring following the expansionary policy the Federal Reserve undertook in the aftermath of the Financial Crisis—which was more than offset by the substantial increase in the reserves-to-deposits ratio that resulted in a crash of the money multiplier over this period. The response of OCDs at commercial banks seems diametrically opposed to the response of OCDs at thrifts. However, the magnitude of both these responses have monotonically decreased over the sample—faster in OCDs at commercial banks. The response of OCDs at commercial banks became muted since onset of the Great Moderation. The Financial Crisis of 2007 and the unconventional policy period that followed did not seem to have a material impact on the responses of OCDs at commercial banks and thrifts, but they led to lower OCDs at thrifts.

Panel (b) of Figure 3.12 shows that the short-run positive responses of savings at commercial banks, and at thrift institutions, to monetary policy shocks have become less pronounced since the mid-1980s. In the short run, retail money markets respond negatively to expansionary monetary policy shocks over the sample.

Panel (c) of Figure 3.12 shows that IMMFs, repurchase agreements, and T-bills respond positively in the short run to expansionary policy shocks, whereas LTDs respond in the same direction to the federal funds rate.

We next explore the longer-term responses to exogenous reductions in the federal funds rate. Figure 3.13 shows the median time-varying responses between the fifth and twelfth quarter post shock. Qualitatively, the responses in Panel (a) of this figure are similar to those of Panel (a) in Figure 3.12. The response of currency during the 1990s is now positive and the magnitude response following 2007 continues to increase after the short-run effect at display in the previous chart.

Panel (b) of Figure 3.13 shows that the expansionary effect of the federal funds rate drop continues to exert the same influence on the components of DM2 after the short-run response. This is evidenced by the higher magnitudes but same sign of the responses in Panel (b) of Figure 3.13 as those in Panel (b) of Figure 3.12.

Panel (c) of Figure 3.13 shows that the direction of the responses of DM4 components continue their initial movement displayed in the previous chart. The response of IMMFs is now more pronounced in the post 1980s period. Additionally, commercial paper responds positively to expansionary monetary policy shocks—subsequently turning significantly negative in the aftermath of the Financial Crisis.

Finally, we estimate the overall responses of DM1, DM2, and DM4 to expansionary monetary policy shocks. Figure 3.14 shows the median—over all horizons (up to 20 quarters) post shock—time-varying responses. Panel (a) of Figure 3.14 shows that while demand deposits do not respond significantly for most of the pre-2008 sample, currency responds largely positively between the mid 1980s and the mid 2000s, exhibiting a straightforward liquidity effect. Then, the response turns significantly negative in the run up to the Financial Crisis before returning significantly positive during the ZLB period and beyond. Reductions in the federal funds rate seem to pass through to OCDs at thrift institutions, whereas the positive response of OCDs at commercial banks ceases to bind since the mid 1990s.

Panel (b) of Figure 3.14 shows savings increase following expansionary shocks. The response of savings at thrift institutions are more muted than those of savings at commercial banks following the ZLB period. In stark contrast are the responses of STDs whose negative response to expansionary monetary policy shocks became much more pronounced since the aftermath of the Financial Crisis. RMMFs provide a middle ground in that the response is negative—similar to the STDs response—but the magnitude monotonically decreases as it progresses through the sample—similar to the savings responses.

Panel (c) of Figure 3.14 shows LTDs generally move in the same direction in response to exogenous federal funds rate drops, whereas IMMFs and repurchase agreements by and large move in the opposite direction. Finally, the response of treasury bills to expansionary monetary policy shocks dramatically increases following the 2007 Financial Crisis. This response is probably driven by the massive accommodative stance of both conventional and unconventional monetary policy during the period. Conversely, commercial paper responds negatively to the same shocks since the mid 2000s, and the negative response became more pronounced during the ZLB period and beyond. CP has been typically used by firms for the near-term financing of operating expenses (e.g. payroll). Our results suggest that the easing of short-term rates in the post 2008 period made other substitutes for firms to borrow in the very short term viable.

3.9 Concluding Remarks

There is a substantial and growing literature that investigates the relationship between monetary policy and properly measured monetary aggregates known as Divisia (DM) indices. Much of the recent empirical work in this area has focused on Divisia at various levels of aggregation, with DM2 receiving perhaps the most interest, and the broadest DM4 measure garnering increasing consideration of late. There has been far less attention committed to a more disaggregated empirical investigation of the composition of Divisia—what little there is available thus far has mostly focused on movements in the price duals or user costs. This study constitutes a first attempt to document transmission effects of short-term rates on components of Divisia quantity aggregates.

We find considerable time variation in the transmission of shocks in the short term rate onto monetary balances reflected in DM1, DM2, and DM4. Furthermore, there are marked qualitative differences in the responses of various monetary assets, which indicates the possibility of important substitution effects. For example, we find that currency, savings, OCDs at commercial banks, IMMFs, and repurchase agreements *generally* respond positively to exogenous drops in short-term rates. Conversely, OCDs at thrifts, RMMFs, STDs at commercial banks, and LTDs by and large respond negatively to expansionary monetary policy shocks.

The post 2008 period seems to exert a substantial change in the response of many monetary assets. Currency, demand deposits, and repurchase agreements increase substantially, and the responses of T-bills are raised dramatically during this period. The magnitude response also increases meaningfully—but in the opposite direction—for STDs, both at commercial banks *and* thrifts, as well as LTDs and commercial paper. The only response whose magnitude seems to reduce substantially following the ZLB period is IMMFs. This would seem to be explained by a *flight-to-safety* effect on behalf of institutional investors toward an increase in treasury holdings.

Furthermore, our estimated monetary service factors show more volatility at higher levels of aggregation and seem to more closely mirror the shape of short-term interest rates at lower levels of aggregation. Both of these features seem sensible.

Finally, an aggregate model shows a delayed reaction of economic activity, both in GDP and the price level, to monetary shocks. Our estimates find a strongly significant price puzzle, which is endemic in the monetary VAR literature. The effects of exogenous monetary policy shocks seem to elicit much larger responses on economic activity in the 1970s and 1980s than they do more recently. This seems consistent with the notion that the Federal Reserve has become less passive and more forward-looking since the mid-1980s. It is likely that higher degrees of fine-tuning and a more gradual management of the short-term interest rate has led to higher degrees of anticipation of the monetary policy stance by financial markets. While the 2007 Financial Crisis brought out an aggressive Federal Reserve response—and our results imply it had important effects on money markets—a concerted effort on minimizing uncertainty associated with the policy response (e.g. forward guidance and large scale asset purchases) would reduce the effect of unanticipated movements on the federal funds rate. Our results are consistent with the massive response of reserves during this period.

Overall, we document important time variation in the transmission of short-term rates onto money markets. We show that financial and monetary markets reacted strongly to Federal Reserve policy post 2007 even while the response of economic activity remained slower and perhaps more muted. The strong monetary response not only varied quantitatively over time, but qualitatively across asset classes. If the monetary transmission mechanism exhibits both quantitative and qualitative variation over time, then, rather than a unified textbook prediction, more granular work is needed in this line of research.

3.10 Appendix for Chapter 3: Figures

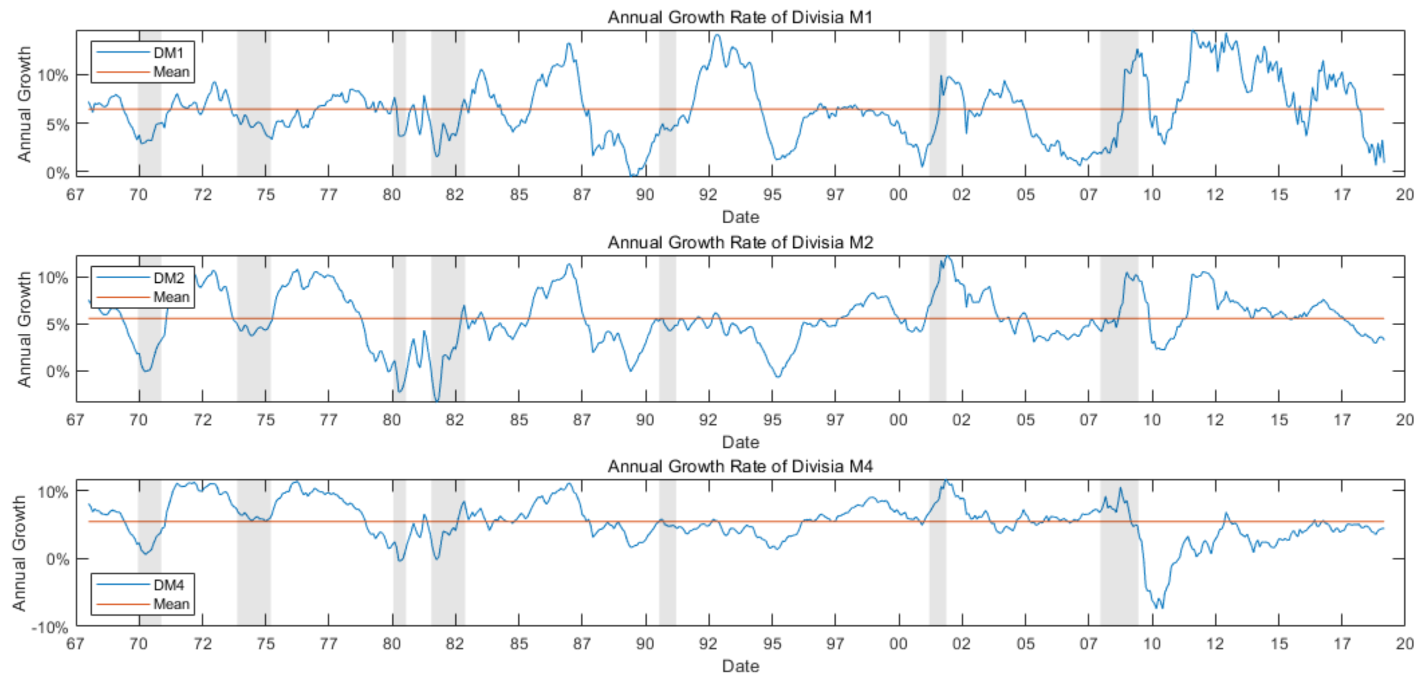
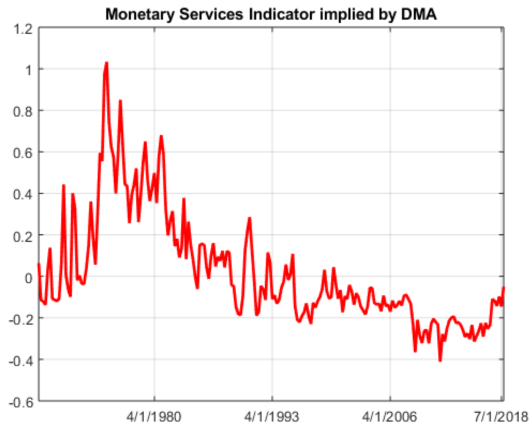
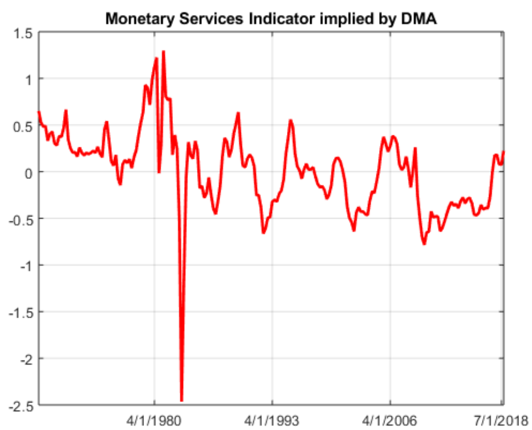


Figure 3.1: Annualized Growth Rates of DM1, DM2, and DM4 Divisia Indices

(a) MSF Estimated Factor: DM1



(b) MSF Estimated Factor: DM2



(c) MSF Estimated Factor: DM4

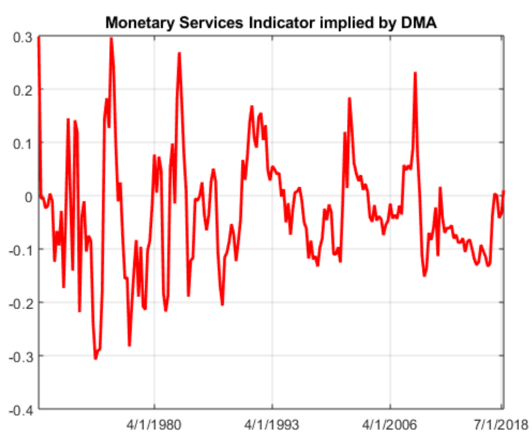


Figure 3.2: Dynamic Model Averaging (DMA) Estimation of Monetary Service Factor (MSF) by cycling through components in DM1, DM2, or DM4.

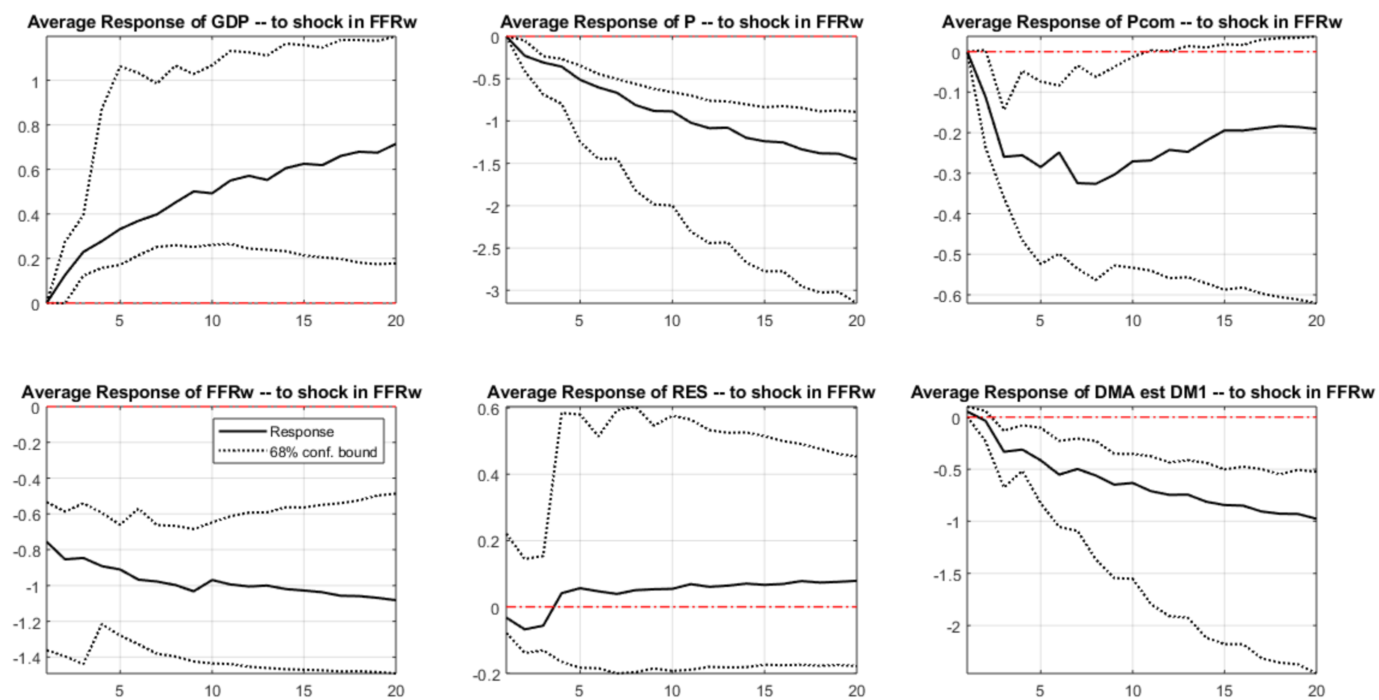


Figure 3.3: Avg. Responses to 1 std reduction in the federal funds rate. DM1 explanatory factor

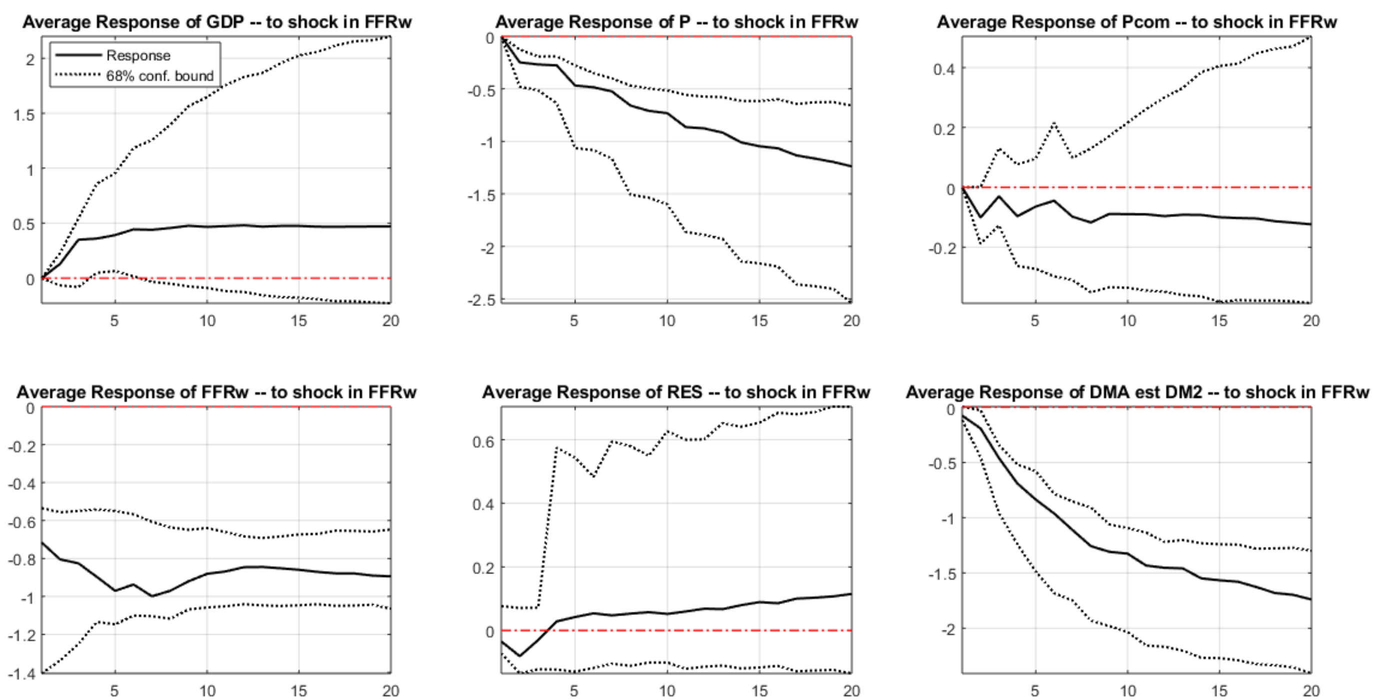


Figure 3.4: Avg. Responses to 1 std reduction in the federal funds rate. DM2 explanatory factor

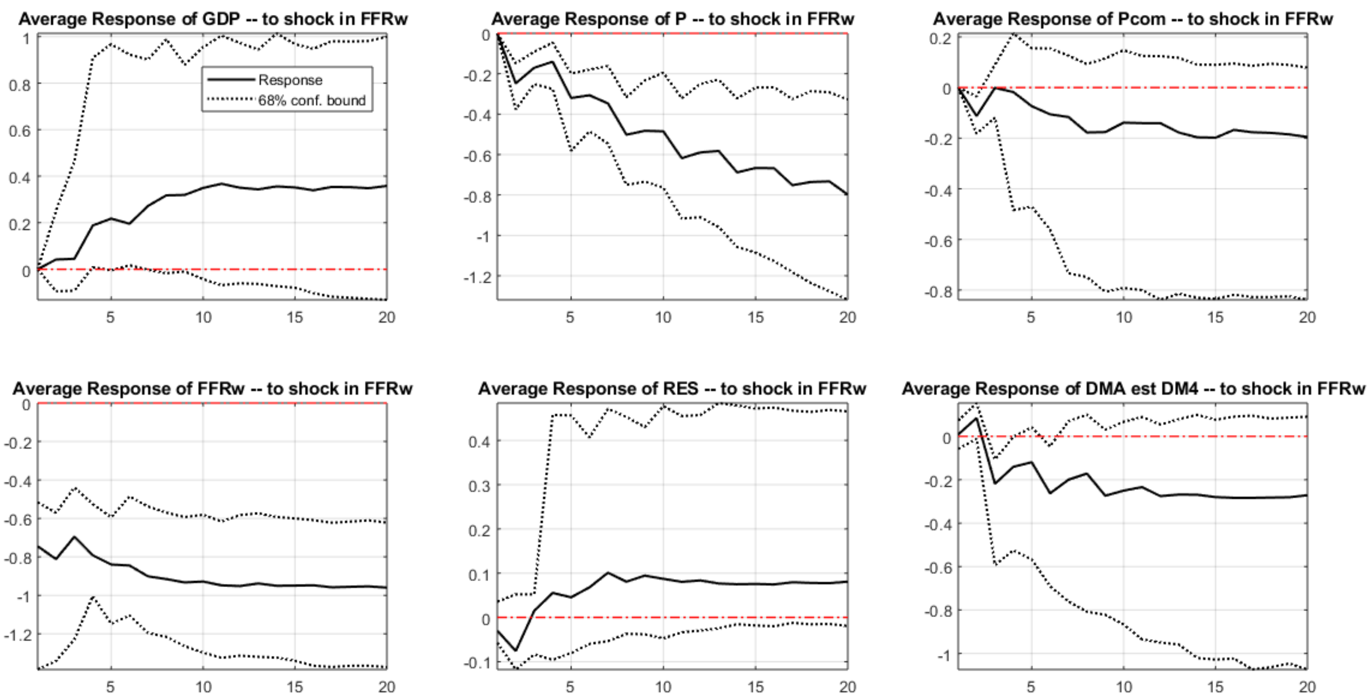
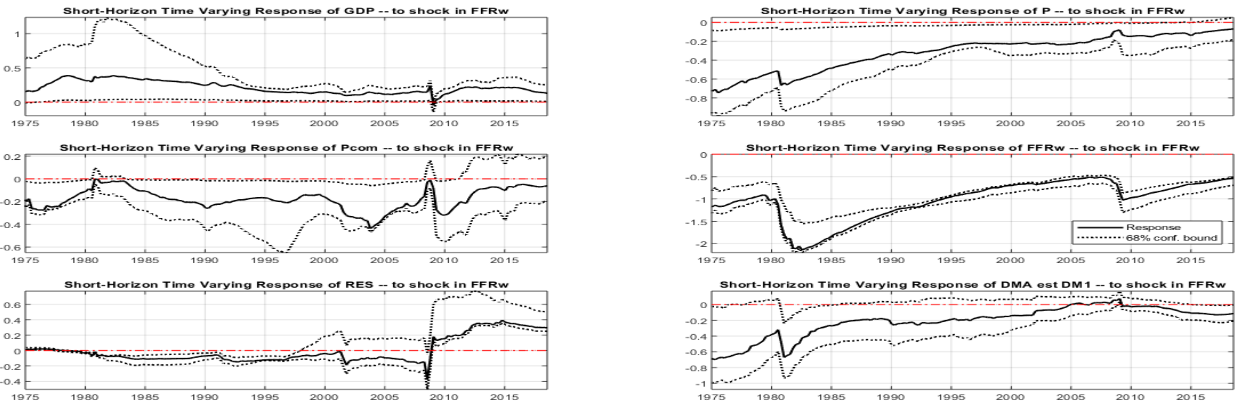
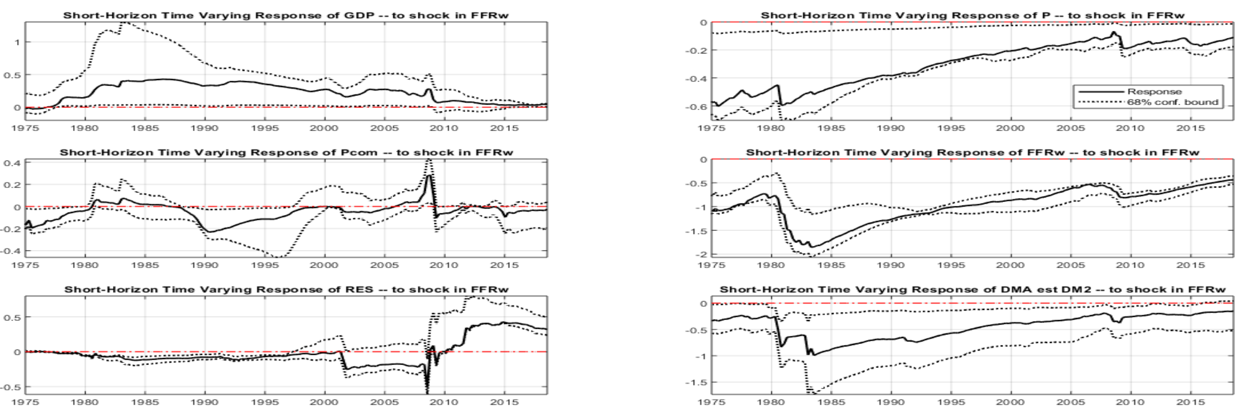


Figure 3.5: Avg. Responses to 1 std reduction in the federal funds rate. DM4 explanatory factor

(a) MSF Factor: DM1



(b) MSF Factor: DM2



(c) MSF Factor: DM4

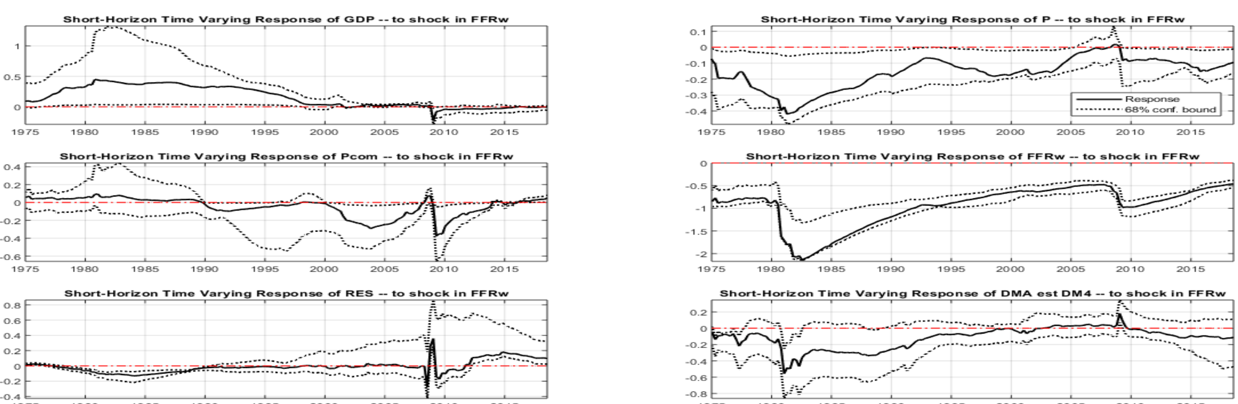
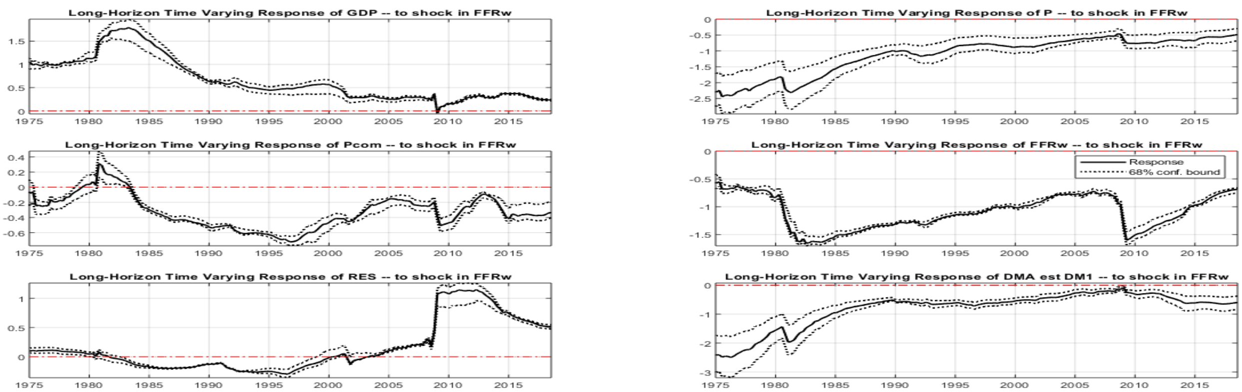
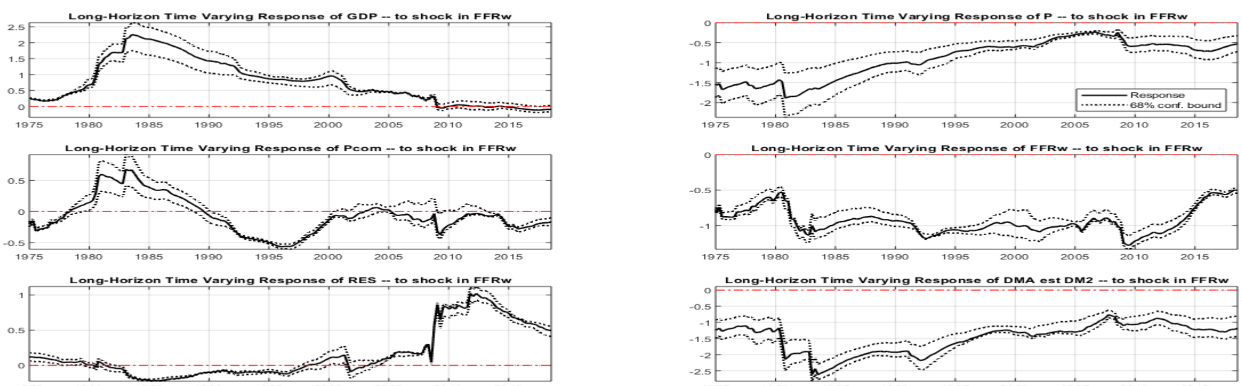


Figure 3.6: First-Year Responses to Exogenous Expansionary Monetary Policy Shocks

(a) MSF Factor: DM1



(b) MSF Factor: DM2



(c) MSF Factor: DM4

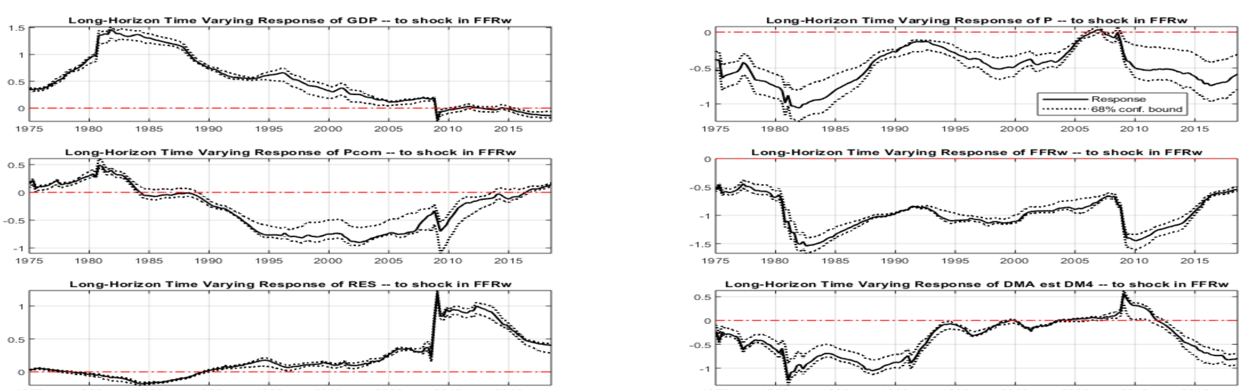
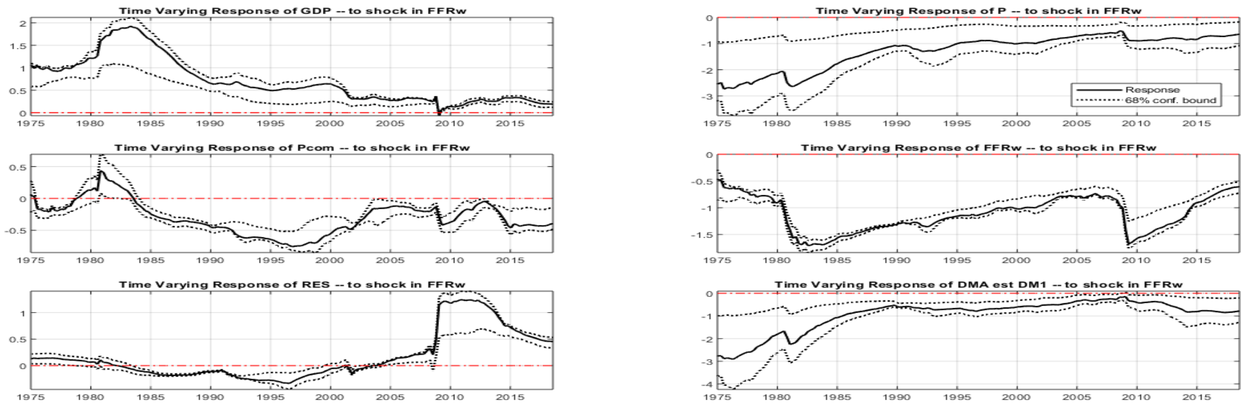
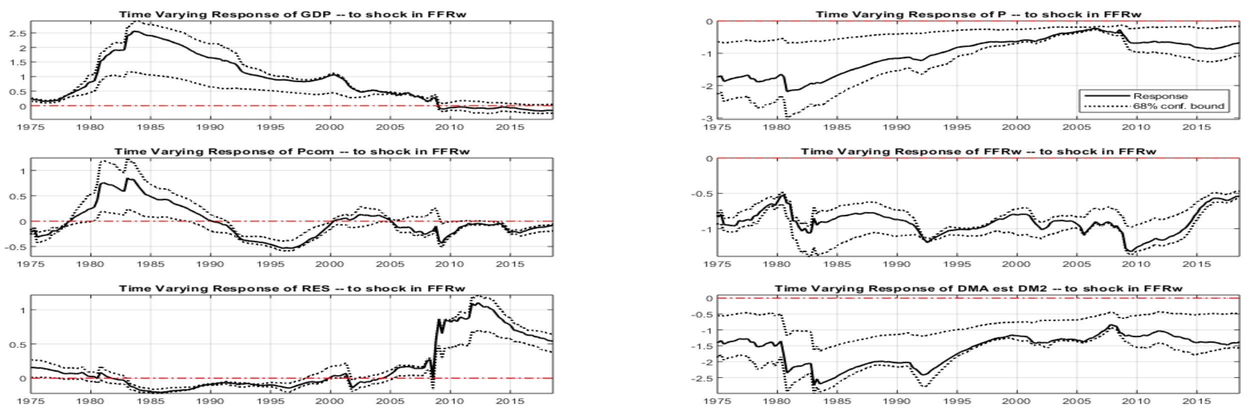


Figure 3.7: Long-Term Responses to Exogenous Expansionary Monetary Policy Shocks

(a) MSF Factor: DM1



(b) MSF Factor: DM2



(c) MSF Factor: DM4

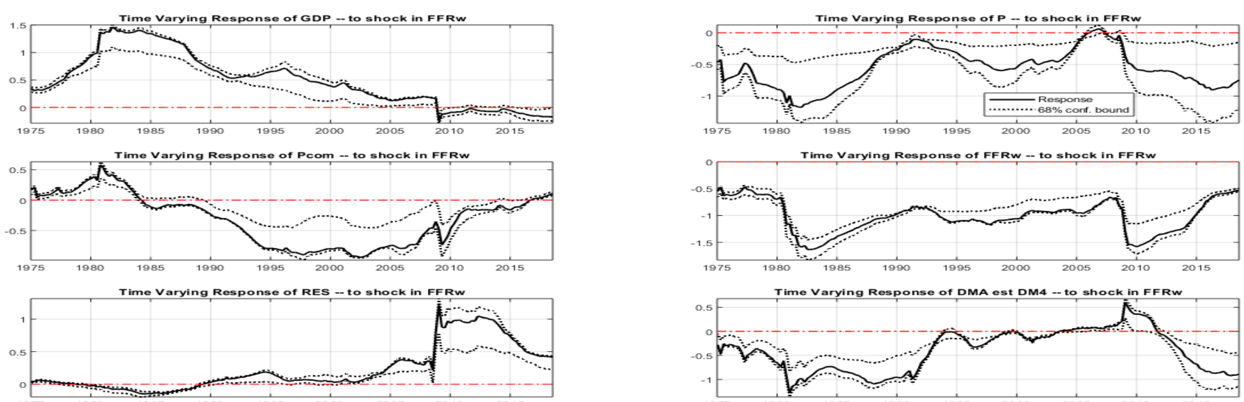


Figure 3.8: Time-Varying Responses to Exogenous Expansionary Monetary Policy Shocks

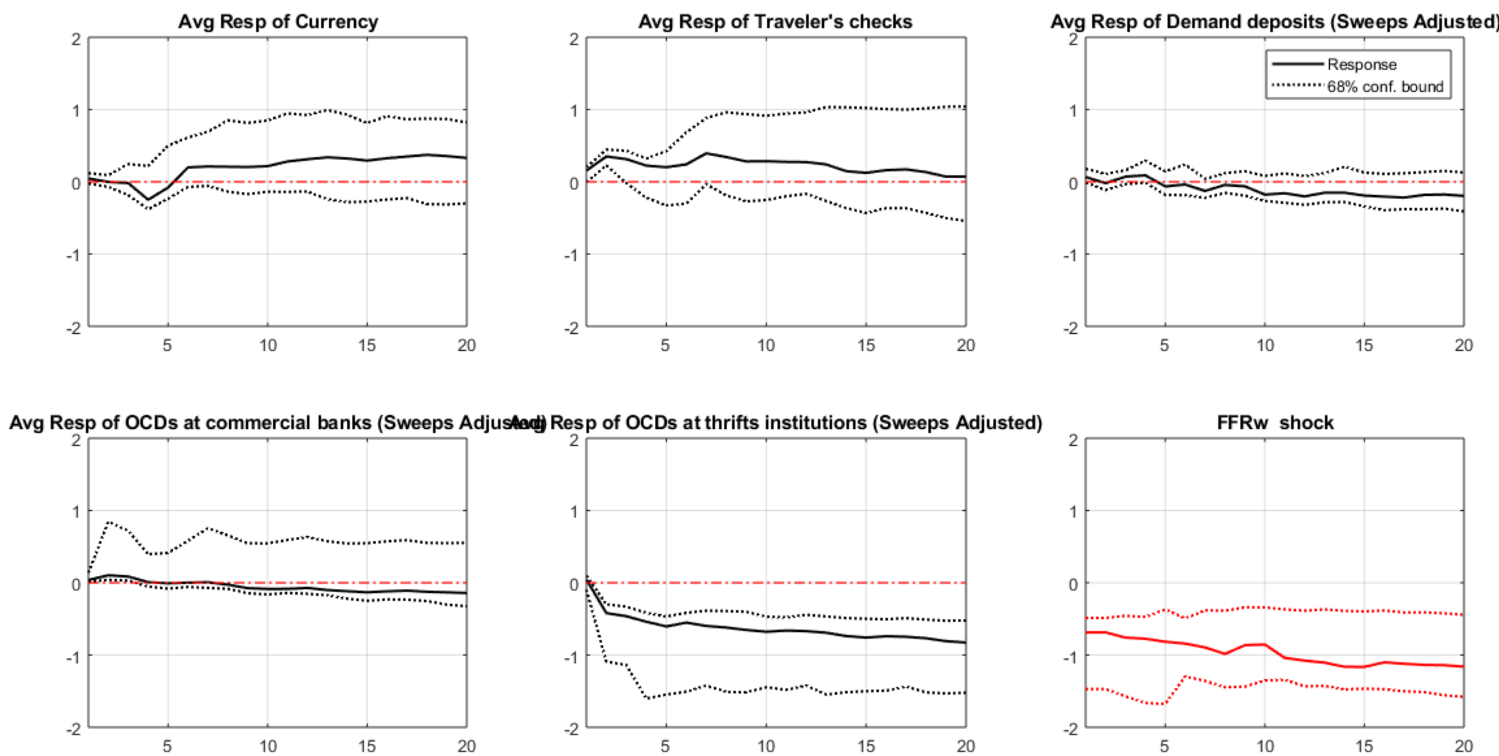


Figure 3.9: Avg. Component Responses to 1 std decrease in the Federal Funds rate: DM1

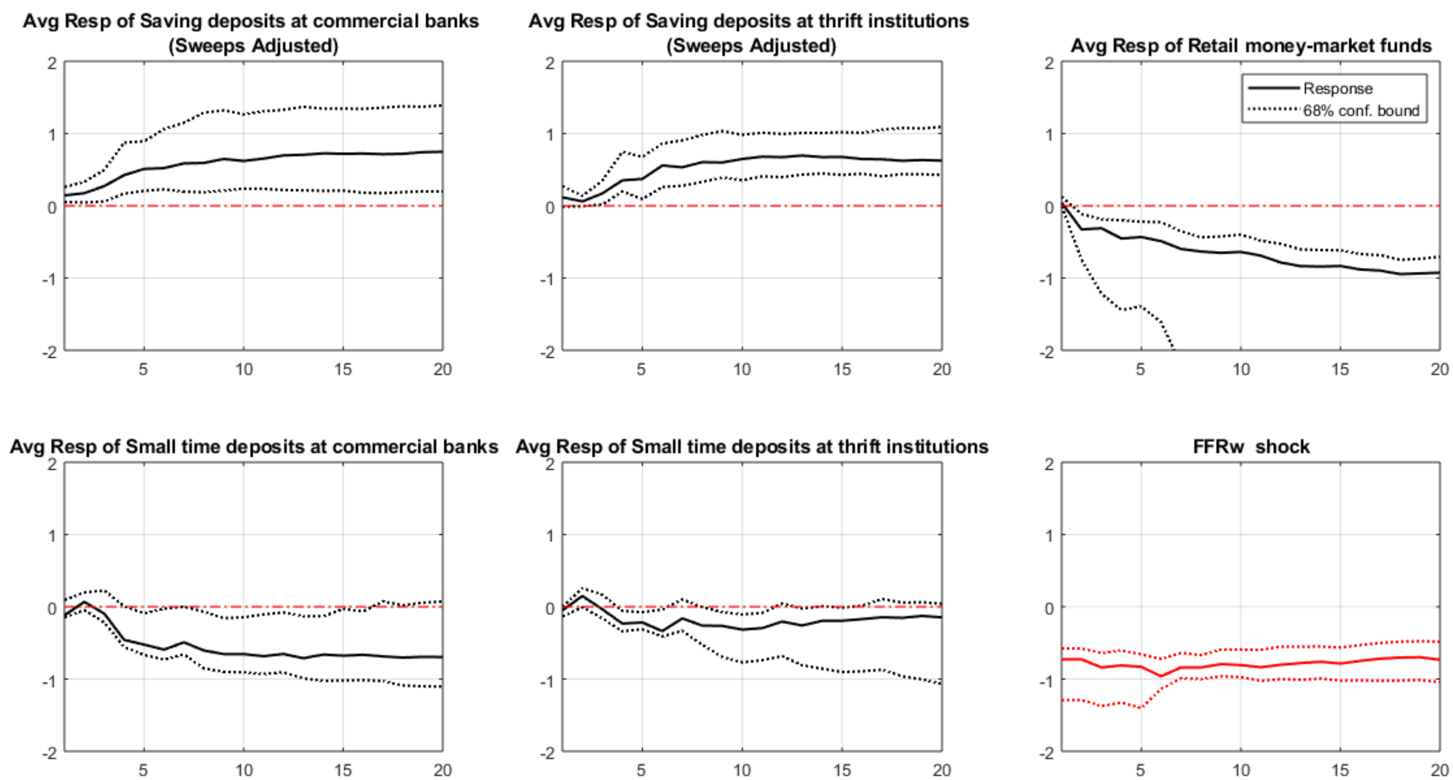


Figure 3.10: Avg. Component Responses to 1 std decrease in the Federal Funds rate: DM2

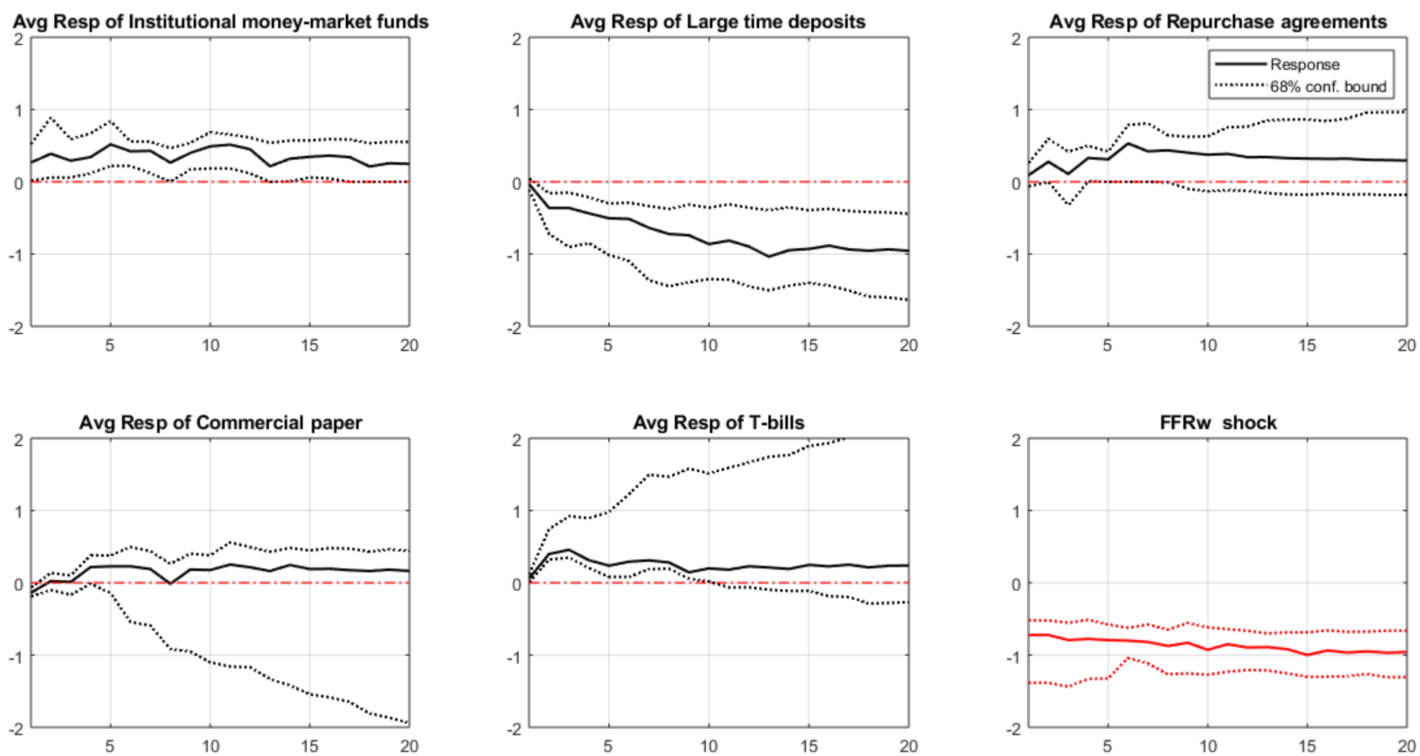
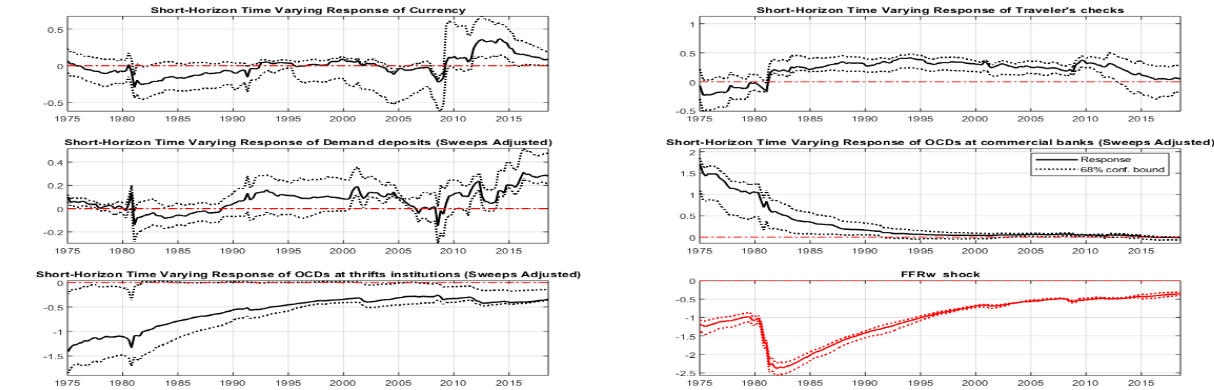
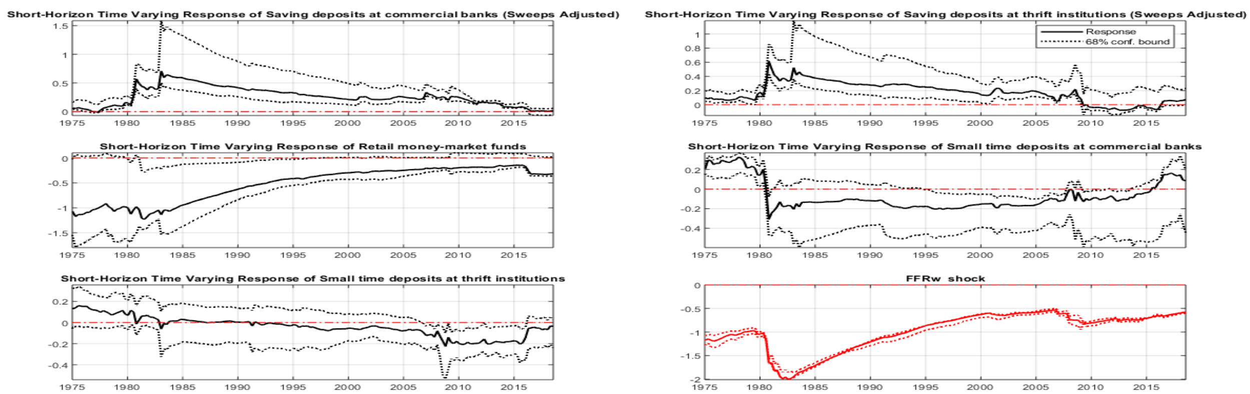


Figure 3.11: Avg. Component Responses to 1 std decrease in the Federal Funds rate: DM4

(a) DM1 *components*



(b) DM2 *components*



(c) DM4 *components*

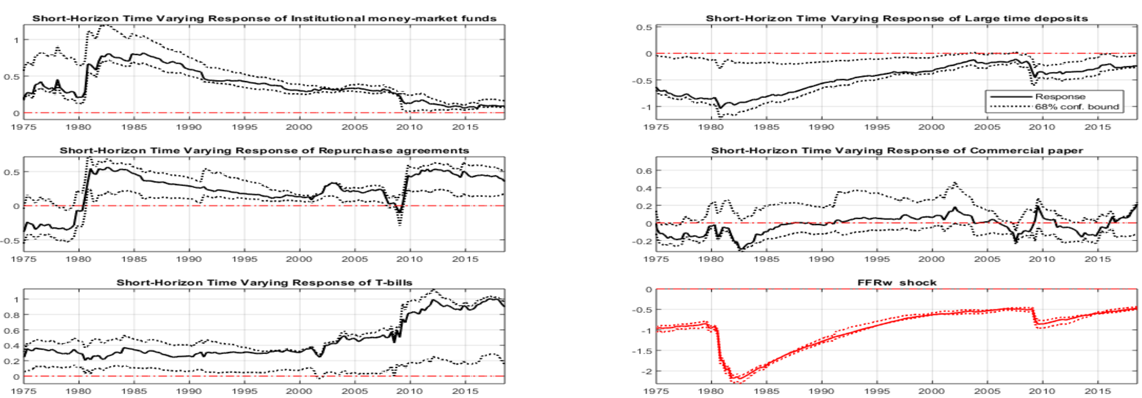
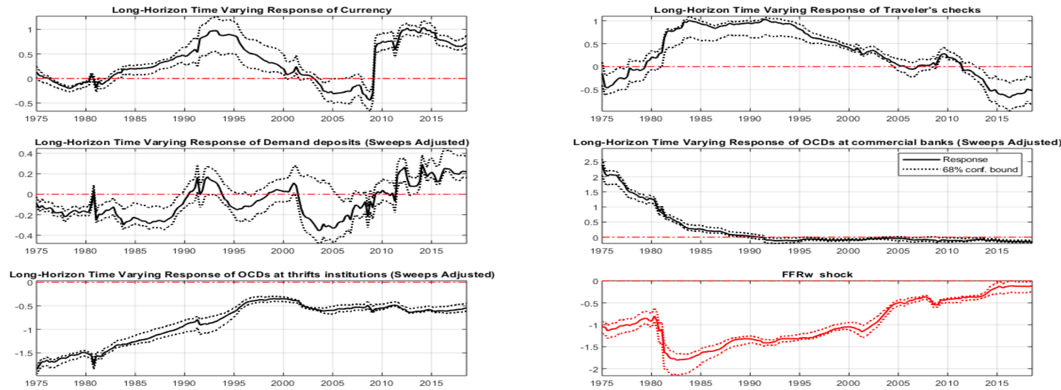
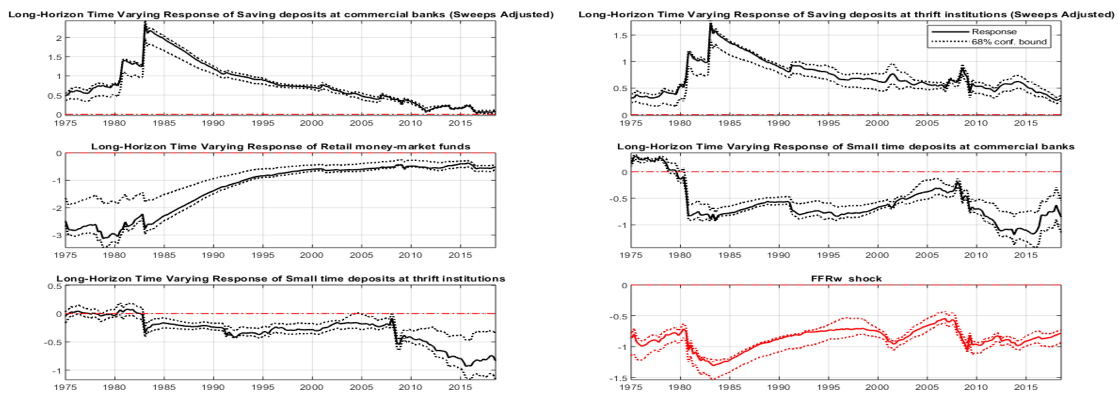


Figure 3.12: First-Year Divisia Component Responses to Exogenous Expansionary Monetary Policy Shocks

(a) DM1 *components*



(b) DM2 *components*



(c) DM4 *components*

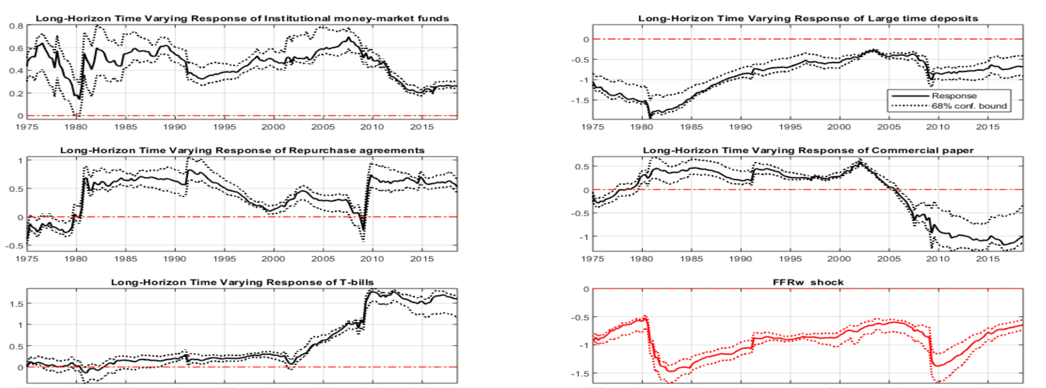
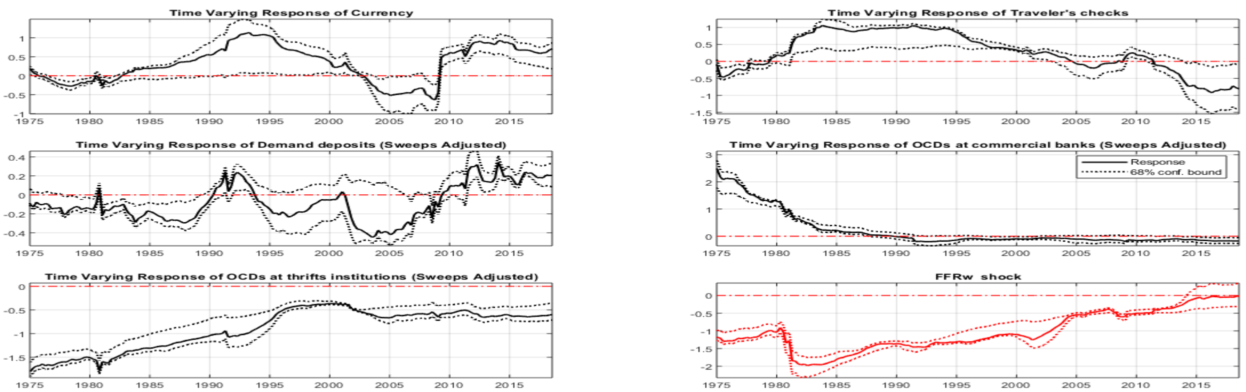
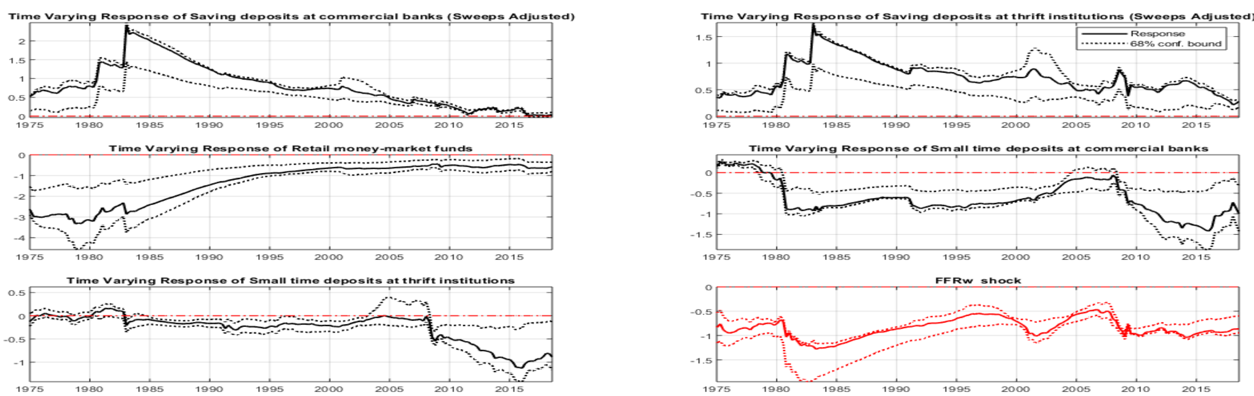


Figure 3.13: Long Term Divisia Component Responses to Exogenous Expansionary Monetary Policy Shocks

(a) DM1 *components*



(b) DM2 *components*



(c) DM4 *components*

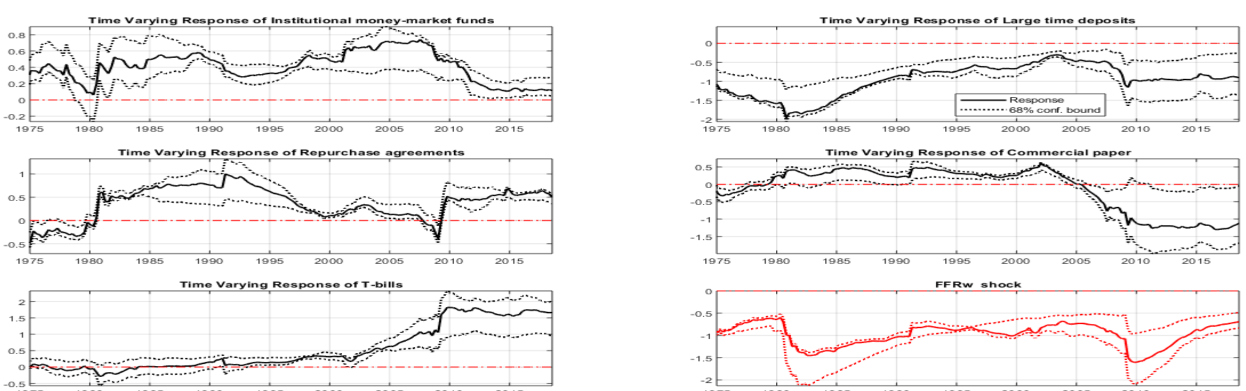


Figure 3.14: Time-Varying Divisia Component Responses to Exogenous Expansionary Monetary Policy Shocks

CHAPTER 4

CONCLUSION

The second chapter considers fluctuations of a 10-year real rate to indicate the monetary policy stance in a structural VAR model. The monetary policy shocks are identified via two external instruments. Monetary policy shocks identified by unexpected changes in the policy rate do not drive significant movements in financial frictions and output. In contrast, monetary policy shocks identified by Unexpected changes in expected volatility of the long-term Treasury yield drive the large swings of financial frictions and output.

The empirical results suggest that the interest rate channel seems a "blind alley", while the risk-taking channel is taking effect. In terms of the impact on the real economy, the cost-of-capital effect seems questionable, but the financial intermediation plays a critical role in the transmission. As an answer to whether monetary policy affects economic activities, the monetary policy transmission to the real economy is effective if we look at the risk-side implication.

The contribution is two-folded. First, this study generates the first event study measure of the risk-side implication of monetary policy announcements. Second, it supplements the scarce empirical evidence for the validity of the risk-taking channel.

The third chapter constitutes a first attempt to document transmission effects of short-term rates on components of Divisia quantity aggregates.

On average, the substitution effect among monetary assets seems dominant, in which the interest rate pass-through is effective among most monetary assets, and lower investment returns lead to lower quantities demanded. This effect justifies the mild liquidity puzzle in the responses of MSFs. Specifically, the monetary assets preferred by households generally show clear liquidity effects. Declines in holding costs look to be associated with increasing demand in those money markets. We show evidence of some substitution effects in money markets that are typically preferred by investors and firms. As to those non-zero-maturity monetary assets, risk factors, such as the issuer's creditworthiness and collateralization, are of investors' concern.

For future exploration, we show a significant price puzzle even when incorporating the information content in commodity prices and latent monetary service factors. However, this is mitigated when including MSFs extracted from a higher aggregation of monetary assets in the VAR model.

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BIOGRAPHICAL SKETCH

Zhengyang (Robin) Chen is dedicated to continuing pursuit of high-quality research. His current interest fields include macroeconomics/monetary economics, financial economics, and time series analysis. He enjoys and makes use of high-frequency financial data and disaggregated macro data in macroeconomic studies. His PhD dissertation centers on the identification and measurement of monetary transmission. Under the guidance of the dissertation committee members, and especially its chair, Professor Victor Valcarcel, he has learned a variety of empirical tools and have been brought to the research frontier in the fields. Furthermore, his liberal background in finance and real estate (master's degrees in both fields) fuels his intuition in understanding the nuances surrounding the rapid development of macroeconomic studies. Before the PhD graduation, he presented his work and received extensive feedback in multiple international conferences, such as WEAI and SEM annual conferences, and finance seminars in prestige business schools, such as Texas A&M and UT Dallas.

Furthermore, high-quality undergraduate teaching has been a source of personal fulfillment for him. He has taught Principles of Macroeconomics as an independent instructor with full responsibility of curriculum and examination for 5 semesters. The largest class size reaches 89 students, and evaluation keeps improving every semester up to 4.75 out of 5. He remains devoted to the education of students and looks forward to resolutely continuing this commitment. In addition, he would be very interested in teaching advanced courses in macroeconomic theory, monetary policy, financial institutions, and applied econometrics.

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PhD, Economics, University of Texas at Dallas, 2020 (expected)
MSc, Finance, Johns Hopkins University, 2015
MSc, Real Estate and Infrastructure, Johns Hopkins University, 2013
BBM, International Business, Guangdong University of Foreign Studies, China, 2012

Essays on Monetary Policy: Measurement and Transmission
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Professional Recognitions and Honors:

University Small Research Grant, UTD, 2019
Charles C. McKinney Scholarship, UTD, 2017 - 2019
Vibhooti Shukla Scholarship, UTD, 2017
Graduate Studies Scholarship, UTD, 2015 - 2020
AFIRE (Association of Foreign Investors in Real Estate) Scholarship, JHU, 2013
University Comprehensive Merit Scholarship, GDUFS, 2010, 2011

Invited Seminar and Conference Presentations:

Fall 2019 Finance Seminar, Naveen Jindal School of Management, UT Dallas, USA, 2019
The 6th SEM (Society for Economic Measurement) Annual Conference, Frankfurt, Germany, 2019
PFA Brown Bag Seminars, Mays Business School, Texas A&M University, USA, 2019
The 93rd Western Economic Association International Annual Conference, Vancouver, Canada, 2018

Professional Memberships:

American Economic Association (AEA), 2019–present