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# Identifying Monetary Policy and Central Bank Information Shocks Using High-frequency Exchange Rates\*

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## Abstract

This work investigates effects of conventional monetary policy and central bank information shocks from monetary policy announcements on the U.S. economy. We identify the surprises caused by changes in target rate and central bank's private information embedded in high frequency exchange rate responses around policy announcements. Our identification strategy is based on economic observations that conventional monetary policy effect is restricted, whereas central bank information effect becomes quantitatively more significant during the zero lower bound (ZLB) period. We investigate the impact of identified monetary policy and central bank information shocks on macro variables using proxy SVAR. Contractionary monetary policy decreases output and price level clearly. A positive information shock which also induces increases in interest rate is perceived by private agents as a positive signal related to a future economic status, and induces an increase in output and easing financial condition.

JEL Classification: C36, E52, E58

Key words and phrases: Monetary Policy Shock, Fed Information, Identification through Heteroskedasticity, High-frequency Identification, Proxy SVAR.

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\*This version: Preliminary, please do not quote or circulate.

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# 1 Introduction

The U.S. economy has experienced a clear structural change in terms of the effectiveness of the short-term interest rate as a policy instrument. The federal funds rate had been near zero and the central bank cannot stimulate the economy by lowering the interest rate further. During this period, the central bank relies on unconventional policy instruments—forward guidance and large-scale asset purchases (LSAP)—to try to influencing expectations on short-term interest rates. Not only during ZLB period and through unconventional policy instruments, central bank has affected market expectations on short-and long-term interest rates and influenced the economy through effective communications. As a key channel of communication with public, the Federal Open Market Committee (FOMC) announcements deliver systematic information about current and future interest rate policies and also the economic outlook. In this work, we revisit a fundamental question on how monetary policy shocks influence economy. Especially, to answer the question, we consider two dimensional surprises embedded in FOMC announcements: one from conventional changes in target rate and another from central banks information about future monetary policies and economic outlook.

To extract expectations about the path of interest rates, financial variables have widely used in various literature.<sup>1</sup> Especially, estimates of monetary policy shock using financial variables have become more popular and precise with the availability of high frequency data. Some recent works explore monetary surprises extracted from high frequency financial market instruments which have been used to quantify the various dimensional impacts of monetary policy announcements. Swanson (2017) identifies conventional and unconventional, forward guidance and large-scale asset purchases, monetary policy shocks using high frequency futures on short-term interest rates and long-term government bond yields. Nakamura and Steinsson (2018) show that information about future economic outlook embedded in policy announcements influence private agents expectation on key macro variables by measuring changes in high-frequency financial variables around FOMC announcements. Jarociński and Karadi (2018) disentangle monetary policy shock from central bank information components using high-frequency financial instruments and sign restriction identification scheme. Miranda-Agrippino and Ricco (2018) also identify true monetary policy shock by controlling central bank information using central bank’s private forecasts and resolve empirical puzzles reported in previous literature.

Our paper adds to a growing and active literature on investigating the multidimensional impacts of monetary policy announcement on the economy using the high frequency financial data. This paper contributes to the existing literature in three main aspects. We consider changes in high frequency exchange rates around FOMC announcements to identify monetary policy shock.<sup>2</sup>

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<sup>1</sup>Among many, see Cook and Hahn (1989), Svensson (1994), Soderlind and Svensson (1997), Kuttner (2001), Cochrane and Piazzesi (2002), and Piazzesi (2002).

<sup>2</sup>Faust, Rogers, Wang and Wright (2007) study the joint movements of exchange rates of the U.S. and foreign term structures over narrow windows around macro announcements using high frequency data, and Neely (2015) shows that unconventional policy can reduce international long-term yields and the value of the dollar even at the

In our work, using high-frequency exchange rate has more meanings than simply taking different high-frequency instruments. We observe that responses of exchange rate are more significant than ones from other high-frequency financial instruments during ZLB periods, and significant fluctuations on high-frequency exchange rate on policy announcements help us to investigate the effects of monetary policy shocks on economy both qualitatively and quantitatively. Also, according to Rosa (2011), exchange rate is fluctuated by central bank information more than actual changes in target rate. We take into account exchange rate channel directly to investigate market responses to central bank information. Secondly, to disentangle two dimensional, conventional monetary policy and central banks information components from monetary policy announcements, we consider a novel identification scheme which uses an existence of heteroskedasticity on measured monetary policy shocks before and during ZLB period. Our strategy reflects the economic observations that conventional monetary policy effect is restricted during ZLB period, whereas central bank information effect becomes quantitatively more significant through various unconventional monetary policy channels. Lastly, we consider proxy SVAR (structural vector autoregression) models to measure impacts of conventional monetary policy and central bank information shocks from FOMC announcements on the U.S. economy.

Our identification strategies and estimation provide a better understanding on how policy surprises from policy target rate changes and central banks information influence economy. First of all, high frequency response of exchange rates on FOMC announcements is a good external instrument of monetary policy shock in our VAR model but identified monetary policy shock provides some questionable responses on macro and financial variables with wide confidence intervals. However, disentangled conventional monetary policy and information shocks from our proxy of monetary policy shock show more clear and intuitive responses: policy surprises caused by raises in target rate decrease the output and price level significantly as macroeconomic theory has expected, whereas policy surprises caused by central bank information corresponding to tightening monetary policy induce a significant increase in the output and weak decrease in the price level. This could be interpreted as evidence that a positive central bank information shock updates economic agents' beliefs and signals them a positive future economic outlook (signaling effect). Second, depending on periods, pre-ZLB and during ZLB, extents of policy surprises caused by target rate change and central bank information are different, but effects of each policy surprise on economy are overall similar regardless of sample periods.

The rest of the paper is organized as follows. In section 2, we describe our conceptual idea on two dimensional—conventional monetary policy and central bank informational—shocks based on previous literature and a simple theoretical model. Section 3 introduces our empirical approaches to identify multidimensional shocks using high frequency responses of exchange rate around FOMC announcements and heteroskedasticity in measured monetary policy shocks. Section 4 provides

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zero bound using high frequency responses of exchange rates on FOMC announcements. Their works, however, are not directly comparable to ours, which identifies monetary policy shock explicitly using high frequency response of exchange rates around FOMC press release.

empirical method and estimation results to investigate effects of conventional monetary policy and information shocks on the U.S. economy. Section 5 reports sub-sample analysis as a robustness check. Section 6 concludes the paper, and Appendix collects additional figures and details on our analyses.

## 2 Monetary Policy and Central Bank Information Shocks

Our empirical approach for multidimensional shocks from policy announcements is connected to several important strands of literature on monetary policy and its effect: information asymmetry between central bank and the public, central bank communication and private agents' expectations, and also effects of unconventional monetary policies. In this section, we provide some key literature related to our conceptual idea and theoretical background for our empirical analysis.

### 2.1 Related Literature

Our conceptual idea on central bank information shock is closely related to the empirical finding from Nakamura and Steinsson (2018): forecasts about output growth increases with a positive policy news shock which may contain information about future economic outlook and monetary policy.<sup>3</sup> The response of output growth forecasts they observed is the opposite of what standard New Keynesian models imply about a monetary tightening. To explain this puzzling finding, they build a model in which Fed announcements affect beliefs not only about monetary policy but also about other economic fundamentals via an information channel.<sup>4</sup>

The existence of policy surprise through an information channel implies an information asymmetry between the central bank and the public. Romer and Romer (2000) argue that the U.S. Federal Reserve has superior ability relative to the private agents to process publicly available information to produce economic forecasts. They argue that the private sector can use policy actions to learn about the confidential FRB staff forecasts. Barakchian and Crowe (2013) and Campbell et al. (2016) show in a updated sample that the private information of the Fed, measured as the difference of the FRB staff forecast and private forecasts, can be used to predict monetary policy surprises around subsequent monetary policy announcements. This suggests that surprises can be informative about the central bank information.<sup>5</sup>

Our paper also adds to recent research like Campbell et al. (2016) and Hansen and McMahon (2016), which aims to quantify the impact of central bank information revelation on expectations

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<sup>3</sup>Similar evidence is reported in Campbell et al. (2012) and Campbell et al. (2016), and Miranda-Agrippino (2016) in terms of anticipatory effects from monetary surprises. They find that a contractionary monetary policy shock can induce a significant and persistent increases in output and an equally sizable reduction in unemployment while prices slightly contract.

<sup>4</sup>See also Zhang (2017) for a theoretical model to support the information channel of monetary policy.

<sup>5</sup>Some disagreements exist on information asymmetry between the central bank and the public: Faust et al. (2004) challenge this view and show evidence against the claim that surprises were informative about the Fed's private information.

and the macroeconomy. Campbell et al. (2012) introduce Delphic forward guidance in a form of openly stated prediction or expectation from the central bank regarding the future stance of the economy or monetary policy. Campbell et al. (2016) show that private forecasts that are revealed through policy actions, which they measure as the fitted value in a regression on federal funds futures surprises on the Fed’s private information, lead to subsequent increases in private sector expectations, albeit with a lag. Hansen and McMahon (2016) use methods in computational linguistics to turn announcements into quantitative measures of central bank communication on the state of the economy and on policy that can be introduced into a VAR framework.

Above two strands of literature on central bank’s private information and its role are also related to impact of unconventional monetary policies. During the ZLB period, the central bank relies on unconventional policy instruments—forward guidance and quantitative easing (QE)—to try to influencing expectations on short-term interest rates and lower long-term interest rates through communications. Swanson (2017) and Rogers et al. (2017) consider three separate measures of U.S. monetary policy surprises—target, forward guidance, and LSAP by taking into account of the special circumstances at the ZLB. In this work, however, we mainly focus on signaling effect from unconventional policies instead of distinguishing effects from different unconventional monetary policies. Indeed, many of the monetary policy announcements provided information about both types of unconventional policy simultaneously. In particular, several authors have argued that LSAPs affect the economy either partly or wholly by changing financial markets expectations about the future path of the federal funds rate (e.g., Woodford (2012) and Bauer and Rudebusch (2014)). To the extent that the signaling channel is operative, even a pure LSAP announcement would have important forward guidance implications in both Delphic and Odyssean ways.

## 2.2 Theoretical Background: Belief and Forecasts

Our empirical methodology presupposes the presence of multiple independent signals reaching the market, both about change in interest rate and central bank information about future policy and economic outlook. Gürkaynak et al. (2007) and Rosa and Verga (2008) show that on the meeting days of the monetary policy committee two pieces of news systematically hit financial markets, the new level of the policy rate in force for the following month and statement that provides a rationale for the policy action and an assessment of the economic outlook over the foreseeable future.

We consider a simple illustrative framework to provide the intuition behind the informational content of monetary surprises around policy announcements. The model we refer is a variant of the canonical New Keynesian model: near-rationality is assumed, and households hold subjective beliefs as in learning literature.<sup>6</sup> Based on (heterogeneous) subjective expectations, private sector behavior in the model can be described by following equations which are counterparts of the dynamic IS and

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<sup>6</sup>Among many, see Branch and Evans (2006), Preston (2005), and Eusepi and Preston (2011).

Phillips curve in a canonical New Keynesian model as below:<sup>7</sup>

$$x_t = \hat{E}_t \sum_{T=t}^{\infty} \beta^{T-t} \left[ (1 - \beta)x_{T+1} - \frac{1}{\sigma}(i_T - \pi_{T+1} - r_T^n) \right] \quad (1)$$

$$\pi_t = \hat{E}_t \sum_{T=t}^{\infty} (\alpha\beta)^{T-t} [\kappa x_T + (1 - \alpha)\beta\pi_{T+1} + \eta_T] \quad (2)$$

where  $\hat{E}_t$  denotes private agents' subjective expectations based on information up to time  $t$ ,  $x_t$  is the output gap,  $\sigma$  is the relative risk aversion parameter,  $i_t$  denotes nominal interest rate,  $\pi_t$  denotes the inflation rate,  $r_t^n$  denotes the natural rate of interest,  $\beta$  denotes the subjective discount factor, and  $\eta_t$  is an autoregressive cost push shock. The slope of the Phillips curve is given by  $\kappa = (1 - \alpha\beta)(1 - \alpha)/\alpha$ .

The behavior of the central bank follows a version of the Taylor rule.

$$i_t = \phi_\pi \pi_t + \phi_x x_t + u_t$$

The central bank reacts to inflation and output gap, and  $u_t$  is the monetary policy shock which follows AR(1) process. We rely on near-rationality assumption and a learning mechanism to make the central bank's expectations, given exogenously to private agents, affect those of private agents, which are endogenous in rational expectations framework. Private agents have the forecasting model expressed below

$$\begin{aligned} z_t &= H\bar{a}_{t-1} + \Omega s_{t-1} + e_t \\ \bar{a}_t &= F\bar{a}_{t-1} + v_t \end{aligned}$$

where  $z_t = [x_t \ \pi_t \ i_t]'$  is a vector containing endogenous variables that private agents need to predict and  $s_t = [r_t^n \ \eta_t \ u_t]'$  denotes a vector that observable exogenous disturbances at time  $t$ .  $\bar{a}_t$  indicates a vector of  $n_a$  unobserved time-varying terms, possibly random walk drifts. Following Eusepi et al. (2015), it is assumed that the number of the underlying driving forces of drift terms,  $n_a$ , is equal to two and denote as  $a^\pi$  and  $a^x$  respectively.<sup>8</sup> These can be regarded as nominal and real factor. The nominal factor reflects uncertainty about the inflation target of the central bank, and the real factor represents fundamental uncertainty about long-term technological advance.<sup>9</sup>

<sup>7</sup>As in Eusepi and Preston (2010, 2011), we consider the anticipated utility approach instead of Euler equation learning in many other learning literature to describe the long-term expectations influenced by central bank communications. See Appendix for details of a model.

<sup>8</sup> $a$  denotes the estimate of  $\bar{a}$ , which is unobservable to private agents.

<sup>9</sup>The real factor can be also interpreted as a shock to higher-order belief, or private agents' sentiments as in Angeletos and La'O (2013). For example, persistent positive waves of the real factor can be considered as strong optimism of the real activities in the economy, as perceived by private agents.

Exogenous disturbances follow the stationary AR(1) process

$$s_t = \Phi s_{t-1} + \epsilon_t$$

where  $\epsilon_t$  are *i.i.d.* shocks. It is also assumed that parameters that govern reactions to fundamental disturbances  $\Omega$  are known to private agents and coincide with the rational expectations' counterparts. Hence, private agents only need to learn about the unobserved drift terms which capture uncertainties about monetary policy path and economic growth.

Based on the estimated time-varying drift terms  $a_{t-1}$  up to time  $t - 1$  and the beliefs given above, private agents compute their own forecasts as

$$\hat{E}_t^P z_T = HF^{T-t} a_{t-1} + \Omega \Phi^{T-t} s_t$$

The central bank is also near-rational and has its own perceived law of motion, which can be used to predict future endogenous variables. Perceived law of motion of the central bank is given as follow

$$z_t = \Omega s_t + e_t$$

which coincides with the rational expectations solution to the model. Compared to that of private agents, perceived law of motion of the central bank clearly shows that central bank's expectations are well anchored, as there are no time-varying terms  $\bar{a}$ . This formulation seems reasonable as many central banks predict their economy by using their country-specific DSGE models with rational expectations. The central bank announces its own forecasts of endogenous variables, including the nominal interest rate, after observing the realization of disturbances.

$$\hat{E}_t^{CB} z_T = \Omega \Phi^{T-t} s_t$$

Under the model, we specify the components which induce unexpected changes in financial market around the FOMC announcements. Just before the policy announcement, private agents in financial markets have their own forecasts conditioning on all information available up to time  $t - \Delta t$ . Private agents update their forecasts based on central bank announcement on her own forecasts.<sup>10</sup> Naturally, any changes in asset prices ( $mps_t$ ) within a narrow measurement window ( $\Delta t$ ) around monetary policy announcements can be considered as a function of difference between central bank's forecasts ( $\hat{E}_t^{CB} z_T$ ) and private agents' forecasts ( $\hat{E}_{t-\Delta t}^P z_T$ ), and monetary policy disturbance,  $u_t$  revealed during a measurement window ( $\Delta t$ ).<sup>11</sup>

<sup>10</sup>The tendency of private agents reliance on the central bank's information in forming expectations on future endogenous variables depends on central bank's credibility. Here, we assume that central bank has a high credibility (but possibly not full) on her policy decision.

<sup>11</sup>Here, we assume that asset price changes within the narrow measurement window,  $\Delta t$  mainly capture all the relevant information as it becomes available under the fixed risk premium. The possible existence of time-varying



$$mps_t = p_t - p_{t-\Delta t} \quad (3)$$

$$= f(u_t, \hat{E}_t^{CB} z_T - \hat{E}_{t-\Delta t}^P z_T) \quad (4)$$

$$= f(u_t, a_{t-1}) \quad (5)$$

where  $\hat{E}_t^{CB} z_T - \hat{E}_t^P z_T = -HF^{T-t} a_{t-1}$ . Once monetary policy surprise,  $u_t$  is observed at  $t$  with a policy announcement, private agents update their forecasts on interest rate, output and inflation rate accordingly, and those updates induce changes in financial markets immediately. Differences between forecasts of private agents and central banks are not only from newly observed monetary policy shock component but also from partially uncovered uncertainty component,  $a_{t-1}$ . In this framework, we can consider a response of asset prices around monetary policy announcements as a combination of two (possibly independent) components: conventional monetary policy shock ( $u_t$ ) and additional information provided by a central bank which partially uncovers uncertainty embedded in private agent's expectations for monetary policy path and also for real economic status ( $HF^{T-t} a_{t-1}$ ). Especially, in this specification, the information for monetary policy path and real activities embedded in the central bank announcement is related to formulating private agents' long-term expectation of endogenous variables which is consistent with a stylized empirical finding that monetary policy announcements have a long-term effect on macro variables especially interest rates as in Nakamura and Steinsson (2018).

### 3 Identification of Monetary Policy and Information Shocks

In this section, connected to the previous section, we introduce our empirical approaches to measure a proxy of monetary policy shock ( $mps_t$ ) using high frequency exchange rate response around FOMC announcements, and decompose a measured policy shock into conventional monetary policy shock ( $u_t$ ) and central bank information component ( $a_{t-1}$ ).

#### 3.1 A Proxy of Monetary Policy Shock

Previous literature on high frequency identification of monetary policy shock in the U.S. mainly focuses on unexpected changes of federal funds futures, euro dollar futures, treasury bond yields around FOMC announcements. In this work, we explicitly consider high frequency response of exchange rates around FOMC press releases to identify monetary policy surprises. There are two crucial reasons make response of exchange rates around FOMC announcements the ideal alternative for a proxy of monetary policy shock.

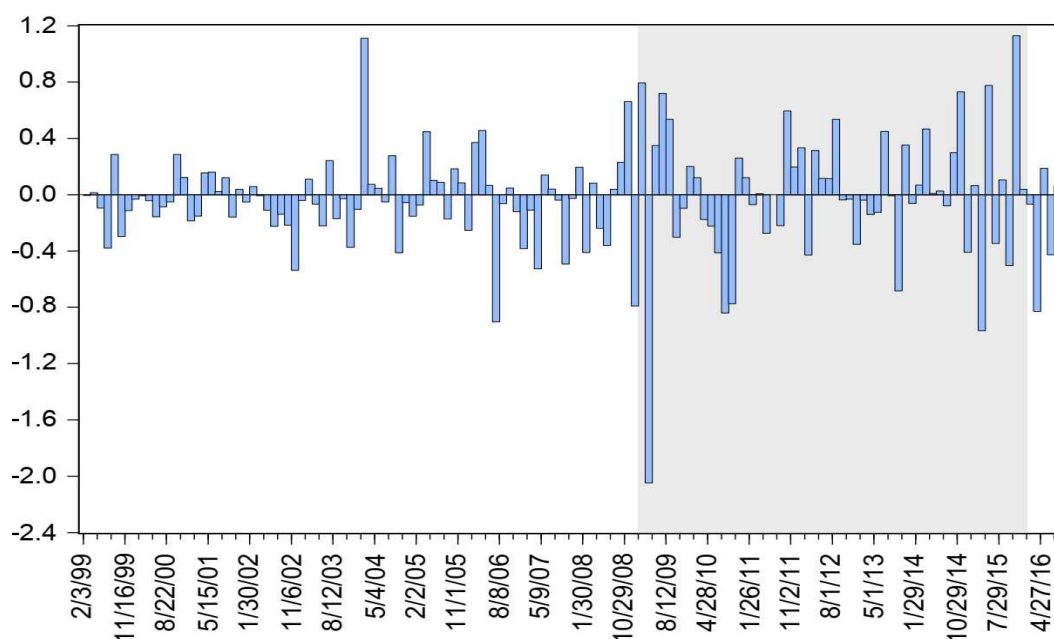
First, as claimed in previous literature using long-term interest rate and equity price markets for identification of monetary policy shock, exchange rate markets efficiently incorporate all the

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risk premium in a measured response in asset prices is still in debate.

relevant information embedded in a monetary policy announcement as it becomes available. Exchange rates directly reflect these information and therefore, their short-term dynamics can be interpreted as updates of policy surprises and the available information about future monetary policy and economic condition in general. There are considerable evidences from event study literature showing that (global) interest rate and exchange rates respond immediately and substantively to U.S. monetary policy shock. Among many, see Faust et al. (2003) and Rogers et al. (2017), and Swanson (2017).

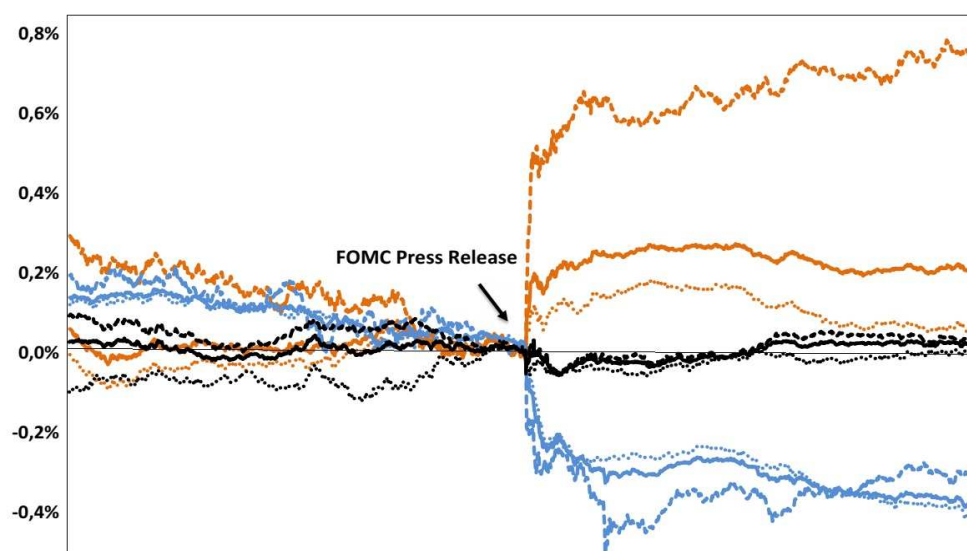
Figure 1: Changes of EUR/USD on Press Releases: 1999:2-2016:4



Second, we observe a considerably large degree of fluctuation and the existence of surprise component in the price formation on exchange rate markets on monetary policy meeting dates. This significant variation may help to identify the effect of monetary policy decision to the economy, especially during ZLB. Figure 1 presents changes in the U.S. dollar to euro around FOMC press releases from February 1999 to April 2016. Shaded areas show that during ZLB period, still monetary policy surprises are transmitted to exchange rates. Since December 2008, the federal funds rate has been near zero and changes in the one-month U.S. dollar money market rate is also near zero. But we still observe significant movements in the U.S. dollar to euro around FOMC press releases. Figure 2 summarizes how the U.S. dollar to euro have been changed around FOMC announcements depending on sample periods and signs of policy shock.<sup>12</sup> Regardless of sample periods, we observe an appreciation of the U.S. dollar with a positive monetary policy shock and vice versa, which is consistent with a standard macroeconomic theory. Also, overall, reaction of

<sup>12</sup>For this preliminary analysis, we identify the monetary policy shock and its sign as in Gertler and Karadi (2015) using daily changes on financial variables on FOMC dates.

Figure 2: Responses of EUR/USD Depending on Different Sample Periods and Shocks



Notes: The orange, black and blue lines are percentage changes of U.S. dollar to euro relative to time of FOMC press release (2:15pm) when signs of identified monetary policy shocks are positive, neutral and negative respectively. For each color, solid, dashed and dotted lines represent dynamics using full sample, ZLB and pre-ZLB periods respectively. Dynamics cover full day of FOMC meetings.

exchange rates to monetary policy surprise is stronger during ZLB than pre-ZLB period. We find that responses of the U.S. dollar to other currencies on FOMC announcements exhibit similar patterns. Glick and Leduc (2015) find that monetary policy surprises since the Fed lowered its policy rate to the effective lower bound have had larger effects on the value of the dollar. The impact on the dollar has been roughly three times that following conventional policy changes prior to the 2007 financial crisis. According to their work, exchange rate channel of the transmission of monetary policy is highly effective during both the conventional and unconventional policy periods, but the effects are significantly larger in the latter period.

Based on above motivations, to identify monetary policy shocks, we work with tick-by-tick high frequency exchange rates for the U.S. dollar versus the euro, the Canadian dollar, the British pound, the Swiss franc, the Japanese yen, the Australia dollar, and the Mexico peso covering from February 1, 1999, to April 31, 2014.<sup>13</sup> We measure exchange rate in the foreign currency needed to buy one unit of U.S. dollars such that a positive change implies an appreciation of the U.S. dollar. We measure the changes in the exchange rates within 30-minutes windows (from 10-minutes before to 20-minutes after) around FOMC press releases.<sup>14</sup> Finally, we calculate high frequency response

<sup>13</sup>The currencies we considered cover around 85 % of currency weights in BIS narrow exchange rate index. High frequency exchange rate data is obtained from Olsen Financial Technologies.

<sup>14</sup>Instead of using daily exchange rate data, considering the immediate reaction of exchange rates to monetary policy decisions and accompanying statements enables us to more accurately identify movements of the exchange rate caused by the Fed policy decision from other relevant news on the same day. Especially, for our approach, using daily exchange rate data may be particularly troublesome which react naturally to news from around the world.

of effective U.S. exchange rate around FOMC announcements according to the currency weights in the BIS narrow nominal effective exchange rate (NEER) index.<sup>15</sup> This measured high frequency (weighted) response of exchange rate is used as a proxy of monetary policy shock, which reflects all information from direct change in target rate and also central bank information on future policy stance and economic outlook.

### 3.2 Identification of Monetary Policy and Central Bank Information Shocks

Based on the measured proxy of monetary policy shock, we investigate the extents of central bank’s direct and information shocks which are revealed from FOMC announcements using identification through heteroskedasticity (Rigobon (2003)). Our measured response of exchange rate is considered as all relevant information from monetary policy announcements, i.e., change in target rate itself and other information which formulates economic agents’ expectation on future monetary policy and economy based on stated central bank’s expectation.<sup>16</sup>

To capture different dimensions of monetary policy shocks from conventional and unconventional monetary policies, previous literature extracts principal components from a selection of futures on short term interest rates and long-term government bond yields; see Swanson (2017) and Nakamura and Steinsson (2018) for details. Rogers et al. (2017) consider residuals of regressions on short term and long term interest rates as separated monetary policy shocks—target, forward guidance and LSAP surprises. Jarociński and Karadi (2018) impose sign restrictions on high frequency stock return and interest rate future to identify monetary policy and central bank information shocks. Miranda-Agrippino and Ricco (2018) also identify true monetary policy shock by controlling central bank information using Greenbook forecasts.

In this work, we use a novel identification scheme to disentangle monetary policy shock from central bank information related to future policy stance and economic outlook contained in FOMC statements. To implement our identification strategy, two different measured high frequency response of asset prices which contain both monetary policy and central bank informational effects are required, and we consider our measured high frequency response of exchange rate and a “policy news shock” from Nakamura and Steinsson (2018) measured around FOMC press releases.<sup>17</sup>

Rigobon (2003)’s identification scheme using heteroskedasticity has used for identification of monetary policy shock in previous literature (Rigobon (2003), Rigobon and Sack (2004), and Nakamura and Steinsson (2018)). We may need to emphasize that our approach is different from one from previous studies in terms of the source of heteroskedasticity. Using identification through

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<sup>15</sup>Our measure denotes whether the U.S. dollar has appreciated overall relative to main trading partners instead of individual foreign currency.

<sup>16</sup>We note that our measured proxy of monetary policy shock around FOMC press releases partially covers the whole monetary policy shocks which also come from different policy announcements and speeches.

<sup>17</sup>We treat “policy news shock” as a candidate containing monetary policy and information shocks based on its construction. Nakamura and Steinsson (2018) discuss the information effect of monetary policy shock using “policy news shock” which is constructed based on a common econometric approach, principal component analysis, and high frequency asset prices, federal funds futures and euro dollar futures with various maturities.

heteroskedasticity in previous studies is based on different movements in financial variables on FOMC dates and normal dates (FOMC announcement vs. non FOMC announcement dates). They point out that event study effects using measured policy shock around FOMC announcements are identified because the ratio of the variance of the announcement shock to the asset return variance becomes arbitrarily large in a narrow interval around the announcement and suggest a heteroskedasticity-dependent method to identify the responses of asset prices to monetary policy shocks.

Our purpose of using this identification method is different from theirs. Here, our interest is disentangling monetary policy from central bank information embedded in measured response of exchange rate around FOMC announcement. Moreover, our source of heteroskedasticity which is essential for this identification method is based on economic observations that change in target rate is effective monetary policy tool and actively used to influence the economy before the ZLB period, whereas central bank information generates more variation in the economy during the ZLB period as the direct change in interest rate is restricted. We may also need to note that our primary purpose is not an identification of structural parameters in simultaneous equations. We use this method to extract monetary policy and central bank information shock components from high frequency response of exchange rate and “policy news shock” on FOMC announcements. On this purpose, we focus on a simple empirical model which represents both measured shock series are the linear combinations of two structural shock components. As in Rigobon (2003), we only consider the existence of heteroskedasticity of the underlying monetary policy and central bank information shocks, and the parameters are stable across the two regimes. That means that how interest rate and exchange rate markets react to components of FOMC announcements is unchanged over time.<sup>18</sup>

To implement this approach, consider a simple model consisting with observed two proxies of monetary policy shock and two underlying shock components.<sup>19</sup>

$$\Delta ex_t = \epsilon_t + \eta_t \tag{6}$$

$$\Delta i_t = \alpha \epsilon_t + \beta \eta_t \tag{7}$$

where  $\Delta i_t$  and  $\Delta ex_t$  represent policy news shock measured by Nakamura and Steinsson (2018) and changes in high frequency exchange rate around 30 minute windows on FOMC announcements. More clearly, both  $\Delta i_t$  and  $\Delta ex_t$  are the measures of the whole monetary policy news revealed in the FOMC announcements.  $\epsilon_t$  and  $\eta_t$  are structural shocks which may be claimed as conventional monetary policy shock and information revealed from FOMC statement.<sup>20</sup> Our empirical model is consistent to a theoretical background mentioned in Section 2. Based on equation (3),  $\Delta ex_t$  denotes

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<sup>18</sup>This assumption is open to dispute.

<sup>19</sup>As policy news shock and response of exchange rate around FOMC announcement is measured within a narrow time window to identify monetary policy surprises, two shock series may reflect full information contained in policy announcement, and potential amount of noise is negligible.

<sup>20</sup>As our objective is to extract orthogonal shock components—direct and information shocks, we specify a model based on a simplicity of description.

$mps_t$ , and  $\epsilon_t$  and  $\eta_t$  represent proxies of  $u_t$  and  $a_{t-1}$  respectively. During the ZLB period, interest rate is at effective zero bound and unconventional monetary policies (e.g., forward guidance) are considered as more effective policy tools. Based on this, we assume that the variance of  $\epsilon_t$  decreases while the variance of  $\eta_t$  increases during the ZLB period.

We solve the model using identification through heteroskedasticity. Following Rigobon (2003), we assume there are two high and low volatility regimes in the fundamental monetary policy and information shocks. Additionally, assume that the structural parameters are stable across the regimes. Under these assumptions the two reduced-form covariance matrices have the structure as below:

$$\Omega_s = \begin{pmatrix} \sigma_{\epsilon,s}^2 + \sigma_{\eta,s}^2 & \alpha\sigma_{\epsilon,s}^2 + \beta\sigma_{\eta,s}^2 \\ \cdot & \alpha^2\sigma_{\epsilon,s}^2 + \beta^2\sigma_{\eta,s}^2 \end{pmatrix} = \begin{pmatrix} A_s & B_s \\ \cdot & C_s \end{pmatrix},$$

where the regime is denoted as  $s \in \{1, 2\}$ , where the variances of the structural shocks in regime  $s$  are given by  $\sigma_{\epsilon,s}$  and  $\sigma_{\eta,s}$ , and where  $\Omega_s$  indicates the reduced form covariance matrix in regime  $s$ . There are six unknown ( $\alpha, \beta, \sigma_{\epsilon,1}^2, \sigma_{\eta,1}^2, \sigma_{\epsilon,2}^2, \sigma_{\eta,2}^2$ ) and two covariance matrices, which provide six equations. If the equations are independent, our model will be exactly identified. With some algebras, we have

$$B_s = \alpha A_s + \frac{1}{\alpha + \beta} C_s - \frac{\alpha^2}{\alpha + \beta} A_s, \quad s \in \{1, 2\}.$$

To implement our identification scheme practically, we test for equality of covariance matrices of  $\Delta i_t$  and  $\Delta ex_t$  in sub-samples (pre-ZLB and ZLB) using the log-likelihood ratio test, and clearly reject the null of equality of covariance matrices at less than 1% significance level. Table 1 presents F-test result for variances of  $\Delta i_t$  and  $\Delta ex_t$  in sub-samples.

Table 1: F-Test for Variances: Pre-ZLB and ZLB

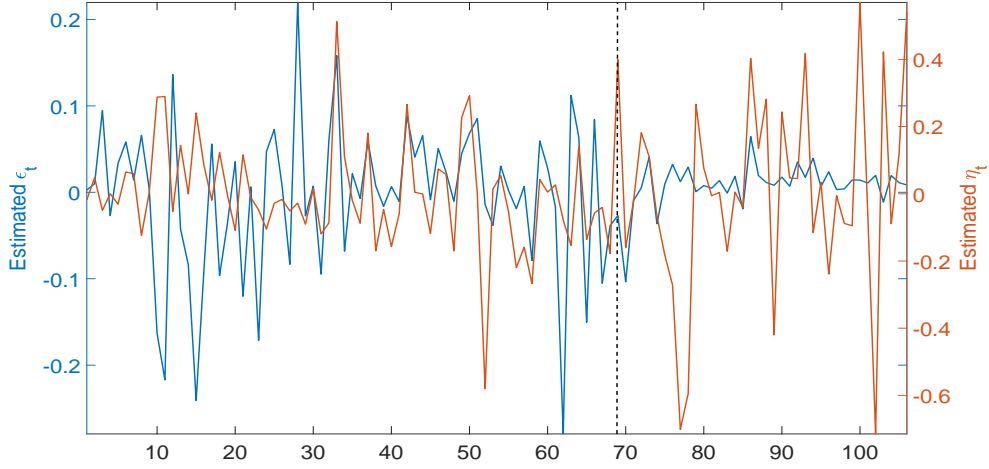
Statistics	$\Delta i_t$		$\Delta ex_t$	
	Pre ZLB	ZLB	Pre ZLB	ZLB
Mean	-0.002	0.004	-0.028	-0.004
Variance	0.0018	0.0002	0.032	0.092
df	67	37	67	37
F-Statistics	9.17		2.89	
p value	5.5E-11		7.7E-5	

By plugging  $A$  and  $B_s$  from reduced form covariance matrix  $\Omega_s$  in regime  $s$ , we obtain the value of  $\alpha$  and  $\beta$ . From equations (6) and (7), we obtain  $\epsilon_t$  and  $\eta_t$  as below,

$$\epsilon_t = \frac{\beta \Delta ex_t - \Delta i_t}{\beta - \alpha}, \quad \eta_t = \frac{\alpha \Delta ex_t - \Delta i_t}{\alpha - \beta}.$$

From our specification, disentangled  $\epsilon_t$  and  $\eta_t$  are orthogonal and identified up to scale.

Figures 3 and 4 show disentangled monetary policy and central bank information shocks em-

Figure 3: Estimated Monetary Policy Shock  $\epsilon_t$  and Information Shock  $\eta_t$ 

Notes: Correlation between two estimated shock series is 0.002. Variances of estimated  $\epsilon_t$  for pre-and during ZLB are 0.008 and 0.0007. For variances of estimated  $\eta_t$  are 0.024 and 0.091 respectively. The vertical dashed line represents December 2008.

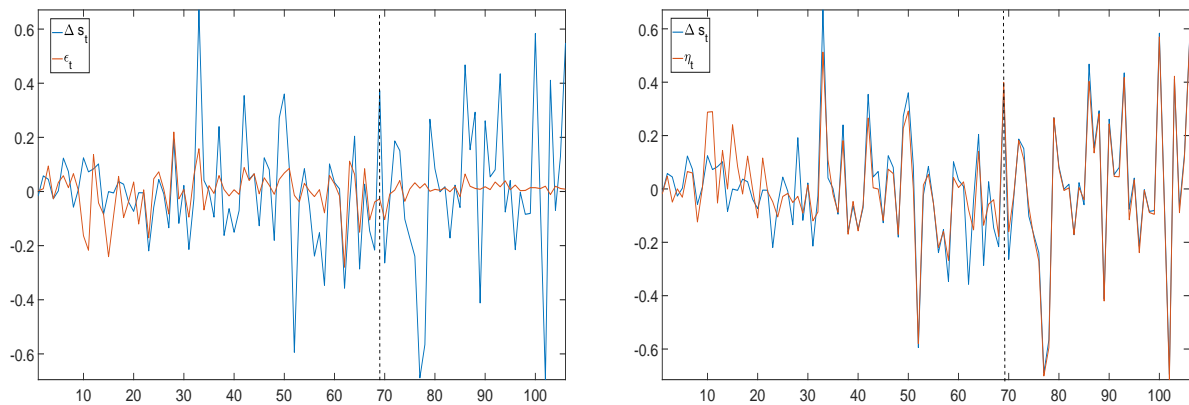
bedded in high frequency response of exchange rate around FOMC announcements. We observe that extents of monetary policy shock on high frequency response of exchange rate are significantly different depending on sub-sample periods, pre-ZLB and ZLB periods. Also, as shown in the right panel of Figure 4, extracted information shock deviates from measured response of exchange rate around FOMC announcement before ZLB period, but not after December 2008; it reflects that conventional monetary shock becomes ineffective during the ZLB period.

Table 2: Variance decomposition

Variables	Pre-ZLB		ZLB	
	Direct	Inform.	Direct	Inform.
$\Delta ex_t$	0.25	0.75	0.007	0.993
$\Delta i_t$	0.994	0.006	0.782	0.218

Based on the variance decomposition in Table 2, extents of monetary policy and central bank information shocks contained in policy news shock and high frequency response of exchange rate are quite different. Direct shock is more important to explain a variation of policy news shock series, which is measured by surprises of interest rates with various maturities. Before ZLB period, direct change in target rate mainly explains the dynamic of policy news shock. Information shock explains around 22 percent of total variation in policy news shock during ZLB period; after December 2008, central bank's active policy behaviors are from unconventional monetary policies which may not be captured enough in policy news shock. On the other hand, most variations in exchange rate shock are based on information shock component. As we expected, conventional monetary policy shock explains less than 1 percent of variation in exchange rate shock during the ZLB period.

Figure 4: Disentangled Shocks and Measured High-frequency Exchange Rate Responses



Notes: The blue solid lines in both plots represent high frequency response of exchange rate around FOMC announcements, and orange lines show extracted monetary policy shock (left) and information shock (right) respectively. The vertical dashed line represents December 2008.

These findings may be (partially) rationalized from too small variance of policy news shock during the ZLB period, which is inconsistent with central bank’s active communications to influence the economy.<sup>21</sup> And Rosa (2011) shows that a variation of response of exchange rate to monetary policy shock may reflect more information from statements than direct changes in target rate, which is consistent with our finding.

## 4 Effects of Monetary Policy and Information Shocks on Macroeconomy

### 4.1 Methodology

To investigate effects from monetary surprises, we consider a VAR model with economic and financial variables and external instruments. Starting with Gagnon et al. (2011), several papers have attempted to analysis the effectiveness of recent monetary policy actions with event studies of FOMC announcements; see, for instance, Krishnamurthy and Vissing-Jorgensen (2011), D’amico et al. (2012), Hamilton and Wu (2012), Li and Wei (2012), and Glick and Leduc (2015). Contrast to previous literature on high frequency identification using an event study to investigate the impact of the U.S. monetary policy on financial or survey based variables, in this work we mainly focus on dynamic responses of economic and financial variables on monetary policy shocks using a VAR

<sup>21</sup>Note that “policy news shock” is the first principal components which explains the most variation among interest rate futures. This shock captures some amount of monetary policy and also information shocks but there is no economic support that news shock contains more variations from information shock. The shock is not defined as “target” and “path” factors as in Gürkaynak et al. (2007) and correlated with both factors. Correlation between news shock and target factor (available only up to 2004) is 0.83 and path factor is 0.55. Target factor is highly correlated with current month federal funds future rate with correlation 0.97.



model. Our use of external instruments in a VAR is similar to one from Gertler and Karadi (2015) which is a variation of the methodology developed by Stock and Watson (2012), Mertens and Ravn (2013), and more recently Stock and Watson (2018).

Let  $Y_t$  be a vector of economic and financial variables. The general structural form of the VAR we are considering is given by

$$AY_t = C + \sum_{j=1}^p B_j Y_{t-j} + \epsilon_t. \quad (8)$$

where  $C$  captures constants,  $A$  capture the simultaneous effect of one endogenous variable to another, the matrices  $B_j$  contain the coefficients on the lag of the endogenous variables up to lag length  $j$  and  $\epsilon_t$  stands for the vector of structural shocks. By multiplying each side of equation (8) by  $A^{-1}$ , the reduced form VAR is obtained as below

$$Y_t = D + \sum_{j=1}^p K_j Y_{t-j} + \nu_t.$$

where  $\nu_t$  is the reduced form shock, given by the following function of the structural shocks:

$$\nu_t = S\epsilon_t$$

with  $D = A^{-1}C$ ,  $K_j = A^{-1}B_j$ , and  $S = A^{-1}$ . Here  $S$  is a square matrix with the dimension equal to the number of endogenous variables. The  $i$ -th column in  $S$  captures the response of the vector of reduced form innovations,  $\nu_t$ , to an increase in the  $i$ -th element of the structural shock  $\epsilon_t$ . As we are only interested in the responses to a structural monetary policy shock  $\epsilon_t^M$ , we only have to identify the column  $s$  in  $S$  that captures the impact of a unit increases in the policy shock  $\epsilon_t^M$  on the vector  $\nu_t$ . Following previous literature, let  $Z_t$  be an instrumental variable such as direct or information shock component in our work, and let  $\epsilon_t^q$  be a vector of structural shocks other than the policy shock  $\epsilon_t^M$ . To estimate the elements in the vector  $s$ , first obtain estimates of the vector of reduced form residual  $\nu_t$  from the ordinary least squared (OLS) regression of the reduced form VAR. Now let  $\nu_t^p$  be the reduced form innovation of the exchange rate equation and  $s^p$  be the element of  $s$  that describes its response to the structural monetary shock,  $\epsilon_t^M$ . Accordingly,  $\nu_t^q$  and  $s^q$  are reduced form error terms and the respective elements in  $s$  that correspond to other variables excluding exchange rate. We obtain an estimate of the ratio  $s^q/s^p$  from the two stage least square regression of  $\nu_t^q$  on  $\nu_t^p$  using the valid instrumental variable  $Z_t$ . The crucial point in this framework is to find an accurate instrument  $Z_t$  which is by definition correlated with  $\epsilon_t^M$  but orthogonal to  $\epsilon_t^q$ .

From the first stage, by regressing  $\nu_t^p$  on an instrument  $Z_t$ , we obtain  $\hat{\nu}_t^p$  as a variation in  $\nu_t^p$  that only captures changes in monetary policy  $\epsilon_t^M$ .<sup>22</sup> In the second stage, we then simply run the

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<sup>22</sup>Carefully note that we consider reduced form residual from exchange rate equation instead of one from interest rate equation for  $\nu_t^p$  because what we considered for an instrumental variable  $Z_t$  represents the variation in exchange

following OLS regression

$$\nu_t^q = \frac{s^q}{s^p} \hat{\nu}_t^p + \zeta_t.$$

where  $\hat{\nu}_t^p$  is orthogonal to the error term  $\zeta_t$  which is all the structural shocks other than monetary policy shock  $\epsilon_t^M$ . Given these estimates and the variance covariance matrix of the reduced form VAR model, we are able to uniquely identify all components of  $s$ . Once we identify  $s^p$  and  $s^q$  separately, those represent how exchange rate and other variables like long-term interest rate respond to structural monetary policy shock,  $\epsilon^M$ .

## 4.2 Data

We consider the U.S. monthly data on a variety of economic and financial variables over the period July 1979 to April 2014 for a proxy SVAR model.<sup>23</sup> Choice of variables in a VAR model follows a benchmark specification by Gertler and Karadi (2015); 1-year government securities rate, the log of consumer price index (CPI), the log of industrial production (IP), and excess bond premium (Gilchrist and Zakrajse (2012)). We consider 5-year and 10-year interest rates to represent a long-term interest rate. For a baseline estimation, we use 5-year interest rate.<sup>24</sup> Two main differences in our estimation from Gertler and Karadi (2015) are as follows. First, our instrumental variable  $Z_t$  is monetary policy or central bank information shock disentangled from high frequency responses of exchange rate around policy announcements. Clearly both conventional and information shocks represent a measures of proxy of monetary policy shock rather than exchange rate shocks in terms of its source. Second, as we consider an exchange rate channel for monetary policy transmission to identify monetary policy shock, (log of) U.S. dollar narrow nominal effective exchange rate (NEER) is considered in our VAR model.<sup>25</sup> The instrumental variable we apply is available for us from the period February 1999 through April 2014. We transform 123 observations on FOMC dates into monthly series by taking into account the dates of the FOMC meetings.<sup>26</sup> As measured monetary policy shock series is shorter than the sample available for the other time series, we use the full sample 1979:7 to 2014:4 to estimate the lag coefficients and obtain the reduced form residuals in VAR and then use the instrumental variable and reduced form residuals for the corresponding period to identify the contemporaneous impact of monetary policy surprises in our VAR approach. For the baseline VAR model, log CPI and log IP are linearly detrended.<sup>27</sup>

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rate induced by monetary policy shock,  $s^p \epsilon_t^M$  explicitly. Policy indicator is an interest rate such as one- or five-year interest rate as in Gertler and Karadi (2015).

<sup>23</sup>We choose the starting point to coincide with the beginning of Paul Volcker's tenure as Federal Reserve Chair and ending point to match with a policy news shock measured by Nakamura and Steinsson (2018).

<sup>24</sup>Using 10-year interest rate gives similar results.

<sup>25</sup>Variables used in our baseline estimation except excess bond premium (EBP) are from Thomson Reuters Data stream. EBP is available from online appendix in Gilchrist and Zakrajse (2012).

<sup>26</sup>FOMC announcements from meetings held at the end of month may be reflected to not that month but next month as mentioned in Gertler and Karadi (2015).

<sup>27</sup>We detrend log CPI and log IP using one-sided HP detrending. Both variables have a clear and very consistent upward trend but the other variables do not have such clear trends.

### 4.3 Estimation Results

First of all, to check whether our measured high frequency response of exchange rate around FOMC announcements is a proper proxy for measured monetary policy surprises, we estimate our proxy SVAR with twelve lags using measured exchange rate responses around FOMC announcement as a proxy variable. The first stage regression that residual of nominal exchange rate regressed on measured policy shock shows that our measured monetary policy shock works well for an instrument. The residuals are computed from the benchmark VAR described earlier. To be confident that a weak instrument problem is not present, Stock and Watson (2012) recommend a threshold value of ten for the F-statistic from the first-stage regression. The F-statistic in our baseline analysis (15.3) is well above this threshold and the instrument explains nearly 7 percent of monthly innovation in the exchange rate.<sup>28</sup> F-statistics obtained by regressing residual of nominal exchange rate on conventional monetary policy and information shocks are around 3 and 12 respectively as we orthogonally decompose both components from high frequency response of exchange rate.

Figures 5 and 6 present the impulse response of both economic and financial variables in our baseline VAR with twelve lags using disentangled monetary policy or central bank information shock as an external instrument.<sup>29</sup> For a better description, we normalize the size of shocks which induces roughly 25 basis point increases in one- and five- year rates for monetary policy and information shocks respectively. The red solid and black dotted lines in each figure report the estimated impulse responses along with 68 percent confidence bands, respectively, computed using bootstrapping methods.<sup>30</sup> Figure 5 shows that a positive monetary policy shock which increases one-year rate 25 basis point induces immediate decreases in consumer price and industrial production which are statistically significant and are consistent with standard macroeconomic theory. With a positive shock, the U.S. dollar appreciates, one year government bond rate increases, and long term interest rate slightly decreases with wide confidence bands. The excess bond premium (EBP) increases, an amount which is statistically significant.

More interesting finding is from responses of economic and financial variables to central bank information shock. Figure 6 presents that a positive information shock let U.S. dollar appreciate and five-year interest rate increase significantly. Interestingly, with this shock, only long term interest rate increases significantly which means that information shock gives a larger effect on longer term interest rate by generating expectations for a future economic status and policy.<sup>31</sup> Consumer

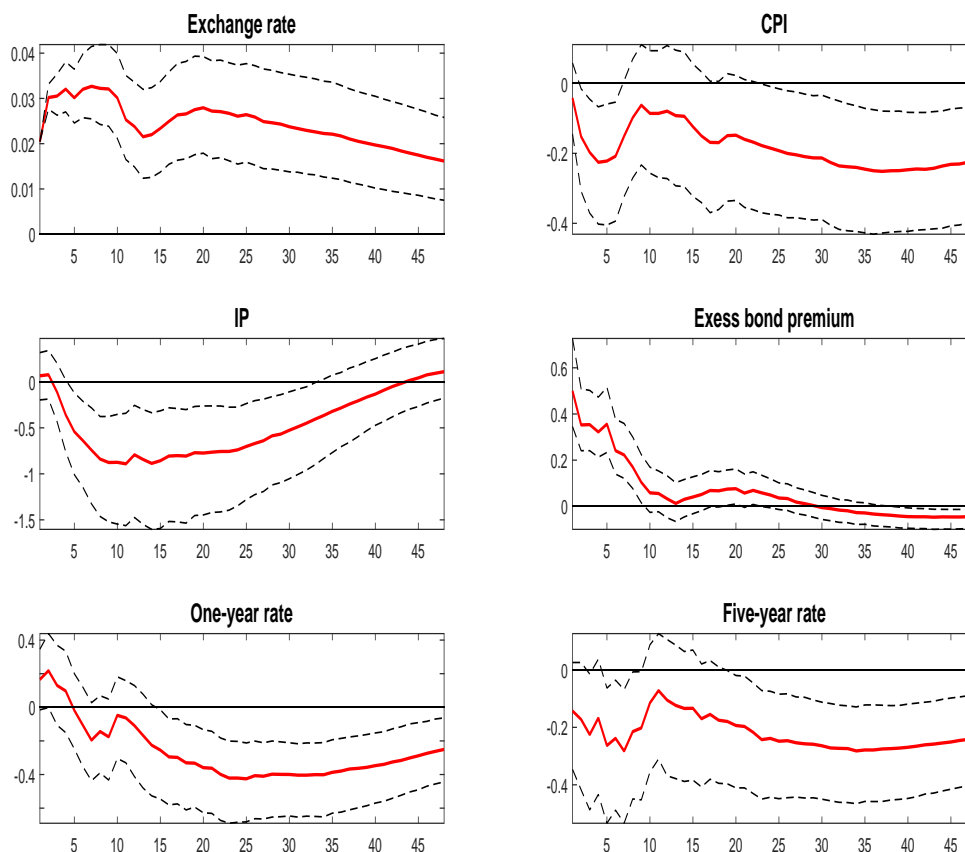
<sup>28</sup>Estimation results with measured exchange rate response and also news shock are available in Appendix.

<sup>29</sup>In this section, we assume that there is no structural change in our VAR model. As we consider the existence of heteroskedasticity in structural shocks for the identification of monetary policy and information shocks, we also conduct sub-sample analysis for pre-ZLB and during ZLB periods which may be more consistent to our underlying identification assumption. We find that our result this section is qualitatively consistent to results from sub-sample analysis in Appendix.

<sup>30</sup>Following Gertler and Karadi (2015) and Mertens and Ravn (2013), we are using wild bootstrap that generates valid confidence bands under heteroskedasticity and strong instruments. To avoid any potential generated regressor problem, the estimation errors related to the instrumental variable regression is incorporated in the reported confidence bands. The number of iterations is 2000.

<sup>31</sup>Size of information shock is normalized to induce about 25 basis point increases in five-year rate.

Figure 5: Impulse Responses of Variables to Monetary Policy Shock



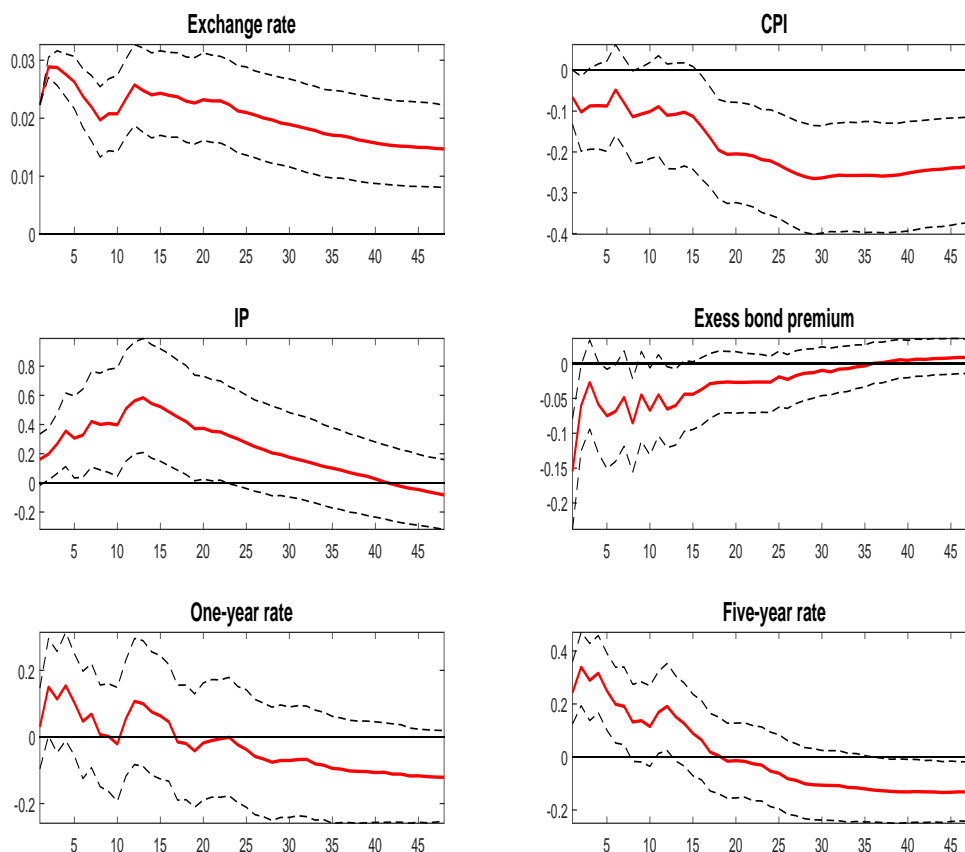
Notes: The figure represents IRFs of (log of) exchange rate, 100 times the log CPI, 100 times the log IP, the EBP, and short- and long-term interest rates to a positive direct shock over the subsequent 48 months. The dashed lines represent 68 % confidence intervals.

price decreases with some lags but industrial production increases clearly. And the excess bond premium decreases with a positive information shock.<sup>32</sup> We have two meaningful findings: (1) as economic agents receive a positive signal related to a future economic status from a central bank statement, industrial production increases.<sup>33</sup> (2) under the expectation of a future economic and financial outlook, credit supply condition becomes even better and it also leads expansion in economic activity. Excess bond premium can be considered as a measure of investor sentiment or risk appetite in the corporate bond market. According to Favara et al. (2016), EBP is counter-

<sup>32</sup>According to Gilchrist and Zakrajse (2012), excess bond premium represents roughly credit supply conditions. Decrease in EBP means expansion in the supply of credit and decreases in private credit cost. Increases in asset prices and expansion in economic activity through the financial accelerator.

<sup>33</sup>The Fed may have a superior information on industrial production as it is produced by the Federal Reserve. We check robustness of our estimation results by considering different variables for real economy like unemployment rate, and obtain similar results.

Figure 6: Impulse Responses of Variables to Information Shock



Notes: The figure represents IRFs of (log of) exchange rate, 100 times the log CPI, 100 times the log IP, the EBP, and short- and long-term interest rates to a positive information shock over the subsequent 48 months. The dashed lines represent 68 % confidence intervals.

cyclical, rising prior to and during economic downturn. Therefore, increase in industrial production and decrease in EBP are empirically plausible observations.

In our specification, central bank information partially reveals the uncertainty about nominal (e.g., inflation target of the central bank) and real factor (e.g., long-term technological advance) perceived by private agents. Especially, positive shocks on the real factor can be considered as strong optimism of the real activities in the economy as shown in our impulse response functions. Contents contained in positive information shock may be signaling that the central bank is forecasting improved economic conditions ahead, and based on our interpretation, private agents react to positive central information shocks similar to news on technological developments which generate similar responses on output, price level and also excess bond premium.

Our finding and interpretation are consistent with ones in previous studies. As shown in

Miranda-Agrippino (2016) and similarly Miranda-Agrippino and Ricco (2018), a contractionary monetary policy shock can induce a significant and persistent increase in output and an equally sizable reduction in unemployment while prices slightly contract. The sign of these response is reminiscent of the responses of survey-based forecast revisions that were discussed in previous studies. Jarociński and Karadi (2018) also draw similar responses from their information shock identified by imposing sign restrictions. Using Blue Chip forecasts, Nakamura and Steinsson (2018) show that a monetary contraction naturally sees agents revise their expectations about real output growth upward, up to about a year into the future. Expected inflation measured using the GDP deflator reacts with the expected sign, but the adjustments are not significant. Similar evidence is reported in Campbell et al. (2012) and Campbell et al. (2016). Campbell et al. (2012) regress Blue Chip forecast revisions for unemployment and CPI inflation on market-based monetary surprises constructed extending the work of Gürkaynak et al. (2007).

## 5 Robustness Check

### 5.1 Sub-sample Analysis

All of our previous results are based on the full sample analysis with the assumption that effects of conventional monetary policy and information shocks on economy are constant. One might wonder if the effects of both shocks are different depending on the sample period. Here, following the previous literature, we investigate whether effects of shocks are different on two sub-sample periods, pre-ZLB and ZLB periods. From the sub-sample analysis, we conclude that the impacts of monetary policy and information shocks do not depend much on whether the economy is at the ZLB or not.<sup>34</sup> Figures 7-10 show that how monetary policy and information shocks effect on the economy depending on periods. Clearly, for both pre-ZLB and ZLB periods, information shocks generate similar responses of economic and financial variables. Conventional monetary policy shock during pre-ZLB period also generates impulse responses of variables which are consistent with previous findings. During ZLB, conventional monetary policy shock is ineffective and as we expect, it generates only insignificant impulse responses on variables.<sup>35</sup>

We observe that regardless of sub-sample periods, effects of monetary policy and information shocks to economy are similar. However, extents of monetary policy and information shock components from FOMC announcements may vary depending on high frequency financial variables used for constructing proxies. Therefore, observed impulse responses on variables, especially output can be different depending on proxies of monetary policy shock. The sub-sample analysis supports our finding from previous sections and reconfirms a need of why we need to disentangle monetary policy and information shocks from measure high frequency policy shock for better understanding

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<sup>34</sup>Swanson (2017) also show that the crucial assumption of his approach—forward guidance has essentially the same effects on medium- and longer-term interest rates before and during the ZLB is valid via sub-sample analysis.

<sup>35</sup>With the shorter time span for sub-sample analysis, we consider 6 lags in a VAR. Considering more lags generates similar responses.

of monetary policy effects.

Lastly, we repeat the sub-sample analysis with conventional monetary policy and information shocks from our measured monetary policy shocks excluding the peak of financial crisis. Abnormal behaviors in financial markets during recent financial crisis are well known, and it may be questionable whether this abnormality mainly drives our estimation findings. We exclude FOMC announcement dates during the peak of financial crisis, from July 2008 to August 2009, to extract direct and information shocks and conduct sub-sample analysis again. Excluding the financial crisis period, we obtain overall similar results from the original sub-sample analysis.

## 6 Conclusion

In this work, we studied the identification of monetary policy shock and effects of monetary policy announcement on the economy by explicitly taking into account responses of exchange rate around FOMC announcements. To identify a monetary policy shock, we consider high frequency exchange rate response around FOMC announcements as an external instrument in a VAR model. For a better understanding on effects of monetary policy announcement, we disentangle conventional monetary policy and information shocks contained in monetary policy announcements using identification scheme in Rigobon (2003).

Three key findings emerge. First, to evaluate the impact of monetary policy behaviors precisely, using raw surprises in financial variables around FOMC announcements as a proxy of monetary policy shock may be improper. For a better understanding on monetary policy and its consequences, disentangled conventional monetary policy and information shocks from FOMC announcements need to be considered. Second, effects of information shock on output, excess bond premium, and monetary policy uncertainty are different from ones to direct shock. Third, extents of direct and information shocks on different sample periods, pre-ZLB and ZLB periods are different, but their effects on the economy are similar on both sub-samples.

These findings suggest both that economic models describing the effect of central bank communication is required to make a better policy advice and that central bank needs to use her power in processing information about the economy over the private sector, which can be useful to influence the economy in a long term not only during ZLB but also at all times.

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## Appendix

### 6.1 Appendix A

We consider a variant of the canonical New Keynesian model. A continuum of household,  $i$ , on the unit interval maximize their lifetime utility

$$\hat{E}_t^i \sum_{T=t}^{\infty} \varphi_T \beta^{T-t} \left\{ \frac{c_T(i)^{1-\sigma}}{1-\sigma} - \chi n_T(i) \right\}$$

where  $\beta \in (0, 1)$  is the discount factor,  $\chi > 0$  measures distutility of labor and  $\sigma$  is the relative risk aversion parameter, subject to the following budget constraint

$$c_t(i) + b_t(i) \leq \frac{1 + i_{t-1}}{1 + \pi_t} b_{t-1}(i) + w_t n_t(i) + \Gamma_t(i)$$

and the No-Ponzi condition

$$\lim_{T \rightarrow \infty} \hat{E}_t^i \left( \prod_{j=0}^{T-t} \frac{1 + i_{t+j}}{1 + \pi_{t+j+1}} \right)^{-1} B_t(i) \geq 0$$

where the variables  $c, n, b, i, \pi, w$  and  $\Gamma$  denote consumption, labor supply, real bond holdings, nominal interest rate, net inflation, real wage and real dividends from firms.  $\varphi_t$  is exogenous preference shifter and the operator  $\hat{E}_t^i$  denotes private agents' subjective expectations based on information up to time  $t$ .

A continuum of monopolistically ally competitive firms maximize profits

$$\hat{E}_t^i \sum_{T=t}^{\infty} \alpha^{T-t} Q_{t,T} [p_t(i) y_T(i) - P_T w_T n_T(i)]$$

subject to the linear production technology and demand function derived from the households' problem

$$n_T(i) = y_T(i) = \frac{p_t(i)^{-\theta_T}}{P_T} Y_T$$

where  $\alpha$  is the Calvo (1983) parameter and denotes probability of not being able to reset price in subsequent period.  $\theta_t > 1$  depicts the elasticity of demand across differentiated goods and follows an exogenous process. The stochastic discount factor  $Q_{t,T}$  is given as

$$Q_{t,T} = \beta^{T-t} \frac{P_t Y_t^\sigma}{P_T Y_T^\sigma}$$

In a symmetric equilibrium, private agents share the same subjective beliefs; thus, aggregate subjective expectations are the same as individual expectations, although agents do not perceive this. Log-linear approximation around the zero-inflation steady state gives following decision rules for consumption and price streams.

$$\hat{c}_t(i) = \hat{E}_t \sum_{T=t}^{\infty} \beta^{T-t} \left[ (1 - \beta) \hat{w}_{T+1} - \frac{1}{\sigma} (\hat{i}_T - \hat{\pi}_{T+1} - \beta(\hat{\varphi}_T - \hat{\varphi}_{T+1})) \right] \quad (9)$$

$$\hat{p}_t(i) = \hat{E}_t \sum_{T=t}^{\infty} (\alpha\beta)^{T-t} [(1 - \alpha\beta)(\hat{w}_T + u_T^*) + \alpha\beta\hat{\pi}_{T+1}] \quad (10)$$

where hat variables are log deviations from their steady states except  $\hat{p}_t(i) = \ln(p_t(i)/P_t)$ ,  $\hat{i}_t = \ln[(1 + i_t)/(1 + \bar{i})]$ , and  $u_t^* = \ln(\theta_t/\bar{\theta})$ . In the remainder, hat notations which denote log deviations from the steady states are dropped for simplicity as there is no confusion arises from this notational simplification.

Define the output gap as  $x_t = y_t - y_t^n = \sigma^{-1}w_t$ . That is, the output gap is the difference between the actual output and the natural output, which is the level of output under a flexible price environment. Aggregating and imposing market clearing conditions to equations (9) and (10) yield equations (1) and (2).

## Appendix B: Policy Announcement and Monetary Policy Uncertainty

We investigate how disentangled direct and information shocks influence monetary policy uncertainty which captures the degree of uncertainty the public perceives about Federal Reserve policy actions and their consequences. As direct and information shocks contain different dimensions of information from central bank announcements, it will be worth to study how monetary policy uncertainty reacts to direct and information shocks from policy announcements. Specifically, we consider a news-based index of monetary policy uncertainty (MPU) measured by Husted et al. (2017). Their measure of MPU follows the news-based search approach in Baker et al. (2015). Their approach to constructing the MPU index is to tract the frequency of newspaper articles related to monetary policy uncertainty. The underlying identification assumption is that increased newspaper coverage on words related to monetary policy uncertainty indicates that the public receives more uncertainty about central bank actions.

We include measured MPU in our baseline VAR model and analyze dynamic response of MPU on direct and information shocks.<sup>36</sup> As other impulse responses of variables are similar to previous

<sup>36</sup>Measured MPU from Husted et al. (2017) is available online.

analyses, we only report responses of MPU on both shocks. In Figure 11, right after a direct change in target rate, monetary policy uncertainty decreases shortly with wide confidence bands and the effect of shock disappears immediately; weak reactions on monetary policy uncertainty. Information shock following by FOMC announcement reduces monetary policy uncertainty clearly and fluctuates more and takes some time to go back to an initial level. Different responses of MPU on direct and central bank information shocks can be explained by their characteristics. Direct shock is related to central bank’s action which is a clear message and effects the economy immediately. The information shock, however, contains information related to future economic outlook and monetary policy stance, and also may generate an additional uncertainties in terms of interpreting messages and updating economic agents’ expectations. Especially, central bank information shock may be embedded in words in FOMC statements mainly and interpretation of those words for the public can be captured by monetary policy uncertainty.<sup>37</sup>

### Appendix C: Estimation of VAR with Two Different Proxies

Figure 12 shows the impulse responses of both the economic and financial variables in the simple VAR with twelve lags using our policy instrument–high frequency response of exchange rate around monetary policy announcements. The red solid and black dotted lines in each figure report the estimated impulse responses along with 68 percent confidence bands, respectively, computed using bootstrapping methods. After a monetary policy surprise that appreciates the U.S. dollar, one-and five-year interest rates tend to increase. Consumer price decreases significantly. But we observe that industrial production increases slightly and response on excess bond premium is unclear. Responses of industrial production and excess bond premium are somehow puzzling compared to results from previous literature, e.g., Gertler and Karadi (2015).

To clarify the source of puzzling results, we consider different external instruments and re-estimate our VAR model. First, we use federal funds futures and euro dollar futures for policy instruments and one-year rate for a policy indicator as in Gertler and Karadi (2015) and find similar impulse responses to ones from Gertler and Karadi (2015). Also we use measured “policy news shock” from Nakamura and Steinsson (2018) for an instrument of monetary policy shock and one-year rate rate as an policy indicator.<sup>38</sup> Impulse responses of variables are consistent with standard theory as shown in Figure 13: there is a small decline in the consumer price index and in industrial production that are not statistically significant. Five year nominal government bond rate also increases slightly and the U.S. dollar is appreciated by tightening monetary policy. The excess bond premium tends to be increases. An increase in the excess bond premium following

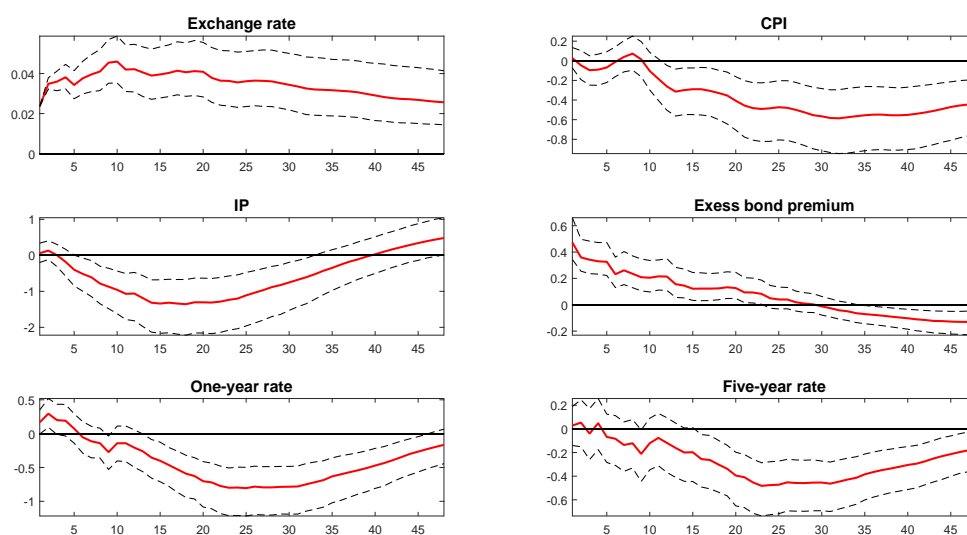
<sup>37</sup>Investigating transmission mechanism of monetary policy shocks–direct and information to monetary policy uncertainty is important and interesting topic but certainly goes beyond the scope of this paper.

<sup>38</sup>Similar to Gürkaynak et al. (2007), the policy news shock is the first principal component of the unanticipated change over the 30 minute windows in the following five interest rates: the current and 3-month federal funds futures, euro dollar futures at horizons of two, three and four quarters in the future. See Gürkaynak et al. (2007) and Nakamura and Steinsson (2018) for details of extracting the first (or first two) principal component(s) from various interest rates.

the monetary tightening is consistent with a credit channel effect on borrowing costs. Responses on monetary tightening policy shock are consistent with standard theory (and Gertler and Karadi (2015)) even if most of them are statistically insignificant with weak instrument issue. In sum, from comparisons with different proxies of monetary policy shock, we observe that our choice of an external instrument produces different responses to output and excess bond premium, not other specifications in our VAR model.

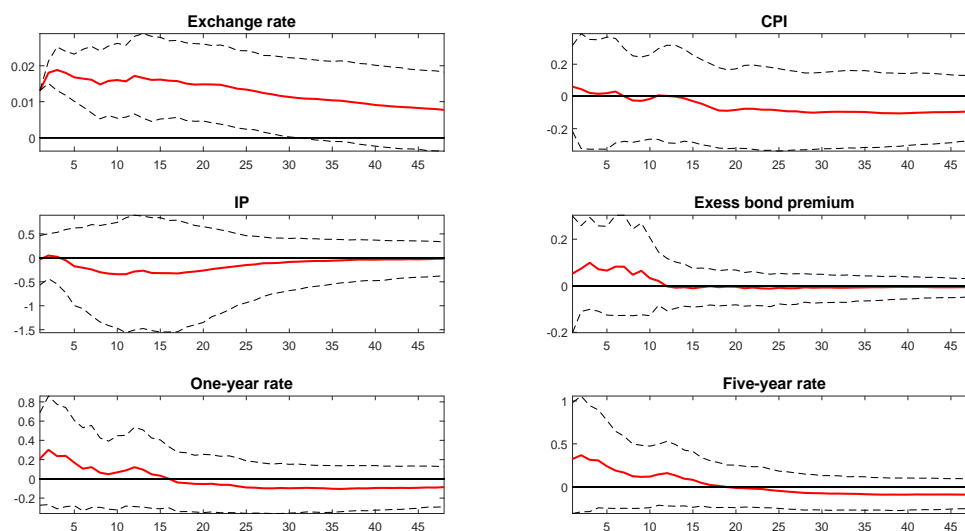
## Appendix D: Figures

Figure 7: IRs of Variables to Direct Shock: Pre-ZLB



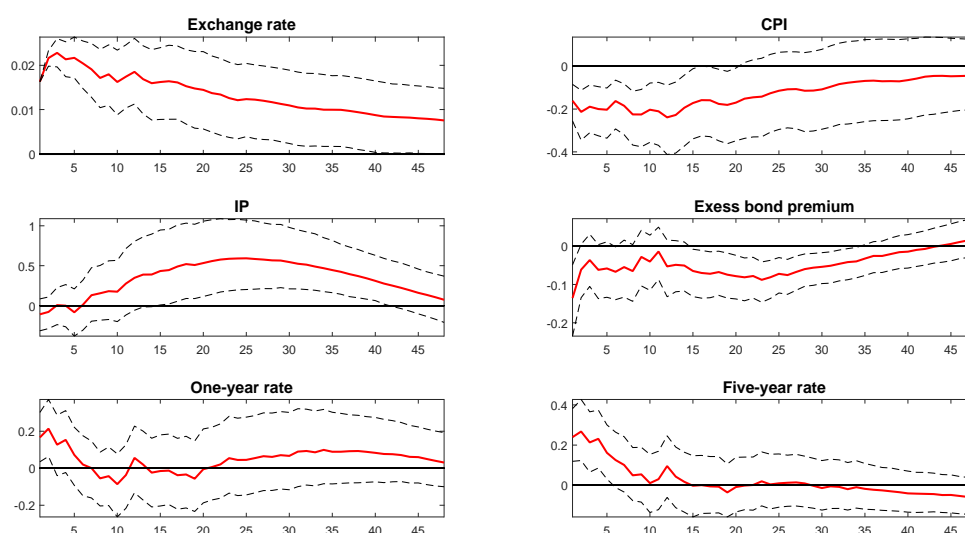
Notes: The figure represents IRFs of (log of) exchange rate, log CPI, log IP, the EBP, and short-and long-term interest rates to a positive direct shock for pre-ZLB period. The dashed lines represent 68 % confidence intervals.

Figure 8: IRs of Variables to Direct Shock: ZLB



Notes: The figure represents IRFs of (log of) exchange rate, log CPI, log IP, the EBP, and short-and long-term interest rates to a positive direct shock for ZLB period. The dashed lines represent 68 % confidence intervals.

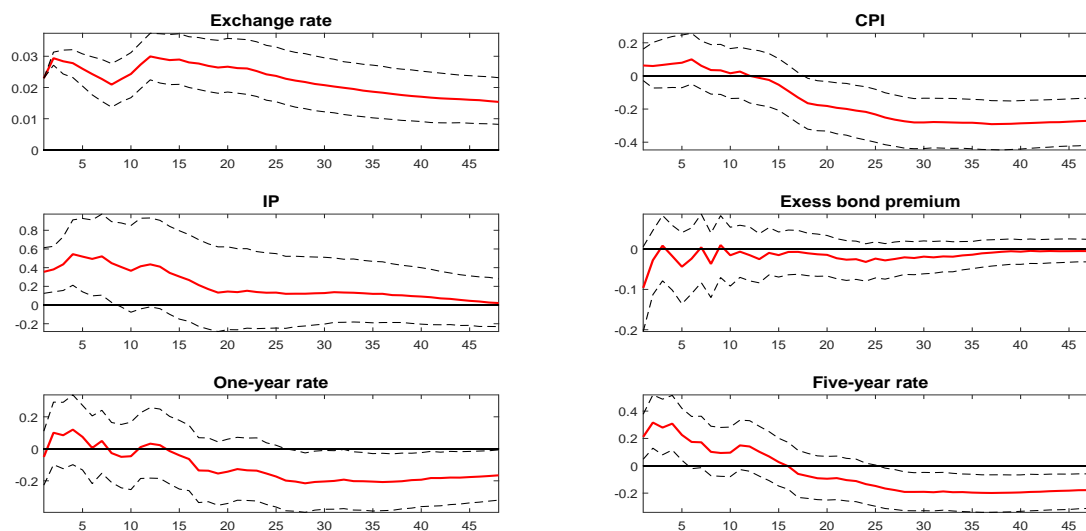
Figure 9: IRs of Variables to Information Shock: Pre-ZLB



Notes: The figure represents IRFs of (log of) exchange rate, log CPI, log IP, the EBP, and short-and long-term interest rates to a positive information shock for pre-ZLB period. The dashed lines represent 68 % confidence intervals.



Figure 10: IRs of Variables to Information Shock: ZLB



Notes: The figure represents IRFs of (log of) exchange rate, log CPI, log IP, the EBP, and short-and long-term interest rates to a positive information shock for ZLB period. The dashed lines represent 68 % confidence intervals.

Figure 11: Responses of MPU to Direct and Information Shocks

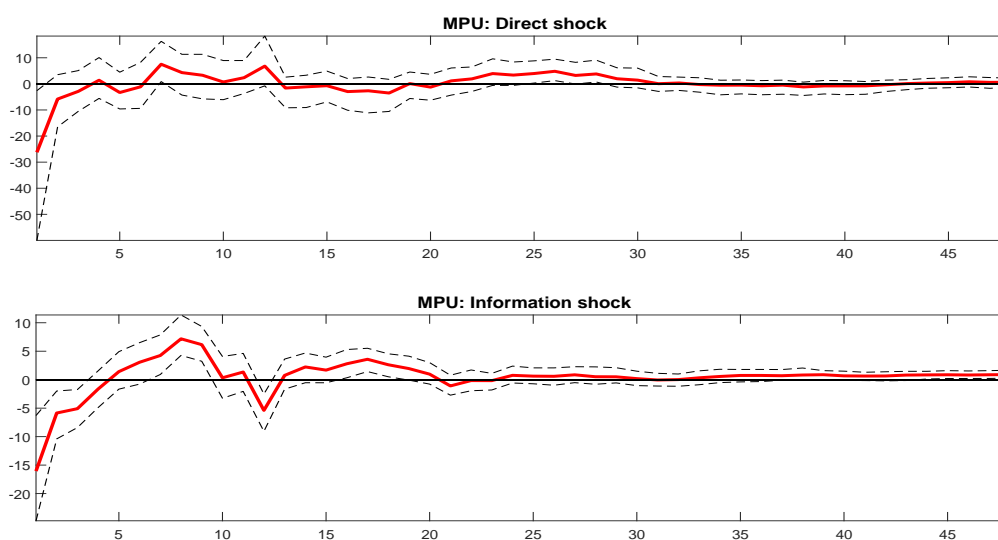
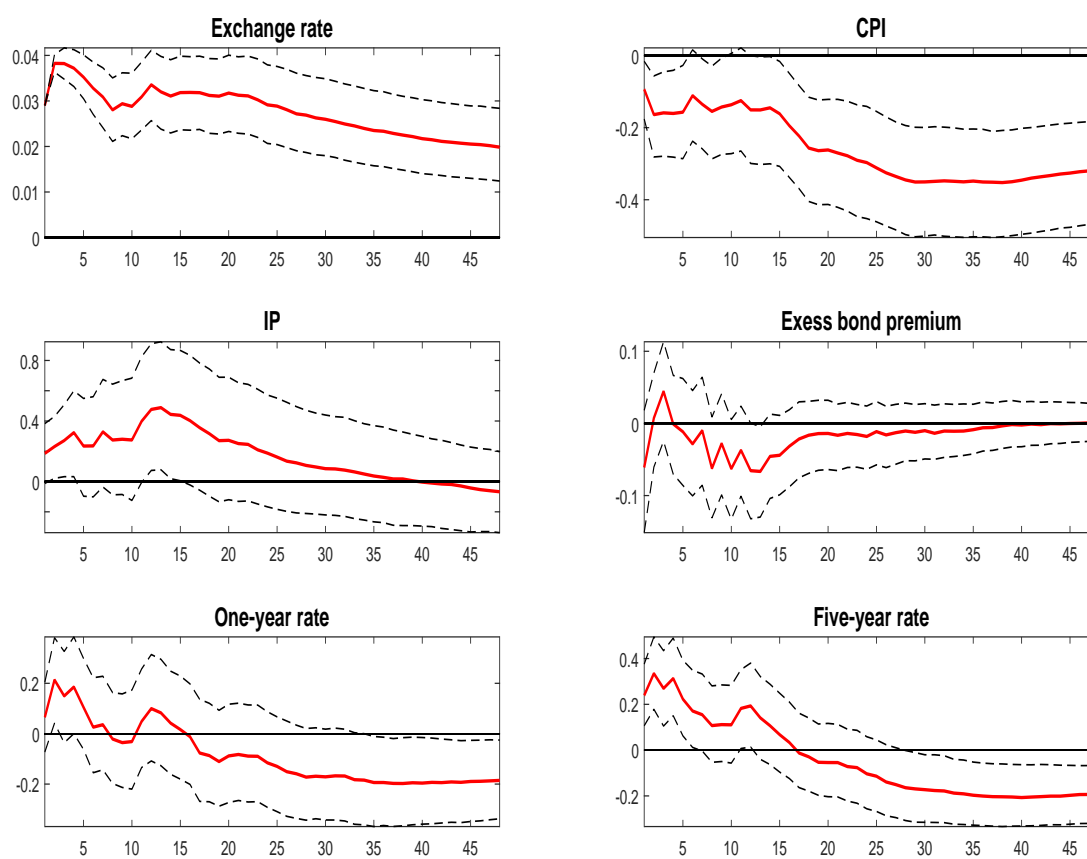
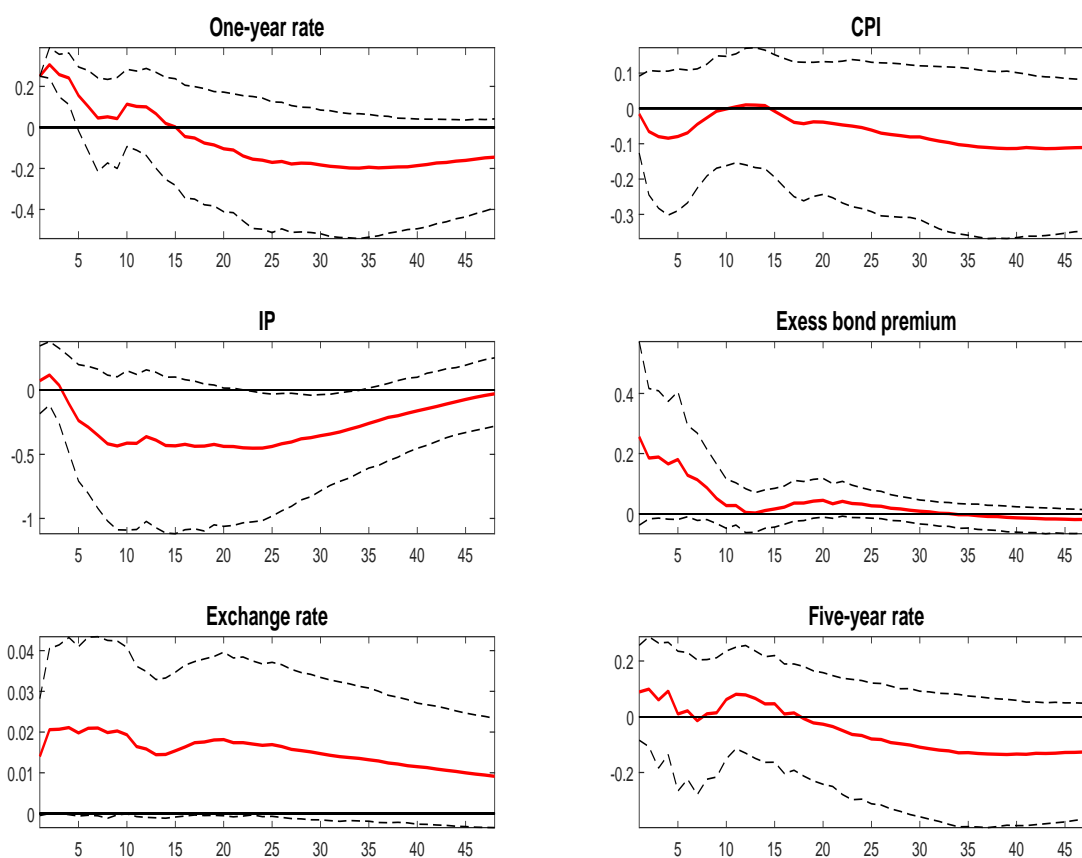


Figure 12: Responses of Variables to Monetary Policy Shock: Exchange Rate Channel



Notes: The figure represents IRFs of (log of) exchange rate, 100 times the log CPI, 100 times the log IP, the EBP, and short-and long-term interest rates to a positive monetary policy shock via exchange rate channel over the subsequent 48 months. The dashed lines represent 68 % confidence intervals.

Figure 13: Responses of Variables to Monetary Policy Shock: Policy News Shock



Notes: The figure represents IRFs of (log of) exchange rate, 100 times the log CPI, 100 times the log IP, the EBP, and short-and long-term interest rates to a positive monetary policy shock, policy news shock, obtained from Nakamura and Steinsson (2018) over the subsequent 48 months. The dashed lines represent 68 % confidence intervals.