A Model of Monetary Policy Shocks for Financial Crises and Normal Conditions

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for Financial Crises and Normal Conditions[*]

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Abstract

Deteriorating economic conditions in late 2008 led the Federal Reserve to lower the target federal funds rate to near zero, inject liquidity into the financial system through novel facilities, and engage in large scale asset purchases. The combination of conventional and unconventional policy measures prevents using the effective federal funds rate to assess the effects of monetary policy beyond 2008. This paper develops an approach to identify the effects of monetary policy shocks in such instances. We employ a newly created broad monetary aggregate to elicit the effects of monetary policy shocks both prior to and after 2008. Our model produces plausible responses to monetary policy shocks free from price, output, and liquidity puzzles that plague other approaches. It also produces a series of monetary policy shocks which aligns well with major changes in the Fed's asset purchase programs.

1 Introduction

What are the macroeconomic effects of monetary policy? Prior to 2008, two conclusions had emerged from a voluminous literature addressing this question. First, since about the mid-1960s, the effective federal funds rate is the single best indicator of the stance of monetary policy. Second, unexpected increases in this interest rate decrease output and prices. In a classic paper which served to advance this consensus, *Monetary policy shocks: What have we learned and to what end?*, Christiano, Eichenbaum, and Evans (1999) thoroughly investigate one of the most widely used methods for identifying monetary policy shocks. Their empirical findings provide strong support for the identifying assumption that the central bank adjusts the federal funds rate in response to changes in output and prices but affects these variables with a lag.[1]

Unfortunately, this approach to identifying monetary policy shocks cannot be extended past 2008. The effective federal funds rate is not indicative of changes in the stance of monetary policy during the protracted seven years it was stuck at its lower bound. Moreover, due to this lower bound constraint, the Federal Reserve engaged in a number of unconventional policies including the creation of new liquidity facilities and large scale asset purchases. In light of these developments, there is renewed interest in the dynamic effects of monetary policy shocks, their importance over the business cycle, and how monetary policy shocks have shaped recent macroeconomic outcomes.

Our objective is therefore to develop a model of monetary policy shocks which can be employed in samples that include the 2008 financial crisis and in normal conditions while maintaining the timing assumption advocated in Christiano et al. (1999). To reach this end, we develop a VAR model which uses a broad monetary aggregate (Divisia M4, or DM4 hereafter) as the policy indicator. This approach is supported by the following four findings. First, unexpected changes in monetary policy in our money-based model do not generate output, price, or liquidity puzzles. Second, during normal conditions, policy shocks from our money-based model have similar effects to those found in the federal funds rate-based model that was widely used prior to the lower bound period. Third, our approach to identifying the effects of monetary policy shocks produces plausible responses which are robust in samples that include or exclude the 2008 financial crisis. Fourth, policy shocks have significant effects on output and prices. Therefore, we reach similar conclusions regarding the effects of monetary policy despite abandoning the federal funds rate as the policy indicator.

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[1] This assumption is inspired by earlier work including Bernanke and Blinder (1992), Gertler and Gilchrist (1994), Eichenbaum and Evans (1995), Christiano, Eichenbaum, and Evans (1996), and Bernanke and Mihov (1998a).

One concern raised by our approach is that the Federal Reserve has not shown any inclination towards using the DM4 aggregate as a policy instrument. This could, for example, call into question our interpretation of the shocks we identify as monetary policy shocks. But we believe our approach minimizes this concern. Using an empirically-sensible calibration for a standard New-Keynesian DSGE model, we show that the dynamic responses following a monetary policy shock to an interest rule can be replicated by an appropriately parameterized money growth rule reacting solely to inflation and output. This suggests a broad monetary aggregate could be used as the indicator of monetary policy in a recursive VAR for the purpose of identifying monetary policy shocks, even if the central bank follows an interest rate rule. Indeed, we also find that the dynamic responses to a policy shock, from our money-based VAR model, are remarkably similar to responses found in the federal funds rate-based VAR model over the pre-2008 sample. Furthermore, when we extend our money-based model to the post-2008 period, our identified monetary policy shocks align well with the narrative regarding the timing of sharp changes in the Federal Reserve's quantitative easing (QE) programs.

Of course, we are not the first to propose using a monetary aggregate as the policy indicator in a recursive VAR. The thorough analysis conducted by Christiano et al. (1999) seemingly closed the book on such specifications due to the puzzling responses of output, prices, interest rates, or other monetary aggregates in response to monetary policy shocks identified when M1 or M2 is the policy indicator. However, our approach employs a newly-developed, broader DM4 aggregate which has not been previously employed as a policy indicator in the monetary VAR literature.

Several factors lead us to work with DM4 as our policy indicator. First, the M4 aggregate includes assets that were especially targeted by the Federal Reserve's liquidity facilities such as institutional deposits, overnight and term repurchase agreements, commercial paper, and Treasury securities. Second, the Divisia variety of M4 is expenditure weighted and accompanied by a corresponding user cost which correlates closely with the federal funds rate prior to the zero lower bound period and remains well defined after 2008. Finally, the most compelling reason that leads us to use this aggregate is the absence of puzzling responses to monetary policy shocks that appear when the more popular M2 aggregate is employed in its place. Our DSGE model supports this empirical finding and provides a structural interpretation of the ability of DM4 – and inability of other aggregates – to identify monetary policy shocks without producing empirical puzzles.

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The remainder of the paper is organized as follows. Section 2 presents a small-scale New-Keynesian model with a monetary aggregate to study how well the effects of a monetary policy shock under an interest rate rule can be characterized by a money growth rule. Section 3 undertakes an empirical investigation in which, motivated by our theoretical analysis, we modify and extend the classic approach to identifying monetary policy shocks with Divisia M4 as the policy indicator. We also explore the robustness of our results to a monthly specification, for which the recursive assumption may be considerably more palatable, and compare our model to the shadow-rate approach to circumventing the zero lower bound. Section 4 concludes with an overview of the results and directions for future work.

2 Monetary policy shocks in a NK model with money

This section uses a small-scale New-Keynesian model of the business cycle to assess whether the dynamics that ensue after a monetary policy shock to an estimated interest rate rule can be characterized by a money growth rule. Trivially, the household's money demand equation defines a level of nominal balances that can support any equilibrium under an interest rate rule. However, we ask the distinct question: Can a nominal money growth rule that reacts only to price inflation and economic activity – excluding an independent reaction to interest rates – replicate the dynamic responses to a monetary policy shock under an interest rate rule? This class of rules is consistent with the central bank's information set in a recursive VAR with output and prices ordered ahead of the policy indicator. We find that for estimated interest rate rules, which feature a high-degree of interest rate inertia, an appropriately parameterized nominal money growth rule can closely replicate the impulse responses of output, prices, narrow and broad money, and interest rates in our small scale model.

2.1 A Small-Scale DSGE Model

This section describes the sticky price model we use as our laboratory to assess the effects of monetary policy shocks under different policy rules. In the appendix the model is derived in detail, however, here we only present the relevant log-linear model equations.

$$y_t = \frac{1}{1+h}\mathbb{E}_t y_{t+1} + \frac{h}{1+h}y_{t-1} - \frac{1-h}{1+h}\left(r_t - \mathbb{E}_t \pi_{t+1}\right) \tag{2.1}$$

$$m_t = \frac{1+\chi(1-h)}{(1+\chi)(1-h)}y_t - \frac{h}{(1+\chi)(1-h)}y_{t-1} - \eta r_t \tag{2.2}$$

$$\pi_t = \pi_{t-1} + \kappa\left(\frac{1}{1+h}y_t - \frac{h}{1+h}y_{t-1}\right) + \beta\mathbb{E}_t(\pi_{t+1} - \pi_t) \tag{2.3}$$

In the above equations, y_t is economy wide output, π_t denotes the quarterly inflation rate, r_t is the nominal interest rate on one-period bonds, and m_t denotes real money balances. Equation (2.1) is the household's Euler equation which relates the habit-adjusted rate of output growth to the real return on a 1-period bond with $0 \leq h \leq 1$ governing the degree of external habits. Equation (2.2) is the household's money demand equation in which $\eta > 0$ is the interest semi-elasticity which is pinned-down for a given value of $\chi > 0$ which calibrates the elasticity of the amount of time the household must allocate to shopping with respect to the velocity of money. Equation (2.3) summarizes the pricing decision firms make when they can only occasionally reoptimize their price. The parameter $0 < \beta < 1$ is the household's discount factor. The parameter $\kappa = (1-\alpha)(1-\beta\alpha)/\alpha$ is the slope of the Phillips curve, in which $1 - \alpha$ is the probability that any given firm is able to reoptimize its price this period. We assume that firms who are unable to optimally set their prices in the current period index their prices according to last period's inflation rate. This assumption, that prices are indexed to lagged inflation, is important for generating empirically plausible dynamics to a monetary policy shock (Christiano, Eichenbaum, and Evans, 2005).[2]

One deviation from the standard models, found for example in Woodford (2003) and Gali (2008), is that a broad measure of money is specified in our model as a CES aggregate of currency and interest bearing assets as in Belongia and Ireland (2014). This adjustment is made to allow for a more direct comparison to the monetary aggregate used as the policy indicator in our VAR model. Although the micro-foundations of monetary aggregation are more clearly spelled out with this specification, Equation (2.2) shows that after log-linearizing, the money demand equation that results is isomorphic to those found in textbook New Keynesian models.[3]

The model is closed with a specification of monetary policy which we assume can be described by an interest rate feedback rule. Our preferred rule includes output growth as opposed to the output

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[2]We omit any non-monetary shocks, as in Christiano et al. (2005), since our focus is on the response to monetary policy shocks.

[3]However, we show in Section 3.6 that our approach to modeling the monetary aggregate is useful for understanding our avoidance of common puzzles relative to the previous structural VAR literature which has used monetary aggregates to identify policy shocks.

gap to align the rule with the information set of the Federal Reserve in our VAR model:

$$r_t = \rho r_{t-1} + (1 - \rho)(\phi_\pi \pi_t + \phi_y(y_t - y_{t-1})) + \varepsilon_t^{mp}, \qquad (2.4)$$

where ε_t^{mp} is an i.i.d. monetary policy shock. Similarly, we allow for monetary policy to be described by a nominal money growth rule

$$\mu_t = \bar{\rho}\mu_{t-1} + (1 - \bar{\rho})(\bar{\phi}_\pi \pi_t + \bar{\phi}_y(y_t - y_{t-1})) - \bar{\varepsilon}_t^{mp}, \qquad (2.5)$$

where $\mu_t = m_t - m_{t-1} + \pi_t$.

2.2   Approximating Monetary Policy Shock Dynamics

We now turn to the question of whether the effects of policy shocks under an interest rate rule can be approximated by policy shocks under a money growth rule. Furthermore, we restrict the policy rules we consider to be consistent with the recursive ordering in our VAR which orders output and prices ahead of the policy indicator. Our results in this section indicate that we are able to qualitatively approximate the responses of the economy under all the interest rate rules considered. However, we show that our quantitative success depends on the degree of inertia in the underlying Taylor rule. Rules with greater inertia are better approximated by money growth rules. Therefore, our empirical strategy is supported by the evidence of a large amount of inertia in interest rate rules over the 1967-2007 period, which we later summarize.

The calibration of the model is standard. Each period is assumed to equal 1-quarter and therefore the household's discount factor $\beta = 0.99$. The slope of the Phillips curve is governed by $\alpha = 0.75$ implying an average duration of prices equal to one year which is consistent with the micro evidence presented in Nakamura and Steinsson (2008). The degree of habit persistence $h = 0.65$ as estimated in Christiano et al. (2005). The interest semi-elasticity of money demand is set to $\eta = 1.9$ as estimated in Ireland (2009). This value is also consistent with the VAR evidence presented by Christiano et al. (2005) which suggests that the short-run interest semi-elasticity is considerably smaller than the longer-run elasticity specified by Lucas (2000). The parameters governing the CES aggregate of monetary assets are calibrated as in Ireland (2014).[4] Given a calibration of η, these

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[4]This equation is described in detail in equation 3.5 in Section 3.6.

parameters simply govern the way households allocate their portfolio between currency and interest bearing bank deposits, enabling us to define the monetary base and alternative monetary aggregates in the model economy.

We consider three alternative interest rules for our model experiment. The first rule is calibrated by estimating Equation (2.4) over the 1967-2007 sample on quarterly data via nonlinear GMM. We measure the short-term interest rate with the effective federal funds rate, inflation with the quarterly change in the logarithm of the GDP deflator, and output growth as the log difference in real GDP.[5] The resulting estimates imply that $\rho = 0.94$, $\phi_\pi = 2.20$, and $\phi_y = 2.69$ and all coefficients are found to be statistically significant. Relative to Clarida et al. (2000), who estimate $\rho = 0.79$, $\phi_\pi = 2.15$, and $\phi_y = 0.93$ using the output gap in place of output growth over the post-Volcker period, we find a bit more inertia in the policy rule and a larger reaction to real activity. However, the coefficient on inflation is in line with their estimates. While we prefer our specification which excludes the output gap — because it is absent from our VAR model — we also consider two rules which include a reaction to the output-gap as opposed to output growth. One is the aforementioned rule estimated by Clarida et al. (2000) (adjusted to represent a contemporaneous reaction function) while the other is the rule calibrated by Taylor (1993) which sets $\rho = 0$, $\phi_\pi = 1.5$, and $\phi_y = 0.13$.

We seek parameters $\bar{\rho}$, $\bar{\phi}_\pi$, and $\bar{\phi}_y$ of the the money growth rule to minimize the distance between the impulse response functions following a monetary policy shock under a given interest rate rule. The responses we seek to match are those of output, the price level, the monetary aggregate, the monetary base, and the short-term interest rate.[6] Following Christiano et al. (2005), we assume that households learn about the monetary policy shock after making their consumption plans and similarly firms learn about the monetary policy shock after setting their prices. This implies that output and prices don't move until the period after the monetary policy, as is the case in a recursive VAR with output and prices ordered ahead of the policy indicator.

A summary of the resulting money growth rule parameters $\bar{\rho}$, $\bar{\phi}_\pi$, and $\bar{\phi}_y$ is reported in Table 1. The money growth rule that best matches the responses under our estimated interest rate rule features no inertia in money growth ($\bar{\rho} = 0$) and positively responds to output growth ($\bar{\phi}_\pi = 0.54$) and inflation ($\bar{\phi}_\pi = 0.65$). A positive response of nominal money growth to output or inflation may

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[5] We use as instruments 1 to 4 lags of output growth, inflation, the federal funds rate, commodity price inflation, Divisia M4 growth, and the 10 year-2 year term spread. This selection of instruments follows closely from Clarida, Gali, and Gertler (2000).

[6] The responses of individual variables are scaled when entered into the loss function so that each variable is of a similar order of magnitude.

seem counterintuitive. But, empirically such estimates are not uncommon (Sims and Zha, 2006). Moreover, what matters from a stabilization standpoint is that the coefficients are less than one. To see this, combine the money growth rule (Equation (2.5)) with the money demand function (Equation (2.2)) (assuming momentarily that $h = 0$) and put r_t on the left-hand-side:

$$r_t = r_{t-1} + (1/\eta)[(1 - \bar{\phi}_\pi)\pi_t + (1 - \bar{\phi}_y)(y_t - y_{t-1}) + \bar{\varepsilon}_t^{mp}]. \tag{2.6}$$

So long as $\bar{\phi}_\pi$, and $\bar{\phi}_y$ are less than one the central bank actively stabilizes the economy (in the sense of Leeper (1991)). Positive values of $\bar{\phi}_\pi$, and $\bar{\phi}_y$ that are less than one simply moderate this countercyclical monetary policy response.

To best match the rule from Clarida et al. (2000), the central bank adjusts money growth negatively in response to output and inflation. For both this rule and the estimated rule, the coefficients on real economic activity and inflation are small and far away from the restrictions imposed that: $-1 < \bar{\rho} < 1$, $-10 < \bar{\phi}_\pi < 1$, and $-10 < \bar{\phi}_y < 1$. However, the money growth rule that best replicates a Taylor (1993) rule reaches the lower bound constraint for $\bar{\phi}_\pi$.

The resulting impulse responses are illustrated in Figure 1. Under our estimated rule (the first column), output features a hump-shaped response and prices fall gradually suggesting a fair amount of inflation inertia. Monetary quantities fall immediately reflecting a clear liquidity effect. As the initial effects of the shock fade and money growth stabilizes, a long run price effect takes hold leading to permanent declines in the nominal level of narrow and broad money. A nominal money growth rule is able to essentially replicate these impulse responses. Similarly, if we simulate a monetary policy shock under the policy rule estimated by Clarida et al. (2000) we find a near observational equivalence. The fit deteriorates marginally relative to our estimated rule, but the differences are not obvious (see the second column of Figure 1), in this rule which effectively replaces output growth with output but maintains a large degree of policy inertia. Meanwhile, when we attempt to fit impulse responses to a Taylor rule featuring no policy inertia, shown in the third column of Figure 1 the fit for the price level deteriorates more significantly. The money growth rule struggles to generate as persistent a decline in output, and hence, by way of the Phillips Curve, fails to generate a large enough decline in prices.

To understand why monetary policy shocks under a money growth rule are a better fit to the model's dynamics under some interest rate rules than others, suppose for simplicity that $h = 0$ and

$\bar{\rho} = 0$. Then the Taylor (1993) rule is given by:

$$r_t = \phi_\pi \pi_t + \phi_y y_t + \varepsilon_t^{mp},$$

while the implied interest rate rule, under the money growth instrument regime is given by:

$$r_t = r_{t-1} + (1/\eta)[(y_t - y_{t-1}) + (1 - \bar{\phi}_\pi)\pi_t - \bar{\phi}_y y_t + \bar{\varepsilon}_t^{mp}],$$

where the last equality combines the money growth rule (Equation (2.5)) with the money demand function (Equation (2.2)). This implied interest rate rule suggests two potential explanations for the inability to quantitatively fit a nominal money growth rule's monetary policy impulses to those under the Taylor (1993) rule. The first is the large amount of inertia in the implied interest rate rule under a money growth instrument rule that is absent from the Taylor (1993) rule. The second discrepancy could come from the lack of an output growth response in the Taylor (1993) rule. However, the results in the second column of Figure 1 indicate that the lack of an output growth response is not all that detrimental to fitting the impulse responses. In particular, we are able to closely approximate the dynamics under the Clarida et al. (2000) rule which also lacks any reaction to output growth but features a large degree of interest-rate smoothing.

Thus we conclude that interest rate inertia is the primary factor determining whether monetary policy impulses under interest rate rules can be well approximated by money growth rules. Given that a range of evidence supports a high degree of persistence in estimated interest rate reaction functions over the 1967-2007 period, money growth holds promise as an alternative indicator of monetary policy in a VAR over this period. In addition to our policy rule estimates, Clarida et al. (2000) find evidence of inertia in monetary policy over the 1960-1979 sample as well as the 1979-1996 sample. Similarly, using Greenbook data, Orphanides (2001) finds substantial persistence in interest rate changes over the 1987-1994 period. Coibion and Gorodnichenko (2012) also present evidence that target interest rate changes are persistent because of an explicit desire to gradually adjust rates over the 1987-2006 sample. Widespread evidence of interest rate smoothing is reassuring to our empirical strategy since monetary aggregates are thought to have played a less prominent role in Federal Reserve policy over portions of our sample (Sims and Zha, 2006).

3   A Robust Model of Monetary Policy Shocks

The theoretical model laid out above is used to help formulate our new strategy for identifying monetary policy shocks based on the reduced-form vector autoregression (VAR):

$$z_t = B_1 z_{t-1} + \ldots + B_q z_{t-q} + u_t \tag{3.1}$$

where q is the number of lags and $E u_t u_t' = V$ is the covariance matrix for residuals.[7] Correspondingly, a linear structural model may be written as:

$$A_0 z_t = A_1 z_{t-1} + \ldots + A_q z_{t-q} + \varepsilon_t \tag{3.2}$$

where $\mathrm{E} \varepsilon_t \varepsilon_t' = \mathrm{D}$ is the diagonal covariance matrix for structural shocks.[8] The variables in the model are categorized into three groups:

$$z_t = (X_{1t}', X_{2t}', X_{3t}')'. \tag{3.3}$$

Each group might consist of multiple variables; however, in this work, X_{2t} is a single policy indicator. The structure is assumed to take on the following form:

$$A_0 = \begin{bmatrix} A_{11} & 0_{12} & 0_{13} \\ A_{21} & A_{22} & 0_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \tag{3.4}$$

where A_{ij} is an $n_i \times n_j$ matrix of parameters and 0_{ij} is an $n_i \times n_j$ zero matrix. The vector of structural shocks is given by: $\varepsilon_t = (\varepsilon_{1t}', \varepsilon_{2t}', \varepsilon_{3t}')'$. Christiano et al. (1999) prove that under these assumptions the Cholesky factor of V will identify the effects of shocks to the structural equation for X_{2t}.[9]

This identification assumes that the policy variable, X_{2t}, responds contemporaneously to X_{1t}, a set of important macroeconomic variables that slowly adjust to policy and a variety of other nominal

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[7]In all of our VAR models, $q = 5$ except in our monthly VAR in which case $q = 13$.

[8]For our purposes, X_{2t} is a single variable and so we only require that D take on a *block-diagonal* form. This condition is sufficient to make the policy shock uncorrelated with the other structural shocks.

[9]Keating (1996) generalizes Christiano et al. (1999), showing that if $n_2 > 1$ and A_{22} is a lower triangular matrix, the Cholesky factor of V will identify the effects of structural shocks for all n_2 shocks in ε_{2t}. Structures that take on this form are defined as partially recursive.

shocks. Throughout our analysis we follow Christiano et al. (1999) and identify monetary policy shocks using a block-recursive formulation in which X_{1t} consists of real GDP, the GDP deflator, and a commodity price index. The first two variables are included because of the assumption that central banks consider real output and prices when determining the stance of monetary policy. If the policy variable is the federal funds rate, a reaction to these two variables is consistent with a Taylor Rule formulation which is often assumed to describe the central bank's policy rule. The commodity price index has been included in previous work because it was thought to encapsulate current information about future price movements that forward-looking central banks tend to monitor. A key identifying assumption is that monetary policy has no contemporaneous effect on X_{1t}.

The third set of variables, X_{3t}, consists of money market variables that respond immediately to X_{1t} or X_{2t} but only affect these variables with a lag. In the benchmark specifications of Christiano et al. (1999), X_{3t} includes nonborrowed reserves, total reserves, along with M1 or M2. When Christiano et al. (1999) use money as the policy indicator then this lower block includes interest rates in its place. We follow their approach and include interest rates, or more precisely the user cost of DM4, in this block. Our use of the user cost is based on the fact that macroeconomic models typically include at least one interest rate. The user cost is a function of all interest rates relevant to the monetary aggregate and has not been subject to a lower bound constraint. An added advantage is that the user cost and the federal funds rate are highly correlated during the period when the federal funds rate was well above the zero lower bound.[10]

In contrast to the Christiano et al. (1999) specification, we exclude nonborrowed reserves (which take on negative values beginning in 2008) and replace total reserves with the monetary base. We choose to work with the monetary base instead of total reserves since an open market operation that changes the amount of inside money has the same effect on the monetary base irrespective of how the composition between currency and reserves is affected. However, in practice, we find little difference in the impulse responses when we replace the monetary base with total reserves.

3.1 Baseline VAR Model

We propose using DM4 as the policy indicator variable to identify monetary policy shocks. Although the Federal Reserve has never formally targeted such a broad monetary aggregate, the theoretical

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[10]Using quarterly data from 1967 to the end of 2007, the correlation is 0.96 for the series in levels and 0.74 when both are differenced.

analysis in our DSGE model suggests this does not preclude its use as a policy indicator for measuring the effects of monetary policy shocks.[11] Indeed, in this section we show this approach is capable of producing impulse responses which: i) are free from empirical puzzles, ii) are robust across samples that include or exclude the recent zero lower bound period, and iii) have significant effects on output and prices. Figure 2 reports results based on the sample period ending in 1995:Q2 used in Christiano et al. (1999), the pre-crisis period ending in 2007, and the full sample ending in 2015, respectively.

We first analyze impulse responses to a negative monetary policy shock over the pre-crisis period in our baseline model which uses DM4 as the policy indicator. The results are shown in the second column of Figure 2 along with 90% probability intervals.[12] The impact response of output is restricted to be zero by assumption. But in subsequent periods output falls with a trough response after about two years before gradually increasing towards zero. This generates a hump-shaped dynamic for real GDP which has been a hallmark feature of monetary VARs. The negative output response is significant for three years after the initial shock. Prices display considerable inertia, not moving until six quarters after the shock. Importantly, we find no evidence of a price puzzle as the price level eventually falls a statistically significant amount two years later and the point estimate is never positive. Commodity prices fall even faster than the overall price level. The first column of Figure 2 shows the impulse responses over the Christiano et al. (1999) sample. The dynamics over this shorter sample are broadly similar and any minor differences in the point estimates between these two samples appear to be statistically insignificant.

The reaction of the monetary base and the user cost of DM4 are left unconstrained following the shock. The monetary base falls on impact by a statistically significant amount and is consistently negative thereafter. Furthermore, we identify a statistically significant liquidity effect on impact as the DM4 user cost rises on impact. However, this weighted average of rate spreads returns to its pre-shock value fairly quickly, with the short-run liquidity effect being the only significant response. In all, the decline in output and prices along with the rise in user cost reveals the ability of our DM4 model to produce impulse responses which are consistent with theoretical predictions about the effects of contractionary monetary policy shocks and free from the output, price, and liquidity puzzles that plague many monetary VARs.

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[11]We note that as in Bernanke and Blinder (1992) (see their footnote 4), there are no Lucas critique concerns raised by our approach since we are not analyzing the effects of a proposed change in the policy rule but instead we are analyzing the response of the economy over particular historical periods.

[12]All impulse response functions in the paper are accompanied by 90% probability intervals calculated using the approach in Sims and Zha (1999), as implemented in Koop and Korobilis (2010).

We now extend the sample period over which we estimate our VAR to include the recent financial crisis and ensuing zero lower bound period. The impulse responses are shown in the third column of Figure 2. Qualitatively the effects are similar to the pre-crisis sample responses. Output falls with a hump-shaped pattern, prices respond sluggishly — beginning to fall after about four quarters, but significantly falling more than two years after the shock — while interest rates, measured by the user cost of money, rise on impact before returning towards zero after about one year. This shows that in samples which include the recent crises our DM4 model continues to produce plausible impulse responses free from output, price, and liquidity puzzles.

Although the impulse responses are qualitatively unchanged across samples, there are two quantitative differences when we extend our model through the end of 2015. First, prices fall by less than they did in the pre-crisis sample. The dampening of the price response becomes even more apparent when comparing the responses in the sample ending in 1995 and the full sample. This is consistent with the widespread belief that the Phillips curve has flattened over time (Blanchard, 2016). We also find substantial quantitative differences in the behavior of the monetary base in the full sample. Including the crisis period causes the base response to become very large compared to the pre-crisis sample. This suggests that the Fed had to inject a much larger amount of monetary base into the banking system to achieve a given amount of liquidity at the zero lower bound. In practice, large increases in the monetary base were accompanied by increases in the Federal Reserve's asset holdings. The increase in the Fed's assets occurred primarily through various rounds of QE.

The change in the response of the monetary base in the post crisis sample indicates a shift in monetary policy towards balance-sheet oriented policies. While this matches the narrative description of U.S. monetary policy post-2008, we now examine if our time series of identified shocks is consistent with this narrative. Figure 3 recovers the structural shocks from our VAR model to verify this interpretation. The series of policy shocks aligns with changes in the Federal Reserve's QE policies, cresting at the initiation of each of the three rounds of QE. Our identification strategy is even able to isolate the taper tantrum that occurred in the second quarter of 2013 as a large negative monetary policy shock.[13] The ability of our VAR model to isolate policy surprises which broadly

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[13]In May, then Chairman Bernanke suggested during congressional testimony that the pace of asset purchases may be tapered if the U.S. economy continues to improve and then reiterated this view in a press conference after the June FOMC meeting. Financial conditions tightened considerably with the yield on the 10-year Treasury note jumping nearly 50 basis points over this span, indicating that financial markets weren't expecting this shift in policy.

align with the narrative description of monetary policy reinforces the interpretation of our identified shocks as changes in the stance of monetary policy.

3.2   Comparison to the Christiano, Eichenbaum, and Evans (1999) Model

In this section we show that our money-based model of monetary policy shocks delivers similar conclusions regarding the effects of monetary policy when compared to the benchmark model of Christiano et al. (1999). Christiano et al. (1999) convincingly argue that using the federal funds rate as the indicator of monetary policy delivers the most sensible dynamics of all the models they consider. When we compare impulse responses using our preferred DM4 indicator in place of the federal funds rate in their FF (federal funds rate) benchmark model over admissible sample periods we find remarkably similar impulse responses from both a qualitative and quantiative standpoint. We view this as further evidence in favor of our approach since the primary issue with the workhorse model of Christiano et al. (1999) is the sample limitations following the global financial crisis and ensuing zero lower bound period.

We first compare our approach to identifying monetary policy shocks with the FF benchmark specification of policy shocks estimated over the original Christiano et al. (1999) sample. Figure 4 reports our estimated impulse responses. The first column is their FF benchmark model which uses the federal funds rate as the policy indicator and the second column is the DM4 benchmark model which replaces the federal funds rate with DM4.

The output and price responses generally share the same dynamics and statistical significance in both the FF and the DM4 benchmark models. Across these two benchmark specifications output falls with some delay and has a U-shaped response to a monetary contraction. The negative output response is significant after three quarters in the FF benchmark and significant after just one quarter in the DM4 benchmark. The price level response is eventually negative across both benchmark models. There is a longer delay before prices decline in the FF benchmark model relative to the DM4 benchmark model. The price response in the DM4 benchmark is always non-positive and becomes significantly negative after ten quarters. The commodity price response is initially zero, by assumption, but afterwards is consistently negative in both benchmark specifications.[14]

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[14]Comparing impulse responses in our FF benchmark model to those reported in Christiano et al. (1999) one finds only a few very modest differences which can be attributed to using a different commodity price index, a more recent vintage of data, and different lag lengths. A fourth difference is that our sample begins in 1967 due to the availability of the DM4 series.

The responses of the variables across the lower block of the FF and DM4 benchmark models are also similar. The responses of nonborrowed and total reserves in the DM4 benchmark model are always negative and sometimes statistically significant while the declines in the FF benchmark model are not significant. The response of M2 is always negative and frequently significant. Consistent with our DSGE model, we find DM4 can serve as the policy indicator and has similar effects on variables when the federal funds rate was used in this capacity.

We next estimate these two benchmark models (FF and DM4) with more recent data to examine the extent to which the impulse responses are similar over an extended sample period. How far we are able to extend the sample is limited by the effective lower bound on nominal interest rates and problems with nonborrowed reserves during the financial crisis. Nonborrowed reserves began taking on negative values in the first quarter of 2008.[15] Since this variable enters the VAR in log levels, our sample period goes from 1967:Q1 to 2007:Q4. We report the estimated impulse responses in Figure 5.

Once again the FF and DM4 benchmark models yield many responses to a policy shock that are qualitatively similar, consistent with the prediction from our DSGE model. The largest change in the impulse responses when we extend the sample is the response of prices. The FF benchmark model obtains a price puzzle that is initially statistically significant. On the other hand, the DM4 benchmark model has a statistically significantly negative price level response with a delay. The FF benchmark model generates counterintuitive positive responses for nonborrowed reserves and total reserves while the DM4 benchmark model is not subject to these puzzles. These statistically insignificant responses, along with the significant price puzzle, indicate some preference for the DM4 benchmark model even when the federal funds rate is away from the zero lower bound.

3.3 Shadow Rate Approaches to Circumventing the Zero Lower Bound

Shadow federal funds rate models provide an alternative means of dealing with the zero lower bound constraint. This approach replaces the effective federal funds rate with a hypothetical short-term rate that is not subject to a lower bound. Shadow rate VAR models seek to extend the success of federal funds rate-based VAR models of monetary policy pre-2008 to analyze the effects of monetary

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[15]This economic impossibility seems to have resulted from peculiar accounting. Since nonborrowed reserves equal total reserves minus borrowed reserves, some items were included in borrowed reserves that were not included in total reserves.

policy shocks afterwards. In this section, we explore the relative merits of this approach compared to our money-based VAR model.

Figure 6 shows impulse responses to an identified monetary policy shock using a shadow rate as the policy indicator. We utilize our baseline VAR model with the shadow rate in place of DM4 and M2 in place of the user cost. The first column uses the Lombardi and Zhu (2014) rate, the second column uses the Krippner (2013) rate, and the third column employs the Wu and Xia (2016) shadow rate. All three shadow rate VAR models display a persistent, and statistically significant, price puzzle. Aggregate prices rise persistently for the first year following a monetary policy shock. Prices eventually fall, but this decline is not significant after four years. Furthermore, the Krippner (2013) and Wu and Xia (2016) shadow rate VAR models also display a liquidity puzzle, with the monetary base initially rising following an unexpected increase in the shadow federal funds rate. The rise in the monetary base in the Krippner (2013) model is statistically significant for two quarters.

The price puzzles emanating from the shadow rate VAR models lead to uncomfortable implications when considering counterfactual monetary policy regimes. For example, Wu and Xia (2016) present a factor-augmented VAR which also displays a price puzzle to an identified monetary policy shock using their shadow federal funds rate as the policy indicator. Counterfactual exercises which leave their shadow rate at the zero lower bound after 2008 predict that this less accommodative policy stance would have led to lower levels of economic activity but *higher* aggregate prices. This prediction is at odds with theoretical models of unconventional monetary policy (Eggertsson and Woodford, 2003; Gertler and Karadi, 2011).

3.4   Quantitatively Assessing the Effects of Monetary Policy

We now turn to our baseline VAR model to quantitatively assess the effect of monetary policy shocks, focusing especially on the post-2008 period. Historical decompositions show that monetary policy shocks themselves have had positive, but negligible effects on output and prices since 2008. Hence, our baseline VAR model interprets the sequence of policy actions taken after 2008 as the Federal Reserve's endogenous response to economic conditions. Furthermore, we find that were the Federal Reserve to have allowed large deviations from its historical rule in light of the binding zero lower bound and thereby let the money supply collapse – as it did in the Great Depression – the U.S. economy would have experienced years of deflation and a much larger decline in output.

The first column of Figure 7 illustrates the contribution of monetary policy shocks during the zero lower bound period. Over this period, we find that policy shocks have on net been slightly positive (expansionary), leading to marginally higher levels of output and prices than otherwise would have been realized. However, the economic significance of these cumulative policy shocks is rather small with real GDP and the GDP deflator a mere 0.48% and 0.50% higher respectively than they would have been without monetary policy shocks. The evidence from these historical decompositions is echoed in the variance decompositions shown in Table 2. At its peak of about eight quarters, the share of the forecast error explained by monetary policy shocks is only 8.4%, and similarly, monetary policy shocks explain only 6.5% of the forecast error in prices even five years out. Thus, monetary policy shocks are not a major force driving business cycles, a common finding in the monetary VAR literature. We show this finding remains even when the post-2008 period is considered.

The negligible effects of monetary policy shocks on the economy does not imply that monetary policy more generally has not shaped macroeconomic outcomes in recent years. Instead, the small contribution of policy shocks to output and prices suggests that the policy actions taken after 2008 largely represent the systematic component of monetary policy. To make this point clear, we report long-run policy coefficients with the growth rate of DM4 as the "left-hand-side" variable in each sample period in Table 3.[16] We follow Sims and Zha (2006) and report the long response to the growth rate of each individual variable as well as the combined response to all nominal variables. In all samples, we find that the policy response coefficients are generally small and not significant.[17] The point estimates of the long-run response to output growth, price inflation, and the sum of the coefficients on price and commodity price inflation are well below one. And, even after accounting for uncertainty surrounding these estimates, we find no evidence of passive policy behavior. In particular, the upper bound of the 90% probability interval falls below one for the output growth response as well as the individual and combined nominal growth responses in all samples.

The estimates across each sample appear most consistent with a constant DM4 growth rule. Since the Fed has never actually targeted DM4 money growth, we interpret this result as an indication that the Fed behaved 'as if' it stabilized broad money growth. Away from the zero lower bound, such behavior is consistent with an inertial interest rate rule reacting to output growth and inflation.[18]

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[16]We are grateful to an anonymous referee for this suggestion.

[17]The coefficient on commodity price inflation is statistically significant in the first sample, but this response does not appear to be economically significant. We also estimate that the short-run policy reaction of DM4 to output and prices is insignificant. This suggests we could order DM4 first in our recursive VAR. In results available upon request, we find similar impulse responses under this alternative specification.

[18]See equation 2.6 from our DSGE model.

Importantly, this mapping breaks down at the zero lower bound. Therefore, our interpretation of monetary policy as stabilizing broad money growth is useful when comparing monetary policy at and prior to the zero lower bound.

The estimated long-run policy rules sharpen two results established in this paper. First, there is remarkable stability in the qualitative effects of monetary policy shocks across samples. These shocks appear to be deviations from an implied DM4 money growth rule which is also stable across time. Second, the unconventional actions taken by the Federal Reserve largely promoted its traditional stabilization objectives. Therefore, viewed through the lens of our baseline VAR model, post-2008 monetary policy can be interpreted as preventing a prolonged contraction in broad money supply.

To illustrate this last point, we now conduct a second counterfactual where we assume that the Federal Reserve allows the broad money supply to collapse, as it did in the Great Depression. According to Friedman and Schwartz (1963), a sequence of monetary policy contractions turned a financially induced recession into the Great Depression. And more recently, Bernanke (2012) argued that the actions taken by the Federal Reserve following the global financial crisis prevented a repeat of this mistake during the Federal Reserve's second encounter with the zero lower bound.

The second column of Figure 7 supports the view that the actions taken by the Federal Reserve may have prevented something akin to a Great Depression 2.0 from being realized. If DM4 grew at the same rate from 2007:Q4 to 2015:Q4 as did M2 from 1929:Q3 to 1937:Q3, then Real GDP would have fallen by 12.65% (actual decline of 4.35%) from peak to trough and prices would have fallen with the rate of *deflation* reaching 4.1% (actual inflation of 0.26%). These estimates are likely conservative given that Romer and Romer (2013) show inflation expectations were also falling in the Great Depression, whereas our estimates are over a period of largely anchored inflation expectations. With this in mind, and all other caveats associated with comparing two different historical episodes, our baseline VAR suggests that the Federal Reserve's actions after 2008 were not large deviations from its historical policy rule. Instead, they prevented a much larger economic contraction, and likely fought off deflation.[19]

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[19]Our linear model also predicts that a more accommodative policy stance would have led to a stronger economic expansion. Recently, Belongia and Ireland (2017) have shown that if the Federal Reserve targeted a faster rate of money growth in recent years then output and prices would have grown more quickly leading to a more robust economic recovery. This result is supportive of our finding.

3.5 Robustness to Using Monthly Data

The key identifying assumption in the recursive VAR models estimated to this point restricts the impact response of output and prices to zero following a monetary policy shock. This assumption may be more palatable at a monthly frequency than quarterly. Therefore, an important question is whether we find any evidence that output and prices respond within the quarter when we allow for such movements by only imposing the zero impact restriction on monthly data. Of course, the monthly model also implies that the FOMC makes incremental adjustments to the stance of monetary policy 12 times per year when, in reality, the FOMC has only 8 regularly scheduled meetings each year.[20]

Figure 8 shows the impulse responses from our baseline VAR model estimated at a monthly frequency.[21] For the purpose of comparing the impulse responses from this monthly VAR with the baseline quarterly model, we aggregate the monthly impulse responses to quarterly by averaging the impulse responses across three consecutive months.

The impact responses of output and prices in the monthly model are not statistically different from the impact responses in the quarterly model. Therefore, even if we relax the assumption that output and prices are pre-determined within the quarter to simply assuming they are pre-determined within the month, we find no evidence of a quarterly adjustment to output and prices. Even beyond the impact responses, the time paths of output and prices are remarkably similar in our monthly model. The same is true for commodity prices, DM4, and the monetary base. Only the impact response for the user cost of DM4 from the quarterly model falls outside of the probability interval from the estimated monthly model which contains zero. Only 1 out of 102 quarterly model responses falls outside the 90 percent probability bounds. We interpret our findings as strong evidence of robustness to different data frequencies. And while the monthly model does lack a statistically significant liquidity effect, the overall qualitative inference from the monthly VAR aligns with the conclusions from the quarterly model and the quantitative inference is also quite similar.

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[20]Although the Fed has also at times conducted conference calls between its scheduled meeting dates to make additional changes to monetary policy.

[21]Real GDP and the GDP deflator were acquired from Haver Analytics. From 1967:01-1992:04 the monthly nominal and real GDP series are from Stock and Watson (2010) and after 1992:04 are from Macroeconomic Advisers. Both sources use a similar approach of informing their monthly estimates with source data used by BEA to construct the official quarterly data.

3.6 Why is DM4 Useful for Identifying Monetary Policy Shocks?

Our money-based VAR model has been shown to identify monetary policy shocks which result in impulse responses that are free from output, price, and liquidity puzzles across several samples. These results are at odds with the findings of most of the previous research on monetary VAR models that use money as the policy indicator. Eichenbaum (1992), Gordon and Leeper (1994) and Christiano et al. (1999) each consider a VAR model that uses a monetary aggregate as the policy indicator, and all of these works find evidence of an output, price, or liquidity puzzle. However, these previous studies have used narrower aggregates than what we consider. Additionally, the DM4 aggregate is an expenditure weighted measure. We argue this could be another source of divergence between our results and the previous literature.

In practice, Christiano et al. (1999) find that broader aggregates have more success identifying monetary policy shocks than narrower aggregates. One reason for this may be that a broad measure of money provides a wider scope of transmission mechanisms, some of which may be difficult to capture with a narrower aggregate. This provides a potential explanation for why VAR models using M1 as the policy indicator often lead to output puzzles.

M2 has considerably more success than M1 in avoiding output puzzles. However, using M2 as the policy variable we find that after a contractionary policy shock, the price level rises and, in some samples, the monetary base also rises.[22] This casts doubt on the interpretation of shocks to M2 as monetary policy shocks and led us to work with an M4 aggregate which contains institutional money market funds, overnight and term repurchase agreements, commercial paper, and Treasury bills. This aggregate is therefore capable of capturing non-bank transmission mechanisms. For example, Adrian and Shin (2010) show that traditional monetary policy has considerable effects on the repo holdings, and ultimately the "risk-taking," of large broker-dealers. Their finding suggests monetary policy may transmit through money markets and various short-term credit markets in ways captured by DM4 but not by M2.

In addition to plausibly capturing multiple transmission mechanisms of conventional monetary policy, DM4 is better suited than either M2 or DM2 to capture the multiple dimensions of monetary policy used in response to the Global Financial Crisis. In its capacity as lender of last resort, the Federal Reserve created the Primary Dealer Credit Facility which targeted repo markets and

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[22]Contingent on what variables are included in the money-market block, we find that M2-based models exhibit price or liquidity puzzles that are statistically significant in some samples. Although not reported here, these results are available upon request.

the Term Securities Lending Facility which auctioned treasuries in exchange for eligible collateral to promote liquidity in financial markets. The Federal Reserve also provided liquidity directly to investors and borrowers to ensure credit would flow to the economy despite the impairment of lending following Lehman's bankruptcy. These facilities targeted commercial paper markets (the Commercial Paper Funding Facility) and money market mutual funds (Asset-Backed Commercial Paper Money Market Mutual Fund Liquidity Facility) which had come under pressure due to increased demand for redemption. Since M4 contains these asset classes specifically targeted by the Federal Reserve's liquidity facilities it is better able to capture shifts in monetary policy after 2008 than would be a narrower aggregate.

Another important difference between our money-based VAR model and previous papers is that DM4 is an expenditure weighted monetary aggregate of the Divisia variety proposed by Barnett (1980). Nearly all macroeconomic aggregates are expenditure weighted, but surprisingly the most well-known monetary aggregates are not. While the difference may seem innocuous, our DSGE model suggests that unweighted aggregates (e.g. M1 and M2) can produce liquidity puzzles even when expenditure weighted aggregates do not.

In our DSGE model, the monetary aggregate M_t is defined by the CES function:

$$M_t = \left[\nu^{\frac{1}{\omega}} N_t^{\frac{\omega-1}{\omega}} + (1-\nu)^{\frac{1}{\omega}} D_t^{\frac{\omega-1}{\omega}} \right]^{\frac{\omega}{\omega-1}}, \tag{3.5}$$

where N_t denotes currency, D_t denotes interest bearing deposits, $0 \leq \nu \leq 1$ governs the weight placed on each asset in the CES aggregate, and $\omega \geq 0$ is the elasticity of substitution between each asset. An unweighted aggregate, which simply sums the nominal value of currency and deposits, will fail to internalize substitution effects when these are imperfectly substitutable assets.[23] This will result in an endogenous, time-varying gap between the unweighted aggregate and M_t even if ν and ω are constant. On the other hand, an expenditure weighted Divisia monetary aggregate perfectly tracks M_t up to second order (Diewert, 1976).[24]

We can illustrate the implications of this aggregation error in our DSGE model. Figure 9 plots the impact response of the unweighted monetary aggregate after a contractionary policy shock for different values of ν and ω. Across these simulations we hold the interest semi-elasticity fixed

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[23]Only if the assets are perfect substitutes (i.e. ω goes to infinity) would an unweighted aggregate be equal to M_t.
[24]This implies that in our log-linear model the Divisia monetary aggregate will equal M_t.

to maintain a stable money demand function.[25] Two implications emerge from this exercise as it pertains to the empirical literature on monetary policy shocks. First, the liquidity effect, as estimated by response of an unweighted aggregate following a monetary policy shock, is likely to be biased upwards and the degree of this bias will vary over time if the importance of, or substitutability between, some assets shift over time.[26] This is one possible explanation for the seeming difficulty in uncovering a stable response of M2 in monetary VARs (Gordon and Leeper, 1994; Bernanke and Mihov, 1998b). The second implication is that using unweighted aggregates as the policy indicator could easily result in a liquidity puzzle. The graph indicates a substantial range of values for ν and ω for which the interest rate and the unweighted aggregate are positively correlated following a monetary policy shock. This suggests that in addition to breadth, another possible explanation as to why we find no puzzles in our money-based VAR model is because DM4 is expenditure weighted.[27]

We can illustrate the independent contributions of breadth and expenditure weighting of DM4 by estimating our VAR model with DM2 – which is an expenditure-weighted measure like DM4, but decidedly narrower. Figure 10 shows impulse responses to monetary policy shocks with DM2 in place of DM4 (and the user cost of DM2 in place of the user cost of DM4) in our three sample periods. Responses are similar to our baseline DM4 model in both pre-crisis samples. However, the broader, expenditure-weighted DM4 aggregate performs marginally better in isolating monetary policy shocks over the full sample in terms of the impulse response of the price level and especially the monetary base. The main issue with DM2 is that, in the full sample estimates, an exogenous DM2-based policy shock causes the monetary base and DM2 to initially move in opposite directions. In particular, an unexpected tightening in policy, as indicated by a reduction in DM2, causes the monetary base to rise for four of the first five quarters before subsequently turning negative. Also, a tiny price puzzle arises. While neither of these effects are statistically significant, they are at odds with what monetary stimulus is theoretically thought to do.

The relative success when utilizing DM2 instead of M2 as the policy indicator highlights the merits of using expenditure weighted Divisia aggregates over their unweighted, simple-sum counterparts. Of course, our baseline model that utilizes DM4 is not plagued by output, price, nor liquidity puzzles. Therefore, these DM2 results also point to some marginal gain in utilizing a broader, ex-

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[25]This is achieved by adjusting the value of χ.

[26]In results available upon request, we show that the the liquidity effect as measured by the unweighted aggregate is understated, or of the wrong sign, when compared to the response of the weighted aggregate.

[27]For more information on the construction of the DM4 aggregate by the Center for Financial Stability see: http://www.centerforfinancialstability.org/amfm_data.php.

penditure weighted aggregate. The benefits of DM4 are especially visible during the financial crisis period. It is in this full sample that the DM2 model exhibits puzzles not present in our DM4 model. This can be explained by the fact that many of the types of assets targeted by the Federal Reserve during the crisis are components of DM4, but not included in DM2.

4 Conclusion

Much emphasis in the field of monetary economics has centered on understanding the effects of monetary policy on the aggregate economy. One goal of this paper is to characterize these effects under a wide variety of conditions. A good deal of recent work has focused exclusively on explaining, or accounting for, the aftermath of the recent US financial crisis with methodological departures from what was overwhelmingly orthodox just a few years ago. Thus, one might conclude that a consensus model might work under normal conditions, and a different rule book should be used to characterize large financial crises. While there may be certain advantages to studying different periods separately, we do not set out to analyze these sub-periods in a vacuum. Instead, we develop a new method for identifying monetary policy shocks that is suitable in both financial crises and normal conditions.

We extend the identifying assumption that central banks react to real economic activity and prices, but only affect these variables with a lag, to a framework that remains valid whether the federal funds rate is stuck at zero or not. Drawing heavily from the implications of a relatively standard New-Keynesian model of monetary policy, we propose using DM4 money as the policy indicator variable. Although we abandon the federal funds rate as the policy indicator, we reach similar conclusions regarding the qualitative effects of monetary policy. In both our theoretical and empirical analyses, we show that when the federal funds rate is above its lower bound, the dynamic responses are very similar whether DM4 or the federal funds rate is used. Moreover, the money-based model is able to measure the effects of monetary policy when the federal funds rate is at its effective lower bound.

Aside from our work, there has been a concerted effort to discover other options for measuring the effects of monetary policy during the recent zero lower bound period. In particular, Krippner (2013), Lombardi and Zhu (2014), and Wu and Xia (2016) use factor models to estimate "shadow" measures of the federal funds rate that extend beyond 2008. These shadow rates allow economists, in principle, to continue to use macroeconomic models that assign important roles to the federal funds

rate. However, the use of these shadow rates result in price and, in some cases, liquidity puzzles that our money-based model avoids. In addition to the reemergence of these puzzles when using these shadow rates, there is some question about which shadow rate to use. For example, Christensen and Rudebusch (2014) find that estimated shadow rates are sensitive to the number of factors used to estimate the term structure model and, therefore, warn against using the shadow rate to measure the stance of monetary policy.

Due to multiple changes in stewardship and operating procedures of the Fed during our sample of study, an obvious direction for future research is to estimate, rather than impose, dates of potential structural breaks. The efficacy of the monetary response to a financial crisis may be subject to structural change (see, e.g., Boivin, Kiley, and Mishkin (2010) among many others). In fact, there is a long tradition of characterizing the effects of monetary policy as time dependent. In a well-known contribution that excludes the most recent US financial crisis, Sims and Zha (2006) find that even if one assumes that US monetary policy has undergone changes in regime, the differences among them are not large enough to explain the US Great Inflation or its subsequent Great Moderation.

Qualitatively, our results show substantial robustness in the responses to monetary policy in various periods we consider. We expect qualitative conclusions to remain unchanged if we allow for time-varying parameters, although some differences in magnitudes are expected. Indeed our empirical analysis of impulse responses shows that during the financial crisis the Fed had to inject a much larger amount of monetary base into the banking system to achieve a given amount of liquidity. We also find evidence consistent with a flattening of the Phillips curve over time. However, there is no evidence of a fundamental change in the qualitative effects of monetary policy.

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A   Online Appendix for DSGE Model

This section describes the DSGE model used in the paper in detail. Our approach to modeling the household's portfolio of monetary assets follows closely from Belongia and Ireland (2014). The production side of the economy is a standard New-Keynesian model.

A.1   The household

The representative household enters any period $t = 0, 1, 2, ...$ with a portfolio consisting of maturing bonds B_{t-1} and monetary assets totaling A_{t-1}. The household faces a sequence of budget constraints in any given period. In the first sub-period the household buys and sells bonds, receives real wages W_t for hours worked H_t during the period, is paid dividends F_t from intermediate goods firms, purchases consumption goods C_t, pays lump-sum taxes T_t, and allocates its monetary assets A_{t-1}/Π_t net of central bank transfers τ_t between currency N_t and deposits D_t. Any loans L_t needed to finance these transactions are made at this time. This is summarized in the constraint below:

$$N_t + D_t = \frac{A_{t-1}}{\Pi_t} + \frac{B_{t-1}}{\Pi_t} - \frac{B_t}{R_t} + W_t H_t + F_t - C_t - T_t + L_t + \tau_t, \tag{A.1}$$

where $\Pi_t = P_t/P_{t-1}$. In the second sub-period, the household receives deposits with interest $R_t^D D_t$ and receives any residual assets of the bank F_t^b. The household then combines this income with currency to repay loans with interest $R_t^L L_t$. Any remaining funds are carried over into the next period in the form of monetary assets A_t, as summarized below:

$$A_t = N_t + F_t^b + R_t^D D_t - R_t^L L_t. \tag{A.2}$$

The household seeks to maximize their lifetime utility, discounted at rate β, subject to these constraints. The period flow utility of the household takes the following form:

$$U_t = \left[ln(C_t - hY_{t-1}) - \xi H_t - H_t^s \right].$$

The household receives utility from consumption relative to last periods aggregate demand (i.e. the household has external habits) and disutility from working and shopping. Time spent shopping increases with aggregate demand Y_t (i.e. long lines) but is reduced with higher liquidity services.

Therefore the time spent shopping takes the following form:

$$H_t^s = \frac{1}{\chi}\left(\frac{Y_t}{M_t}\right)^\chi. \tag{A.3}$$

The monetary aggregate, M_t, which enters the shopping-time function takes a rather general CES form:

$$M_t = \left[\nu^{\frac{1}{\omega}}(N_t)^{\frac{\omega-1}{\omega}} + (1-\nu)^{\frac{1}{\omega}}(D_t)^{\frac{\omega-1}{\omega}}\right]^{\frac{\omega}{\omega-1}}, \tag{A.4}$$

where ν calibrates the relative expenditure shares on currency and deposits and ω calibrates the elasticity of substitution between the two monetary assets. Given these parameters, χ is left free to calibrate the interest semi-elasticity of money demand.

The representative household faces the problem of maximizing its lifetime utility subject to its budget constraints. Letting $\mathcal{C}_t = [C_t, H_t, M_t, N_t, D_t, L_t, B_t, A_t]$ denote the vector of choice variables, the household's problem can be recursively defined using Bellman's method:

$$
\begin{aligned}
V_t\Big(B_{t-1}, A_{t-1}\Big) = \max_{\mathcal{C}_t} \Bigg\{ & \left[ln(C_t - hY_{t-1}) - \xi H_t - \frac{1}{\chi}\left(\frac{Y_t}{M_t}\right)^\chi\right] \\
& -\lambda_t^1\left(N_t + D_t - \frac{A_{t-1}}{\Pi_t} - \frac{B_{t-1}}{\Pi_t} + \frac{B_t}{R_t} - W_t H_t - F_t + C_t + T_t - L_t - \tau_t\right) \\
& -\lambda_t^2\left(M_t - \left[\nu^{\frac{1}{\omega}}(N_t)^{\frac{\omega-1}{\omega}} + (1-\nu)^{\frac{1}{\omega}}(D_t)^{\frac{\omega-1}{\omega}}\right]^{\frac{\omega}{\omega-1}}\right) \\
& -\lambda_t^3\left(A_t - N_t - F_t^b - R_t^D D_t + R_t^L L_t\right) + \beta\mathbb{E}_t\Big[V_{t+1}\Big(B_t, A_t\Big)\Big]\Bigg\}.
\end{aligned}
$$

The first order necessary conditions can be expressed by the following equations:

$$\frac{1}{(C_t - hY_{t-1})} = \beta\mathbb{E}_t\left[\frac{1}{(C_{t+1} - hY_t)}\frac{R_t}{\Pi_{t+1}}\right] \tag{A.5}$$

$$W_t = \xi(C_t - hY_{t-1}) \tag{A.6}$$

$$\frac{C_t - hY_{t-1}}{M_t} = \frac{\lambda_t^2}{\lambda_t^1}\left(\frac{Y_t}{M_t}\right)^{-\chi} \tag{A.7}$$

$$N_t = \nu M_t \left[\frac{\lambda_t^2/\lambda_t^1}{(R_t - 1)/R_t}\right]^\omega \tag{A.8}$$

$$D_t = (1-\nu)M_t \left[\frac{\lambda_t^2/\lambda_t^1}{(R_t - R_t^D)/R_t}\right]^\omega \tag{A.9}$$

$$M_t = \left[\nu^{\frac{1}{\omega}}(N_t)^{\frac{\omega-1}{\omega}} + (1-\nu)^{\frac{1}{\omega}}(D_t)^{\frac{\omega-1}{\omega}}\right]^{\frac{\omega}{\omega-1}}. \tag{A.10}$$

A.2 The goods producing sector

The goods producing sector features a final goods firm and an intermediate goods firm. There is a unit measure of intermediate goods producing firms indexed by $i \in [0, 1]$ who produce a differentiated product. The final goods firm produces Y_t combining inputs $Y_{i,t}$ using the production technology:

$$
Y_t = \left[\int_0^1 Y_{i,t}^{\frac{\theta-1}{\theta}} \, di \right]^{\frac{\theta}{\theta-1}},
$$

in which $\theta > 1$ governs the elasticity of substitution between inputs. The final goods producing firm sells its product in a perfectly competitive market, hence solving the profit maximization problem:

$$
\max_{Y_{i,t} \in [0,1]} P_t Y_t - \int_0^1 P_{i,t} Y_{i,t} \, di,
$$

subject to the above constant returns to scale technology. The resulting first order condition defines the demand curve for each intermediate goods producing firm's product:

$$
Y_{i,t} = \left(\frac{P_{i,t}}{P_t} \right)^{-\theta} Y_t. \tag{A.11}
$$

Given the downward sloping demand for its product in (A.11), the intermediate goods producing firm has the ability to set the price of its product above marginal cost. To permit aggregation and allow for the consideration of a representative firm, we assume all such firms have the same constant returns to scale technology:

$$
Y_{i,t} = H_{i,t}. \tag{A.12}
$$

The term $H_{i,t}$ in the production function denotes the level of employment chosen by the intermediate goods firm. Given the linear production function, the intermediate goods producing firm's real marginal cost takes the same functional form:

$$
MC_t = (1 - \mathcal{S}) W_t.
$$

A production subsidy, $\mathcal{S}$, is introduced to make the steady state price of goods equal to the marginal cost of production.

The price setting ability of each firm is constrained as in Calvo (1983). In this staggered price-setting framework, the price level P_t is determined in each period as a weighted average of the fraction of firms $1-\alpha$ that are able to re-optimize their price and the fraction α that leave their prices unchanged. Therefore, each firm maximizes the present value of its current and future discounted profits, taking into account the probability that the firm will not be able to re-optimize:

$$\max_{P_{i,t}^*} \mathbb{E}_t \sum_{j=0}^{\infty} (\beta\alpha)^j \frac{\lambda_{t+j}^1}{\lambda_t^1} \left[\Pi_{t+j-1,t-1} P_{i,t}^* Y_{i,t+j} - MC_{t+j} P_{t+j} Y_{i,t+j} \right]$$

subject to

$$Y_{i,t+j} = \left(\Pi_{t+j-1,t-1} \frac{P_{i,t}^*}{P_{t+j}} \right)^{-\theta} Y_{t+j},$$

where $\Pi_{t+j-1,t-1} \equiv P_{t+j-1}/P_{t-1}$ captures the indexation of prices to lagged inflation. The firm's first order condition is given by:

$$\mathbb{E}_t \sum_{j=0}^{\infty} (\beta\alpha)^j \frac{\lambda_{t+j}^1}{\lambda_t^1} Y_{i,t+j} \left(\Pi_{t+j-1,t-1} \frac{P_{i,t}^*}{P_{t-1}} - \Pi_{t+j,t-1} \frac{\theta}{\theta-1} MC_{t+j} \right) = 0. \tag{A.13}$$

Finally, in equilibrium, the aggregate price dynamics are determined by the following price aggregate:

$$\Pi_t^{1-\theta} = \alpha \Pi_{t-1}^{1-\theta} + (1-\alpha)(\Pi_t^*)^{1-\theta}, \tag{A.14}$$

where $\Pi_t^* = P_t^*/P_{t-1}$ and P_t^* is the optimal price firms choose who re-optimize in period t.

A.3   The Financial Firm

The financial firm performs the intermediation process of accepting household's deposits and making loans. The financial firm must satisfy the accounting identity which specifies assets (loans to firms plus reserves) equal liabilities (deposits):

$$L_t + rr D_t = D_t. \tag{A.15}$$

Although changes in banking regulation have effectively eliminated reserve requirements, banks may often choose to hold reserves in lieu of making loans. Therefore, instead of assuming the central

bank controls the reserve ratio rr, we assume it is exogenously fixed and represents the average ratio of deposits banks hold for regulatory and liquidity purposes.

The financial firm chooses L_t and D_t in order to maximize period profits:

$$\max_{L_t, D_t} R_t^L L_t - R_t^D D_t - L_t + D_t - x L_t,$$

subject to the balance sheet constraint (A.15). The term xL_t denotes the real resource costs banks bear in making loans. We assume for simplicity that these resources are not destroyed in the loan production process, but instead are rented and remitted back to the household as dividends F_t^b. Since the loan and deposits markets are perfectly competitive, substituting the balance-sheet constraint into the profit function and imposing zero profits results in the loan-deposit spread:

$$R_t^L - R_t^D = (R_t^L - 1)rr + x(1 - rr). \tag{A.16}$$

This expression describes the loan deposit spread as a weighted average of the (opportunity) cost of accepting one unit of deposits. The fraction rr are held as reserves which bears the foregone revenue of making loans while the remaining fraction $(1 - rr)$ are loaned out which bears the real resource cost of making a new loan.

A.4 Equilibrium and the Output Gap

Here we define the equilibrium conditions which close the model. Equilibrium in the final goods market requires that the accounting identity

$$Y_t = C_t \tag{A.17}$$

holds. Equilibrium in the money market and bond market requires that at all times: $A_t = A_{t-1}/\Pi_t + \tau_t$ and $B_t = B_{t-1} = 0$ respectively. Market clearing in the labor market requires that labor supply equals labor demand:

$$H_t = \int_0^1 H_{i,t} di = \int_0^1 Y_{i,t} di = \int_0^1 \left(\frac{P_{i,t}}{P_t} \right)^{-\theta} di Y_t$$

where the second equality uses the firm's production function (A.12) and the third equality uses the demand for the intermediate goods product (A.11). Therefore, aggregate output is related to price

dispersion and aggregate labor supply by:

$$Y_t = \left[\int\limits_0^1 \left(\frac{P_{i,t}}{P_t} \right)^{-\theta} di \right]^{-1} H_t. \tag{A.18}$$

The production subsidy $(1 - \mathcal{S})$ to the intermediate goods producers is set so that in steady state the subsidy offsets the steady state markup of the monopolistically competitive firm implying $1 - \mathcal{S} = (\theta - 1)/\theta$. Finally, the government funds this subsidy with lump-sum taxes from the household implying the following government budget constraint:

$$T_t = \mathcal{S} W_t H_t. \tag{A.19}$$

A.5   Monetary Aggregates

In addition to the monetary aggregate M_t, three other monetary aggregates are defined in the DSGE model. Since we consider policy rules that stabilize the inflation rate, the price level will inherit a unit root. Therefore, we define all three aggregates in terms of their nominal growth rates. The first aggregate we define is the monetary base, which we denote by $M_t^{\mathcal{B}}$:

$$\mu_t^{\mathcal{B}} = ln \left(\frac{M_t^{\mathcal{B}}}{M_{t-1}^{\mathcal{B}}} \Pi_t \right) = ln \left(\frac{N_t + rr D_t}{N_{t-1} + rr D_{t-1}} \right) + ln(\Pi_t), \tag{A.20}$$

so that $M_t^{\mathcal{B}}$ is equal to the sum of currency and reserves. The second aggregate is a weighted nonparametric Divisia aggregate $M_t^{\mathcal{W}}$ used to approximate the parametric aggregate M_t as defined by Barnett (1980):

$$\mu_t^{\mathcal{W}} = ln \left(\frac{M_t^{\mathcal{W}}}{M_{t-1}^{\mathcal{W}}} \Pi_t \right) = \frac{S_t^N + S_{t-1}^N}{2} ln \left(\frac{N_t}{N_{t-1}} \right) + \frac{S_t^D + S_{t-1}^D}{2} ln \left(\frac{D_t}{D_{t-1}} \right) + ln(\Pi_t), \tag{A.21}$$

where $S_t^N = (R_t - 1)N_t/((R_t - 1)N_t + (R_t - R_t^D)D_t)$ is the share of total implicit spending on monetary assets allocated to currency and $S_t^D = 1 - S_t^N$ is the complimentary share spent on deposits. The third aggregate is an unweighted aggregate $M_t^{\mathcal{U}}$ used to approximate the parametric aggregate M_t:

$$\mu_t^{\mathcal{U}} = ln \left(\frac{M_t^{\mathcal{U}}}{M_{t-1}^{\mathcal{U}}} \Pi_t \right) = ln \left(\frac{N_t + D_t}{N_{t-1} + D_{t-1}} \right) + ln(\Pi_t). \tag{A.22}$$

A.6 The Non-Linear Model

$$\frac{1}{C_t - hY_{t-1}} = \beta \mathbb{E}_t \left[\frac{1}{C_{t+1} - hY_t} \frac{R_t}{\Pi_{t+1}} \right] \tag{A.23}$$

$$W_t = \xi(C_t - hY_{t-1}) \tag{A.24}$$

$$M_t = Y_t^{\frac{\chi}{1+\chi}} (C_t - hY_{t-1})^{\frac{1}{1+\chi}} \left(\frac{\lambda_t^2}{\lambda_t^1} \right)^{-\frac{1}{1+\chi}} \tag{A.25}$$

$$N_t = \nu M_t \left[\frac{\lambda_t^2/\lambda_t^1}{(R_t - 1)/R_t} \right]^\omega \tag{A.26}$$

$$D_t = (1 - \nu)M_t \left[\frac{\lambda_t^2/\lambda_t^1}{(R_t - R_t^D)/R_t} \right]^\omega \tag{A.27}$$

$$M_t = \left[\nu^{\frac{1}{\omega}} (N_t)^{\frac{\omega-1}{\omega}} + (1 - \nu)^{\frac{1}{\omega}} (D_t)^{\frac{\omega-1}{\omega}} \right]^{\frac{\omega}{\omega-1}} \tag{A.28}$$

$$Y_t = \left[\int_0^1 \left(\frac{P_{i,t}}{P_t} \right)^{-\theta} di \right]^{-1} H_t \tag{A.29}$$

$$0 = \mathbb{E}_t \sum_{j=0}^{\infty} (\beta\alpha)^j \frac{\lambda_{t+j}^1}{\lambda_t^1} Y_{i,t+j} \left(\Pi_{t+j-1,t-1}\Pi_t^* - \Pi_{t+j,t-1} \frac{\theta}{\theta - 1} MC_{t+j} \right) \tag{A.30}$$

$$\Pi_t^{1-\theta} = \alpha\Pi_{t-1}^{1-\theta} + (1 - \alpha)(\Pi_t^*)^{1-\theta} \tag{A.31}$$

$$MC_t = \frac{\theta - 1}{\theta} W_t \tag{A.32}$$

$$R_t - R_t^D = (R_t - 1)rr + x(1 - rr) \tag{A.33}$$

$$Y_t = C_t \tag{A.34}$$

$$\mu_t^{\mathcal{B}} = ln\left(\frac{N_t + rrD_t}{N_{t-1} + rrD_{t-1}} \right) + ln(\Pi_t) \tag{A.35}$$

$$\mu_t^{\mathcal{W}} = \frac{S_t^N + S_{t-1}^N}{2} ln\left(\frac{N_t}{N_{t-1}} \right) + \frac{S_t^D + S_{t-1}^D}{2} ln\left(\frac{D_t}{D_{t-1}} \right) + ln(\Pi_t) \tag{A.36}$$

$$S_t^N = \frac{(R_t - 1)N_t}{(R_t - 1)N_t + (R_t - R_t^D)D_t} \tag{A.37}$$

$$S_t^D = \frac{(R_t - R_t^D)D_t}{(R_t - 1)N_t + (R_t - R_t^D)D_t} \tag{A.38}$$

$$\mu_t^{\mathcal{U}} = ln\left(\frac{N_t + D_t}{N_{t-1} + D_{t-1}} \right) + ln(\Pi_t) \tag{A.39}$$

A.7 The Log-Linear Model

In this section we provide a linear representation of the model by taking a first order Taylor expansion of the relevant equations around the steady state. Lower case variables denote log deviations from the steady-state: $g_t = ln(G_t) - ln(G)$, where G is the steady state value of G_t.

The Euler equation can be derived from combining (A.23) and (A.34):

$$y_t = \frac{1}{1+h}\mathbb{E}_t y_{t+1} + \frac{h}{1+h}y_{t-1} - \frac{1-h}{1+h}(r_t - \mathbb{E}_t\pi_{t+1}). \tag{A.40}$$

The money demand equation can be derived in two steps. First, we combine (A.26), (A.27) and (A.28) to show that:

$$\lambda_t^2/\lambda_t^1 = \left[\nu\left(\frac{R_t - 1}{R_t}\right)^{1-\omega} + (1-\nu)\left(\frac{R_t - R_t^D}{R_t}\right)^{1-\omega}\right]^{\frac{1}{1-\omega}}.$$

Then we use this expression for λ_t^2/λ_t^1 in (A.25) along with equations (A.33) and (A.34) to arrive at the following log-linear expression for real money balances:

$$m_t = \frac{1 + \chi(1-h)}{(1+\chi)(1-h)}y_t - \frac{h}{(1+\chi)(1-h)}y_{t-1} - \eta r_t, \tag{A.41}$$

so that in Equation (2.2) $\eta = \frac{1}{R}\left(\frac{\nu((R-1)/R)^{-\omega} + (1-\nu)((R-R^D)/R)^{-\omega}(rr - x(1-rr))}{\nu((R-1)/R)^{1-\omega} + (1-\nu)((R-R^D)/R)^{1-\omega}}\right)\frac{1}{1+\chi}$.

The Phillips Curve can be derived in two steps. First, log-linearizing (A.30):

$$\pi_t^* - \pi_{t-1} = (1 - \beta\alpha)\mathbb{E}_t\sum_{j=0}^{\infty}(\beta\alpha)^j(mc_{t+j} + \pi_{t+j,t-1} - \pi_{t+j-1,t-1}) - \pi_{t-1}$$

$$= (1 - \beta\alpha)\mathbb{E}_t\sum_{j=0}^{\infty}(\beta\alpha)^j\left(mc_{t+j} + \sum_{k=0}^{j}\pi_{t+j} - \sum_{k=0}^{j}\pi_{t+j-1}\right)$$

$$= \beta\alpha\mathbb{E}_t(\pi_{t+1}^* - \pi_t) + (1 - \beta\alpha)mc_t + (\pi_t - \pi_{t-1}).$$

The first relationship linearizes the firm pricing decision. The second equality uses $\pi_{t-1} = (1 - \beta\alpha)\sum_{j=0}^{\infty}(\beta\alpha)^j\pi_{t-1}$ and the third equality rewrites the infinite sum recursively. Next, linearize (A.31) and use the resulting expression $\pi_t - \pi_{t-1} = (1-\alpha)(\pi_t^* - \pi_{t-1})$ to eliminate $\pi_t^* - \pi_{t-1}$ above:

$$\pi_t = \pi_{t-1} + \frac{(1-\alpha)(1-\beta\alpha)}{\alpha}\left(\frac{1}{1-h}y_t - \frac{h}{1-h}y_{t-1}\right) + \beta\mathbb{E}_t(\pi_{t+1} - \pi_t). \tag{A.42}$$

where we have also written real marginal cost in terms of output by combining (A.24), (A.32), and (A.34) and linearizing.

A linear expression for the nominal growth in the monetary base is obtained by log-linearizing Equation (A.35):

$$\mu_t^{\mathcal{B}} = \gamma^{\mathcal{B}}(n_t - n_{t-1}) + (1 - \gamma^{\mathcal{B}})(d_t - d_{t-1}) + \pi_t, \tag{A.43}$$

where $\gamma^{\mathcal{B}} = \frac{\nu((R-1)/R)^{-\omega}}{\nu((R-1)/R)^{-\omega} + rr(1-\nu)((R-R^D)/R)^{-\omega}}$. Log-linearizing (A.36) reveals that: $\mu_t^{\mathcal{W}} = m_t - m_{t-1} + \pi_t$. Log-linearizing (A.39) provides an expression for the nominal growth rate of the un-weighted monetary aggregate:

$$\mu_t^{\mathcal{U}} = \gamma^{\mathcal{U}}(n_t - n_{t-1}) + (1 - \gamma^{\mathcal{U}})(d_t - d_{t-1}) + \pi_t, \tag{A.44}$$

where $\gamma^{\mathcal{U}} = \frac{\nu((R-1)/R)^{-\omega}}{\nu((R-1)/R)^{-\omega} + (1-\nu)((R-R^D)/R)^{-\omega}}$. Log-linear expressions for N_t and D_t are obtained from equations (A.26) and (A.27) as follows:

$$n_t = m_t + \omega \left[(1 + \chi)\eta - \frac{1}{R - 1} \right] r_t \tag{A.45}$$

$$d_t = m_t + \omega \left[(1 + \chi)\eta - \frac{rr - x(1 - rr)}{R - R^D} \right] r_t. \tag{A.46}$$

A.8   DSGE Calibration

We set $\beta = 0.99$ which implies an annualized nominal bond rate of 4% in this quarterly model. We set $\alpha = 0.75$ so the average duration of prices is about 1 year, as found by Nakamura and Steinsson (2008). The degree of habit persistence $h = 0.65$ as estimated in Christiano et al. (2005). The parameters governing the CES aggregate of monetary assets are calibrated as in Ireland (2014) who uses component level data on N_t and M_t to estimate Equation (A.26) so that $\omega = 0.5$ and $\nu = 0.2$. We set $rr = 0.02$ which is the average ratio of reserve to non-currency components of M2 from 1967 to 2007 using data from the Federal Reserve Bank of St. Louis. Using data from the Center for Financial Stability we find that setting $x = 0.0067$ implies the annualized steady state spread between R^L and R^D of 2.7% which is the average interest rate differential between the benchmark interest rate used to measure R_t^L and the own-rate on the non-currency components of M2. The interest semi-elasticity of money demand is set to $\eta = 1.9$ as estimated in Ireland (2009). This value of η is achieved by setting $\chi = 12$.

Table 1: DSGE Model Interest Rate and Calibrated Money Growth Rules

Responses of r_t to	Estimated Interest Rate Rule	Responses of ΔM_t to	Matched Money Growth Rule
r_{t-1}	0.94	ΔM_{t-1}	0.00
Δy_t	2.69	Δy_t	0.54
π_t	2.20	π_t	0.65
Responses of r_t to	Clarida et al. (2000) Rule	Responses of ΔM_t to	Matched Money Growth Rule
r_{t-1}	0.79	ΔM_{t-1}	0.05
y_t	0.93	y_t	-0.71
π_t	2.15	π_t	-1.18
Responses of r_t to	Taylor (1993) Rule	Responses of ΔM_t to	Matched Money Growth Rule
r_{t-1}	0.00	ΔM_{t-1}	-0.32
y_t	0.13	y_t	-4.51
π_t	1.50	π_t	-10.00

Note: The parameters governing the money growth rules are found by minimizing the distance between the impulse response functions under the interest rate rule and the money growth rule. The coefficients on output growth and inflation are restricted not to lie below -10.

Table 2: DM4 Baseline VAR Model (1967:Q1-2015:Q4)

Percentage of Forecast Error Variance Due to Monetary Policy Shocks

	4 Quarters Ahead	8 Quarters Ahead	20 Quarters Ahead
Real GDP	5.55	8.44	6.25
	(1.13, 12.59)	(1.36, 19.68)	(1.23, 17.56)
GDP Deflator	0.25	0.35	6.47
	(0.03, 1.83)	(0.06, 4.25)	(0.52, 18.18)
Commodity Prices	3.43	9.50	18.18
	(0.50, 9.54)	(1.71, 20.87)	(5.76, 29.03)
Divisia M4	70.68	43.73	30.94
	(54.87, 79.59)	(25.39, 58.44)	(11.65, 46.82)
Monetary Base	0.61	1.90	8.58
	(0.24, 5.36)	(0.39, 10.12)	(0.84, 22.52)
User Cost (M4)	3.40	2.41	3.02
	(0.71, 10.62)	(1.00, 9.64)	(1.49, 11.04)

Note: Numbers in parentheses are the boundaries of the associated 90% probability interval.

Table 3: DM4 Baseline VAR Model

Long-Run Policy Responses

Responses of Δ DM4 to	1967:Q1-1995:Q2	1967:Q1-2007:Q4	1967:Q1-2007:Q4
Δ y	0.03	-0.01	0.20
	(-0.23, 0.31)	(-0.28, 0.26)	(-0.06, 0.48)
Δ P	0.02	-0.19	0.01
	(-0.84, 0.87)	(-1.03, 0.62)	(-0.81, 0.85)
Δ Pcom	0.06	0.00	-0.04
	(0.01, 0.12)	(-0.05, 0.05)	(-0.10, 0.00)
Δ P + Δ Pcom	0.08	-0.19	-0.03
	(-0.76, 0.92)	(-1.02, 0.60)	(-0.85, 0.78)

Note: Numbers in parentheses are the boundaries of the associated 90% probability interval.
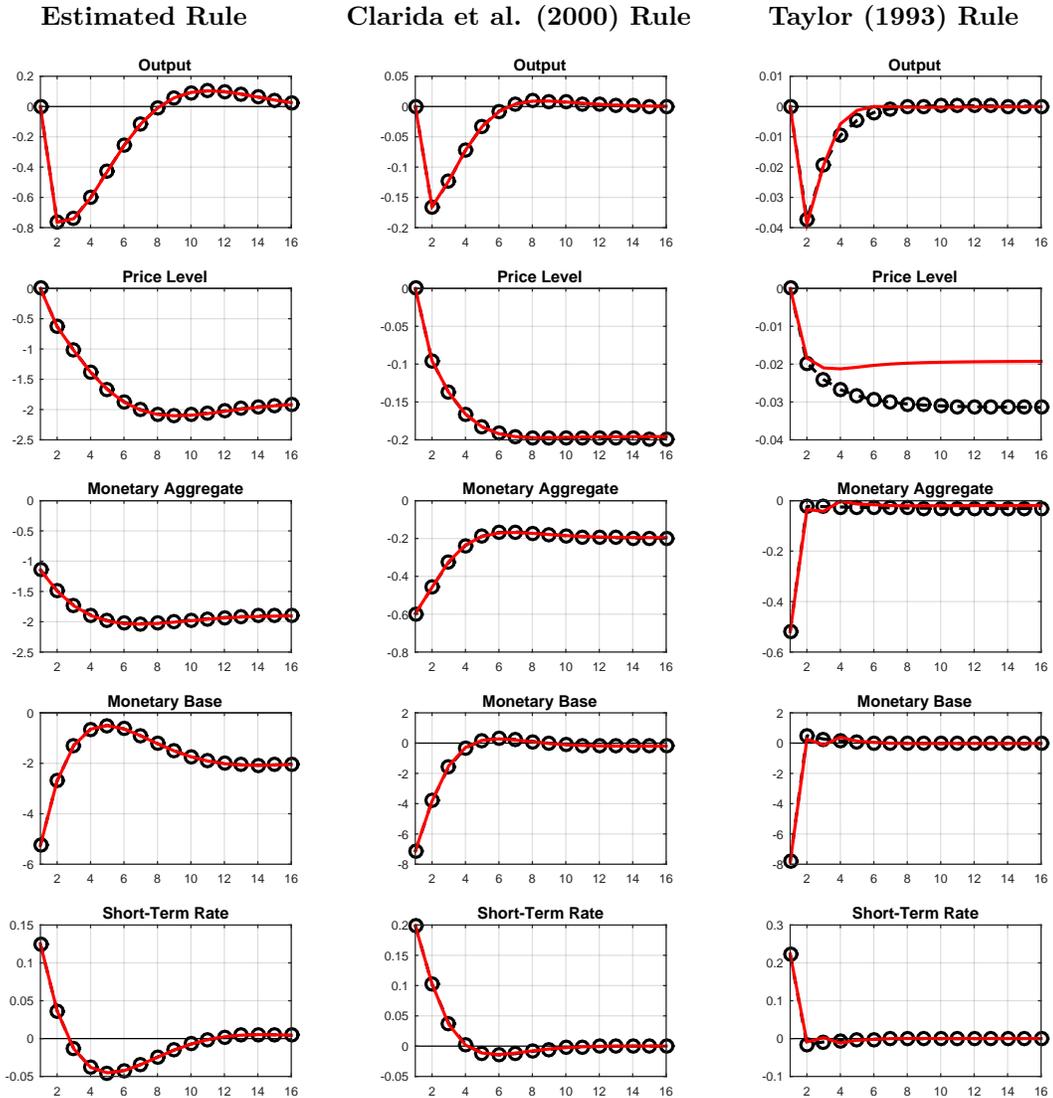
Figure 1: DSGE Model Impulse Responses
Contractionary monetary policy shocks under alternative monetary policy regimes. Dynamics following a monetary policy shock under an interest rate rule are denoted by the black dashed line with circles and the dynamics following a monetary policy shock under the money growth rule are shown by the red solid lines. The parameters governing the money growth rules are found by minimizing the distance between the impulse response functions under the interest rate rule and the money growth rule.
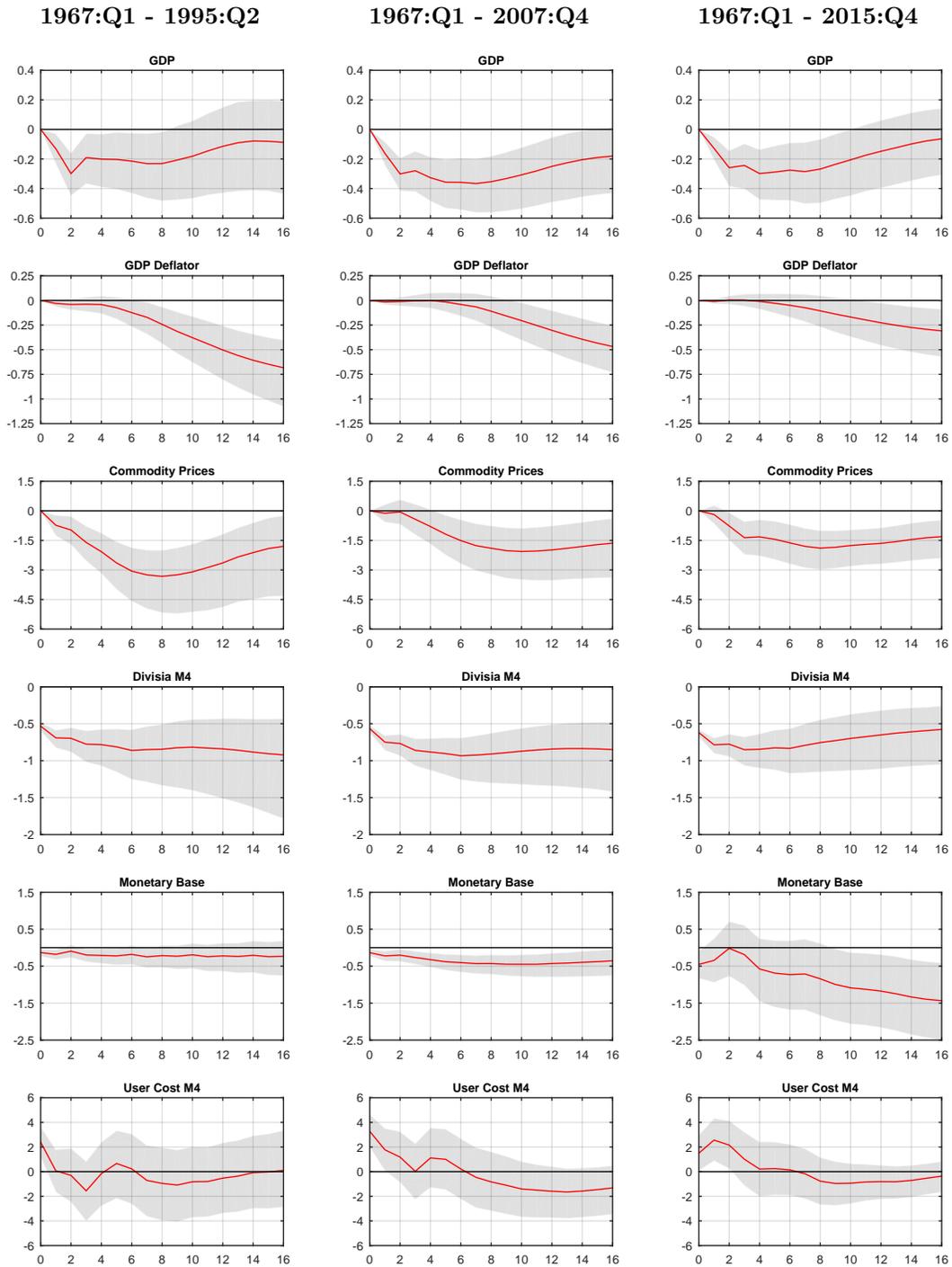
Figure 2: Baseline VAR Model (Various Sample Periods)
The Baseline VAR model uses DM4 as the policy indicator.

Cumulative Monetary Policy Shocks
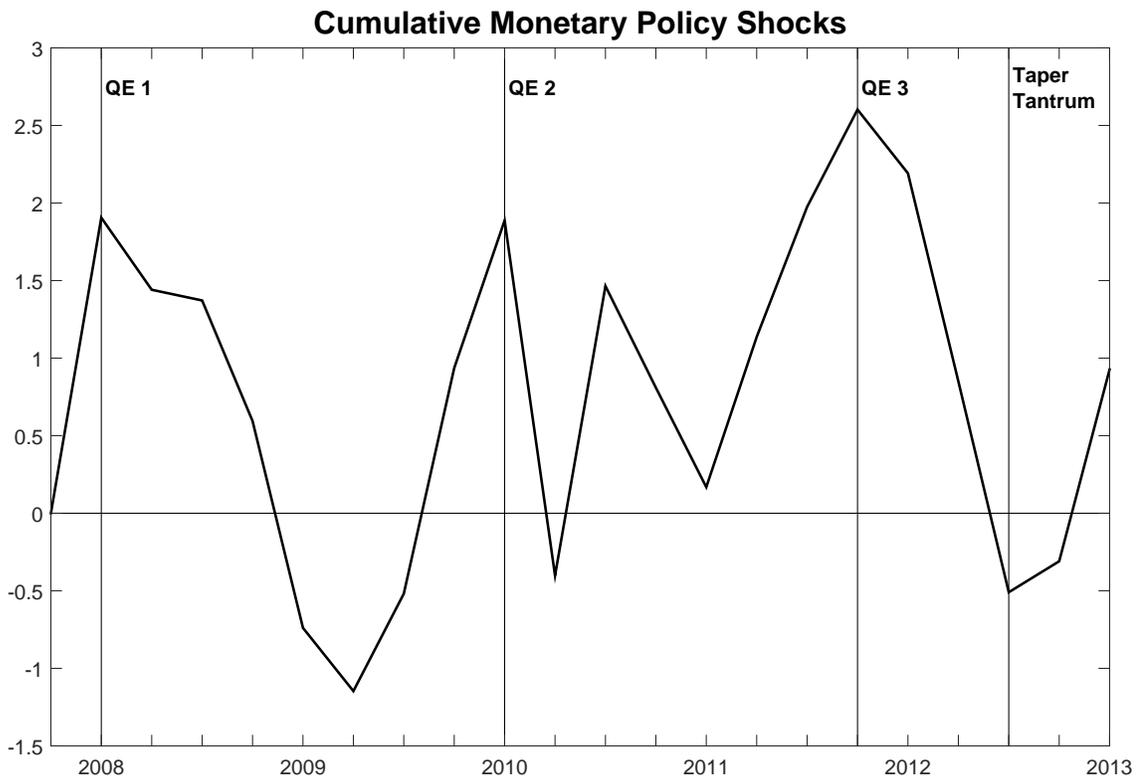
Figure 3: Structural Monetary Policy Shocks
This figure plots the cumulative sum of the structural monetary policy shocks from our baseline VAR model. The vertical bars denote the quarter in which the initiation of each round of QE was officially announced by the Federal Open Market Committee.
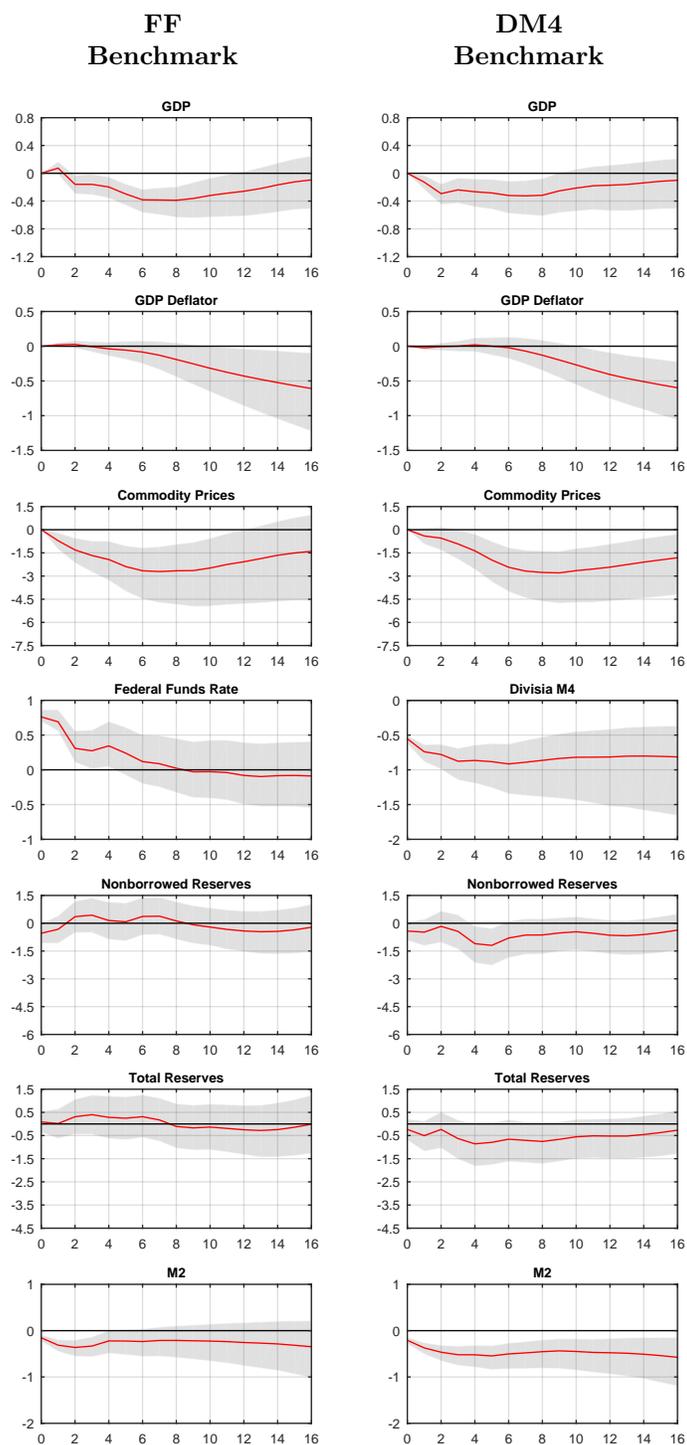
Figure 4: Benchmark Specifications (1967:Q1 - 1995:Q2)
The FF benchmark model of Christiano et al. (1999) uses the federal funds rate as the policy indicator variable. The DM4 benchmark model replaces the federal funds rate in the FF benchmark model with DM4.
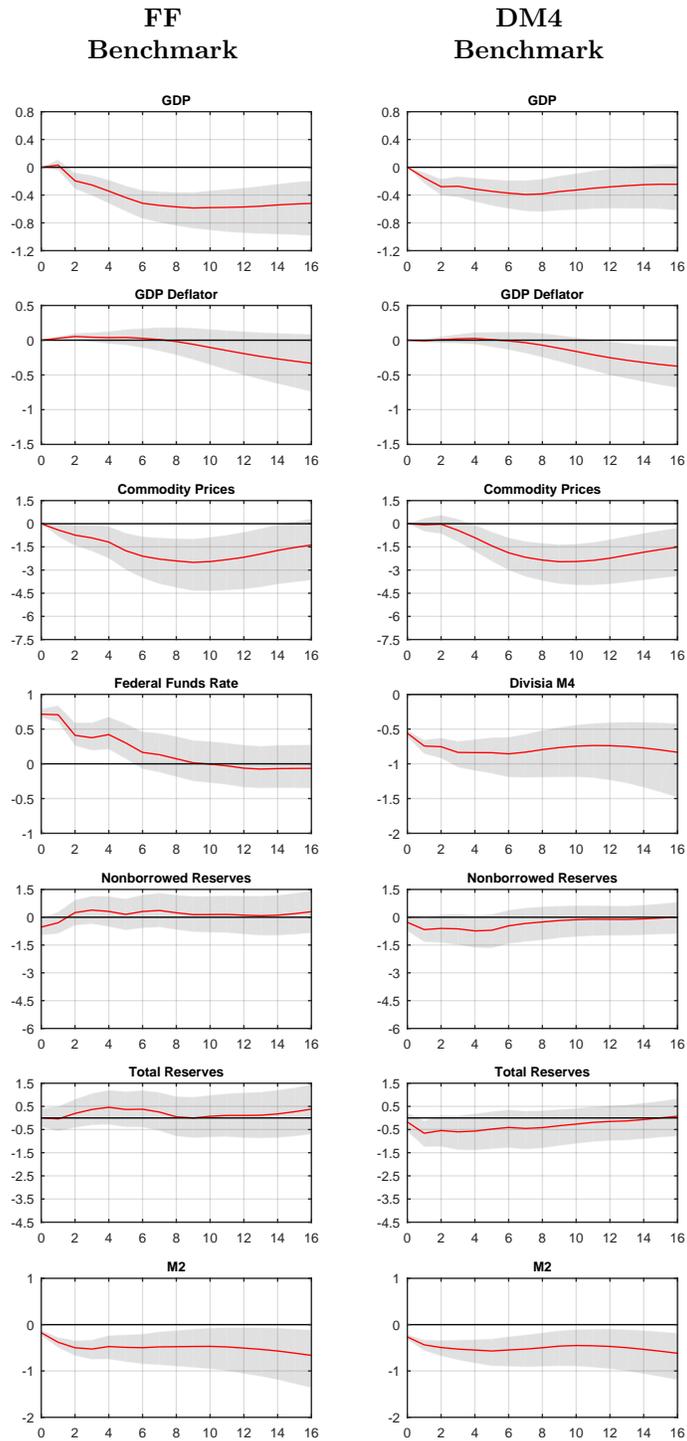
Figure 5: Benchmark Specifications (1967:Q1 - 2007:Q4)
The FF benchmark model of Christiano et al. (1999) uses the federal funds rate as the policy indicator variable. The DM4 benchmark model replaces the federal funds rate in the FF benchmark model with DM4.
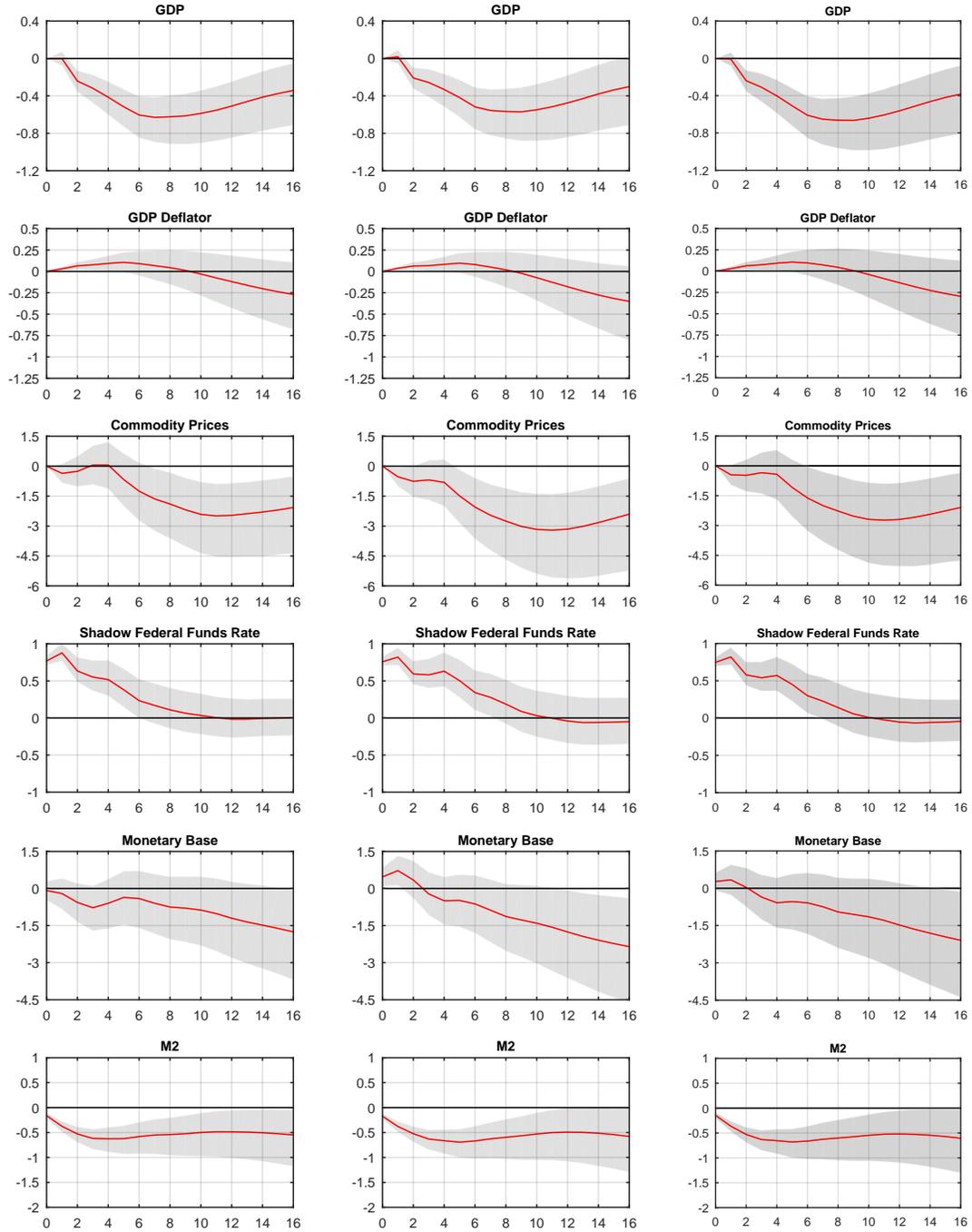
Figure 6: Shadow Rate VAR Models
Shadow rate VAR models replace DM4 with various shadow federal funds rates as the policy indicator variable in our baseline VAR model and adds M2 in place of the user cost of DM4.

No MP Shocks

Great Depression
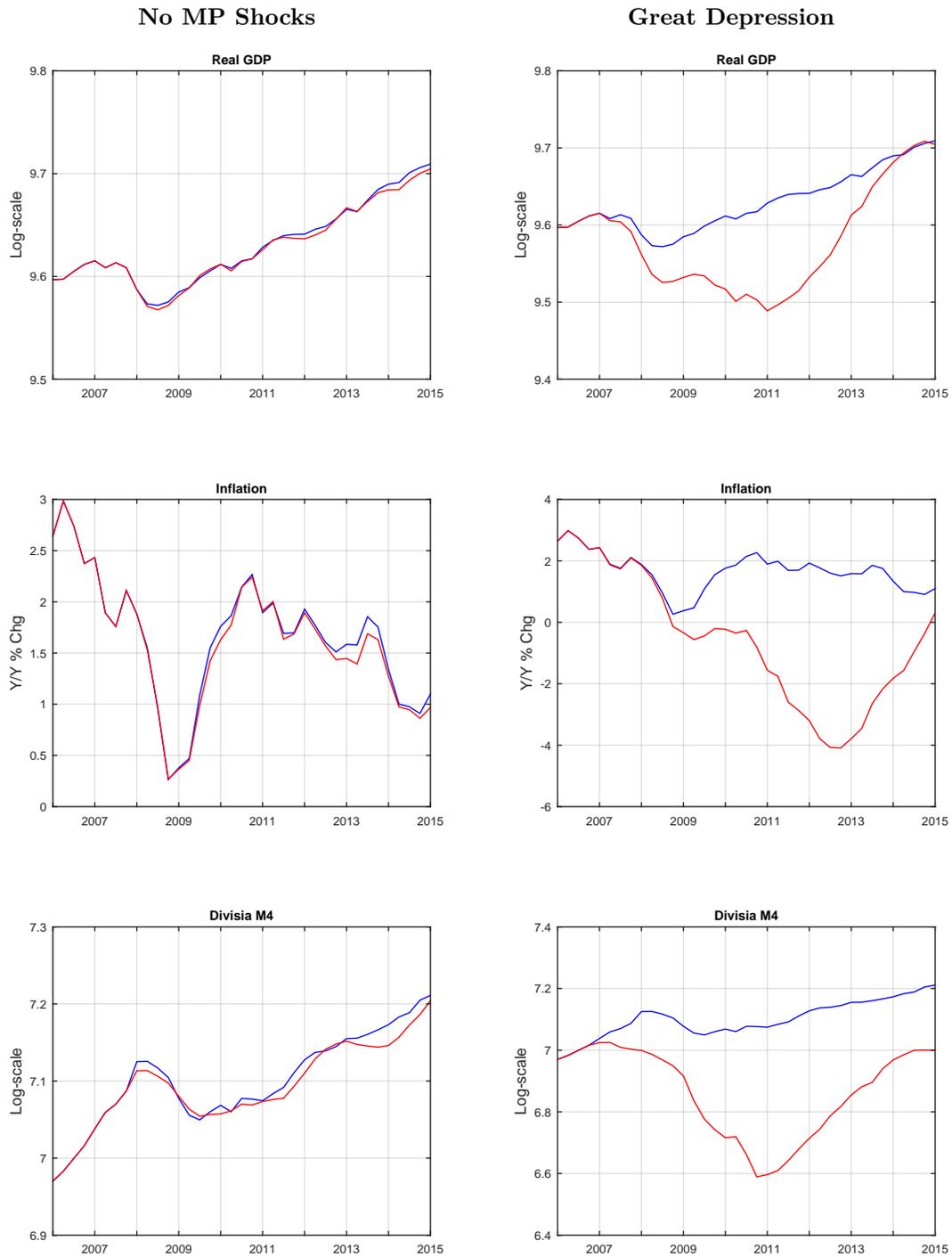
Figure 7: Counterfactual Monetary Policy Shocks
The blue lines are realized data and the red lines are counterfactual data generated from our baseline VAR model. The No MP Shocks scenario generates alternative paths for real GDP, inflation, and DM4 by setting all monetary policy shocks after 2008:Q4 to zero. The Great Depression scenario generates alternative paths for real GDP, inflation, and DM4 by generating a sequence of monetary policy shocks that causes DM4 to grow from 2007:Q4 to 2015:Q4 at the same rate that M2 grew from 1929:Q3 to 1937:Q3.
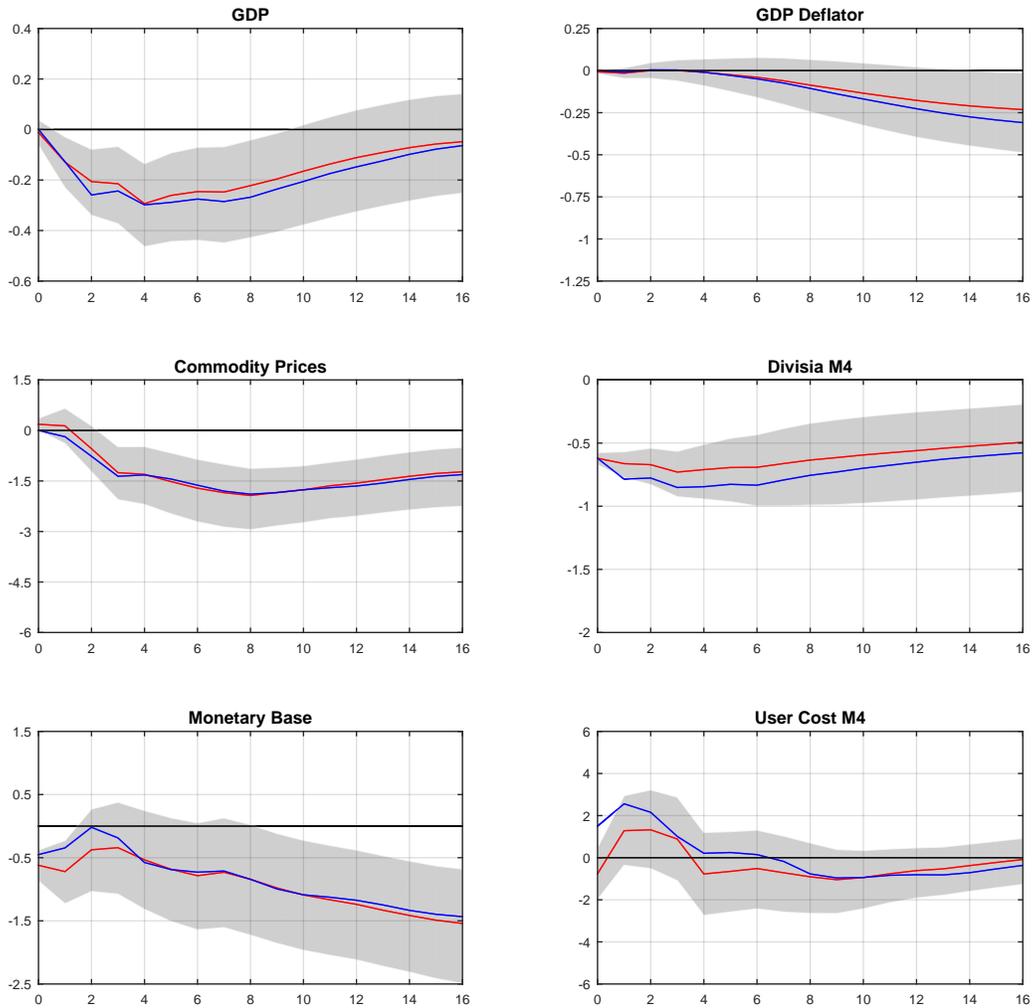
Figure 8: Monthly VAR (1967:Q1 - 2015:Q4)
This figure plots the impulse responses to an identified monetary policy shock in our baseline VAR model using both monthly data (red line is the point estimate and shaded areas are error bands) and quarterly data (blue line is the point estimate). The monthly impulse responses are averaged across three months to generate quarterly impulse responses. The resulting quarterly impulse responses are scaled so that the impact response of DM4 is identical in both sets of impulse responses.
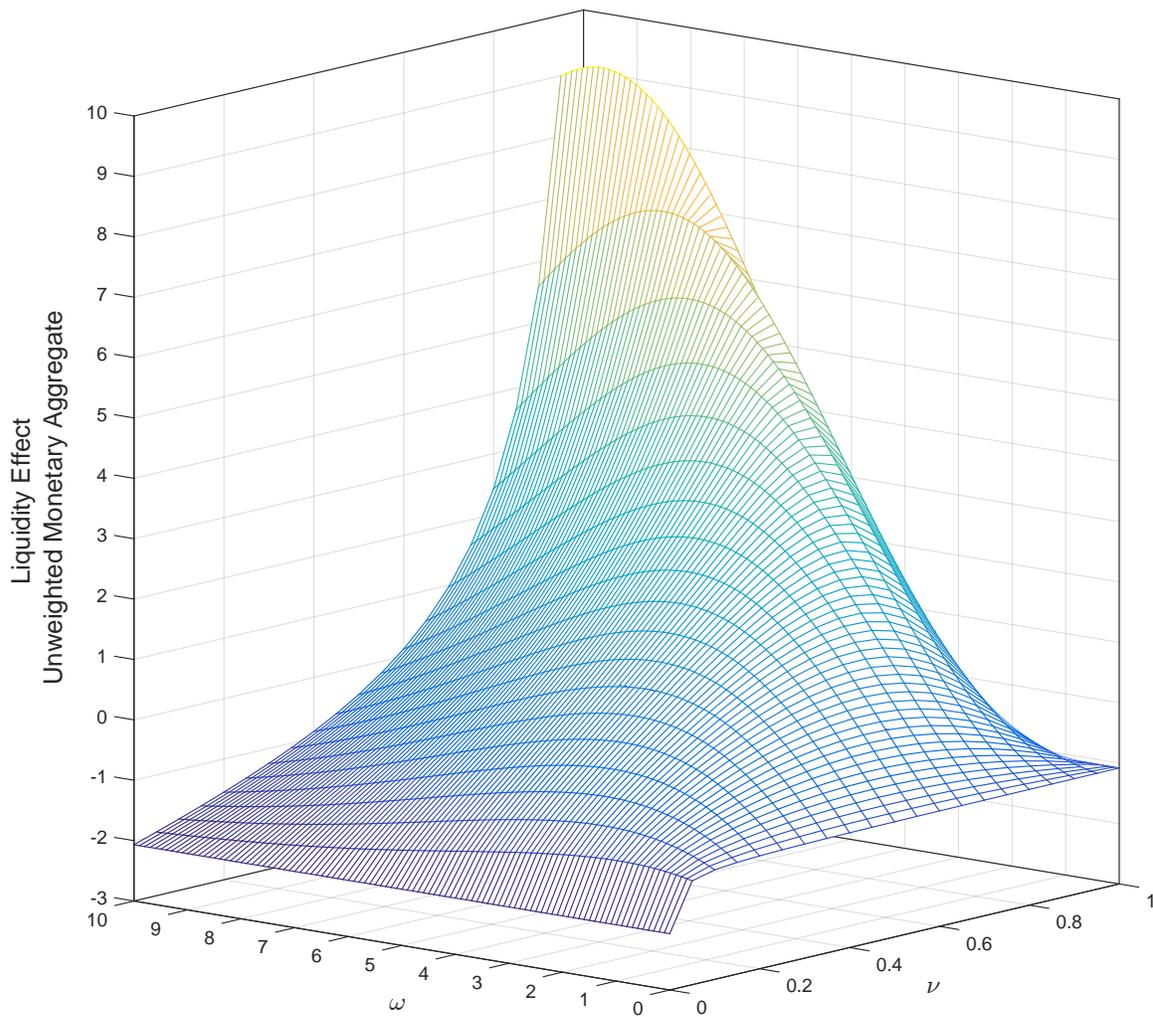
Figure 9: Unstable Liquidity Effects with an Unweighted Monetary Aggregate
This figure shows how the initial period response of an unweighted monetary aggregate (such as M2) to a contractionary monetary policy shock varies as a function of ν, which governs the weight placed on each asset in the CES aggregate, and ω, which is the elasticity of substitution between each asset. For all values of ν and ω, the interest-semi-elasticity of money demand is held fixed at $\eta = 1.9$.
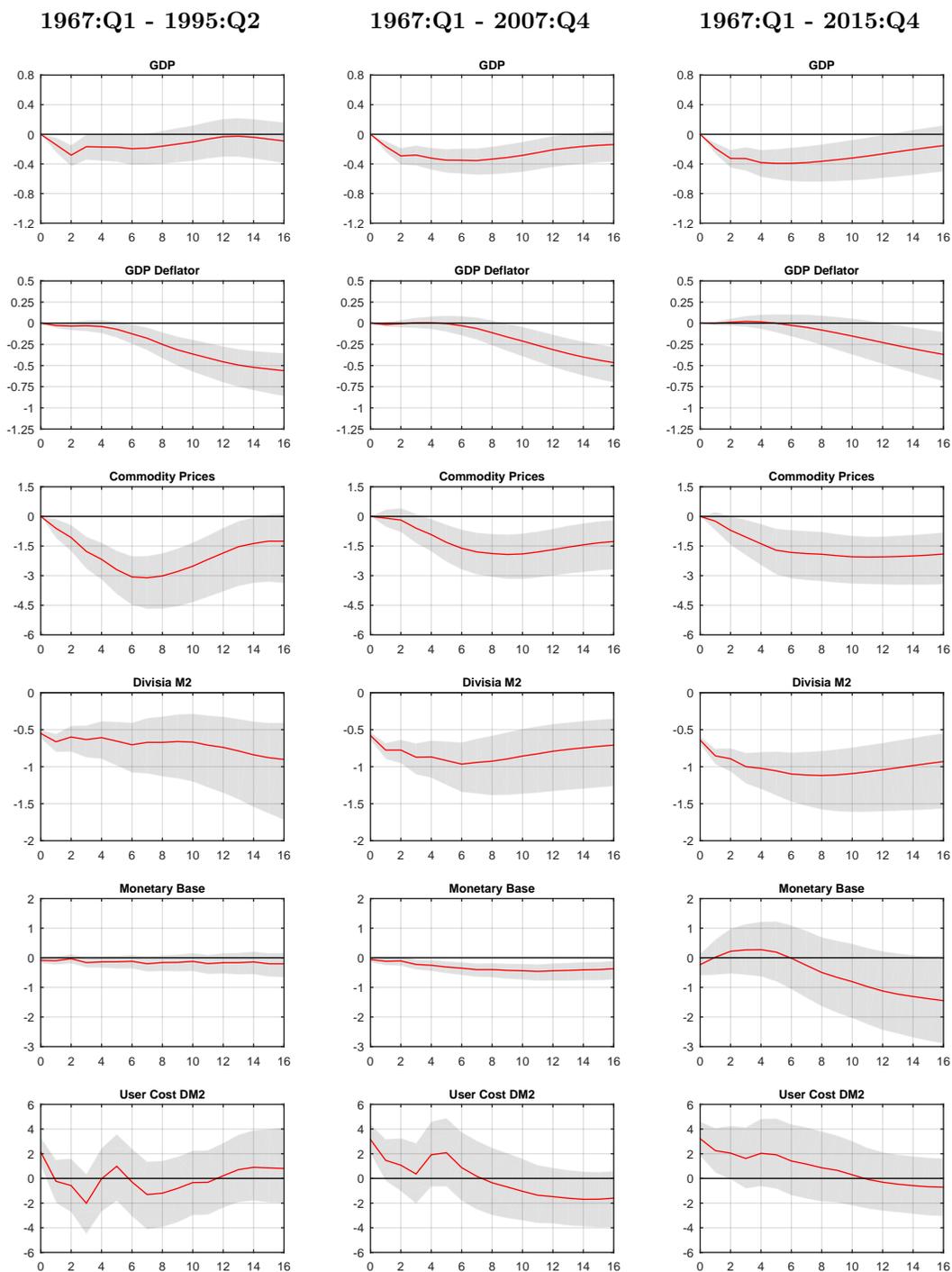
Figure 10: DM2 VAR Model (Various Sample Periods)
This model replaces DM4 with DM2 as the policy indicator and correspondingly substitutes the user cost of DM4 with the user cost of DM2 in the money market block.