Supplementary Appendix: Monetary Regimes, Money Supply and the US Business Cycle since 1959: Implications for Monetary Policy Today

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A Revisiting three pillars of the monetary exchange economy

A.1 The Fisher relation

The "original" Fisher (1896) *effect* derives from a no-arbitrage condition on the expected terms-of-trade between money and commodities (Dimand and Betancourt, 2012, 188).[1] In contrast, the well-known Fisher *relation* or *distinction* between nominal and real interest rates is a simplification (see Laidler, 2013, 3). To be consistent with theory, we need a model that describes (1) how price-level expectations are formed and (2) to what extent asset markets reflect inflation expectations in the difference between nominal (i) and real (r) rates of return.

First, under rational expectations the expected value of fiat money (A) expressed in terms of commodities ($1/P$) equates: $E(A) = E(1/P) \approx 1/E(P)$ and the "original" Fisher *effect*: $i = r - a - ra$ equates with the "conventional" Fisher *relation*: $i = r + \pi + r\pi$, where a is the expected appreciation of the value of money in terms of a basket of commodities and where π is expected inflation.[2] Notably, however, price-level determination with respect to *both* the money stock and the interest rate is crucial to satisfy the Fisher relationship.

Second, given this link between the money stock, commodity prices and rates of return, the Fisher relation further implies—as shown in, for example, Ireland (2014) and Walsh (2010, 457)—that the monetary authority cannot independently determine the nominal interest rate and the expected rate of inflation (or, more correctly, the expected depreciation in the value of money). Instead, given an (intermediate) interest rate target, the money supply adjusts to a growth rate commensurate with the inflation rate, and vice versa.[3]

A.2 Money stock and price-level determination

The key result that Hetzel (1986, 7) brings to light is that for nominal money to play a causal role in determining the price level, "at least some of the determinants of nominal money supply must differ from the determinants of real money demand." And by implication of the quantity theory of money approach, the price level adjusts to equate the real quantity of money supply with the real

[1] See also Laidler (2013) for important clarifications on the use of the Fisher relation in the Great Depression and the Great Recession—especially with respect to monetary policy discussions of the times. Dimand (1999) also distinguishes the actual contributions of Fisher from those of the development of the relation attributed to his name.

[2] It is straight forward to show, using Jensen's inequality and the Cauchy-Schwarz inequality, that $1 \leq E(P)E(1/P) \leq 1+(b-a)^2/4ab$ for a bounded random variable P on the interval $[a,b] > 0$ with $Prob\,(a < P < b) = 1$. With negligible uncertainty about the expected price level ($a \approx b$), $E(P)E(1/P) \approx 1$.

[3] Fisher also used his hypothesis to investigate the term structure of interest rates (Dimand, 1999). The hypothesis then naturally leads to questioning the central bank's control over short- and long-term interest rates and to understanding the transmission of expected policy rate changes across the term structure (see, e.g., Poole et al. (2002, 85), Thornton (2004, 2014), Coibion and Gorodnichenko (2012) and Hummel (2013)).

quantity of money demanded.[4] Put another way, changes in the supply of money are associated with the disequilibrium between the real (market) rate of interest and the natural rate of interest. Further, the ability of monetary policy to manipulate this disequilibrium (through, for example, the policy rate, bank reserves, or price expectations) generates temporary real effects.

Consequently, the problem of multiple equilibria arises if the equilibrium conditions of a model can determine neither the price level nor the nominal supply of money (McCallum, 1986). In this case, alternative price-level sequences will be consistent with given paths for the nominal money stock.[5] In a regime of strict interest rate-targeting, however, the standard three-equation NK model does allow for the price level and real money balances to be determined by the money demand equation and the Fisher equation. Money is irrelevant only because the NK model lacks a deterministic path for the nominal money stock and hence for the price level. In fact, Walsh (2010, 460) shows that "there exists a path for the nominal money supply ... that leads to the same real equilibrium under an interest rate peg as would occur with a flexible price regime". But again, this concept precludes the true specification of money stock determination. An interest rate-targeting regime is simply a special case in a continuum of endogenous monetary policy regimes.

A.3 The behavior of money demand is well defined

Examining data from as far back as 1900, Benati et al. (2017), Ireland (2009) and Lucas (2000) illustrate a strikingly stable relationship between money demand and nominal interest rate. This relationship holds for more recent (post-1980) periods as well (Berentsen et al., 2015; Lucas and Nicolini, 2015; Alvarez and Lippi, 2009). Figure A.1 highlights this relationship in the US data. The fundamental implication of this relationship within the context of a model of money stock determination relates to the relevance of bank reserves (Borio and Disyatat, 2010, 73–80). The critique against the relevance of monetary aggregates is usually based on the empirical regularity that no clear and stable link exists between liquidity (reserves) and interest rates. Specifically, countries that do not employ a reserve regime, can implement the so-called decoupling principle (Borio and Disyatat, 2010, 55–57). As a result, various levels of reserves can exist for a given interest rate. This empirical regularity, however, is somewhat different from the decoupling hypothesis, which allows for a "two instrument-two goal" operational framework. Ireland (2014, 1301) sums

[4] In Hetzel's model, nominal shocks shift both demand and supply curves for money, whereas real shocks shift only the supply of money through changes in the natural rate of interest.

[5] In fact, Carlstrom and Fuerst (2001) show that, because of multiple pricing equations for the nominal interest rate, "seemingly minor modifications in the trading environment result in dramatic differences in the policy restrictions needed to ensure real determinacy." They go on to caution that policymakers should be aware that a lot depends on basic assumptions about the modelling environment in monetary models. See Auray and Fève (2008) and Schabert (2009) for a similar analysis on the (non)equivalence of money supply and interest rate policy rules.

up the difference as follows:

> Thus, although the extra degree of freedom does allow the central bank to target the short-term nominal interest rate and the real quantity of reserves simultaneously, the model shows that monetary policy actions intended to bring about long-run changes in the aggregate price level must still be accompanied by proportional changes in the nominal supply of reserves.

This relationship means that any monetary policy operation that fixes the price of short-term debt (e.g., by paying interest on reserves) can remove the liquidity effect altogether *in the market for reserves* (see, e.g., figure A.2). In fact, Ireland (2014, 1301) finds that when a 25-basis-point increase in the short-term interest rate is brought about, both the *size* and the *sign* of reserves adjustment differ from the liquidity effect that would arise under a "traditional" reserve regime. A large *increase* in the balance sheet arises in the short run because of the simultaneous effect of the market rate on households' demand for deposits and banks' demand for reserves. And as Fama (2013, 180) points out, "There is no conclusive evidence (here or elsewhere) on the role of the Fed versus market forces in the long-term path of interest rates." Ireland (2014, 1303) goes on to show that although interest on reserves dramatically alters the endogenous response of reserves, in the long run, "a monetary policy action that decreases [increases] the price level always requires a proportional reduction [expansion] in the nominal supply of reserves . . . ." That is, the short-run versus long-run dichotomy in the literature raises some concern over the long-run efficacy of a decoupling policy framework. In short, the Fisher effect matters. (See also Hummel, 2013; Cochrane, 2014).

Figure A.2 shows the relationship between reserves and the short-term nominal interest rate for quarterly US data from 1959Q1 to 2007Q3. Nonborrowed reserves (H) show no indication of a relationship with the interest rate. This result is unsurprising, given that for much of this period, the Fed followed a de facto (but not necessarily strict) interest rate-targeting regime (Hetzel, 1981, 1982; Taylor, 1993; Orphanides, 2002, 2003; Sims and Zha, 2006; Walsh, 2010). In fact, the only extended period showing a clear negative log-linear relationship between H and the short-term nominal interest rate is that between 1982Q3 and 1987Q1—a period in which the Federal Reserve followed a borrowed-reserves operating procedure (see Cosimano and Jansen, 1988).

Free reserves (FR), on the other hand, approximate a downward sloping demand function for the entire period from 1959Q1 to 2007Q3.[6] The simple linear ordinary least squares (OLS) regression

[6] There are only two notable outliers over the 48.5-year period (-\$5.2 billion in 1984Q3 and \$5.9 billion in 2001Q3). Free Reserves = Excess Reserves - Borrowed Reserves.

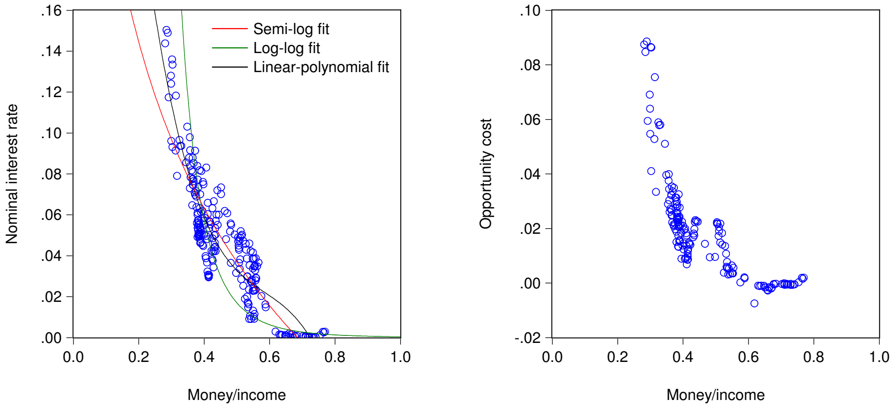

Figure A.1: US Money Demand. The left-hand panel shows the nominal interest rate from 1959Q1 through 2016Q03. The right-hand panel shows the opportunity cost with money zero maturity (MZM) own rate from 1975Q1 through 2016Q03).

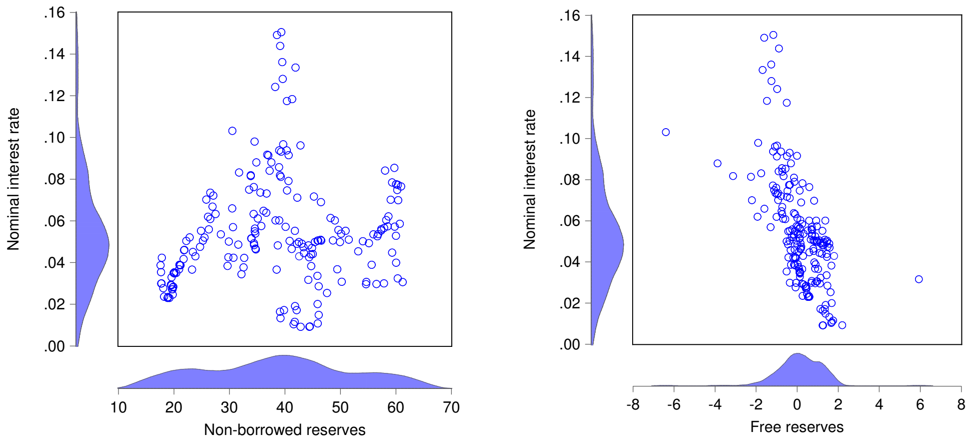

Figure A.2: US Reserve Demand. The left-hand panel shows nonborrowed reserves ($ billions) from 1959Q1 through 2007Q03. The right-hand panel shows free reserves ($ billions) from 1959Q1 through 2007Q03.

gives:

$$FR = \underset{(0.15)}{1.60} - \underset{(2.40)}{27.05}i \ ,$$

with $R^2 = 0.40$ and standard errors in parentheses. In comparison, the semi-log OLS regression for money demand from figure A.1 gives:

$$ln(M/GDP) = \underset{(0.02)}{-0.54} - \underset{(0.27)}{5.54}i \ ,$$

with $R^2 = 0.69$ for the period from 1959Q1 to 2007Q3. Of course, these results serve a descriptive purpose only; for more comprehensive analyses and discussions on the demand for money, see, for example, Duca and VanHoose (2004), Ireland (2009), Walsh (2010) and Lucas and Nicolini (2015).

B The model economy

McCallum's (1981; 1986) two-equation, full employment IS-LM model with a money supply rule showed it was possible to peg the nominal interest to some target value with a money rule and obtain price determinacy. Hetzel (1986) extended McCallum (1986) to include a traditional banking sector for reserves. His model contains four key equations: a Fisher relation, a demand function for real money balances, a monetary rule, and a banking sector relationship between nominal money supply, the short-term market interest rate and bank reserves. Equations B.1 through B.4 represent these four equations as first-order Taylor approximations around a deterministic steady state:

$$\text{Fisher relation} \ : \ i_t = E_t\pi_{t+1} + r_t \tag{B.1}$$

$$\text{Money demand} \ : \ m_t^d - p_t = \phi_y y_t - \phi_i i_t \tag{B.2}$$

$$\text{Monetary policy} \ : \ h_t = \rho_h h_{t-1} - \nu_h(i_t - \bar{i}) \tag{B.3}$$

$$\text{Money supply} \ : \ m_t^s = \frac{1}{rr}(\phi_h h_t - \phi_{fr} fr_t) \ , \tag{B.4}$$

where i_t, π_t and r_t are the nominal interest rate, inflation rate and real rate of interest; p_t, y_t, h_t and m_t denote the price level, output, bank reserves and nominal money stock, respectively. The parameters ϕ_y and ϕ_i are the real income elasticity and the interest rate semi-elasticity of the demand for money, ρ_h is a persistence parameter, and ν_h measures the degree to which the monetary authority smooths the nominal interest rate. Finally, rr is the reserve requirement ratio, where ϕ_h and ϕ_{fr} are the steady state ratios of nonborrowed reserves and free reserves to the money stock.[7]

[7] Note that Equations (15) and (16) in Hetzel (1986, 10) imply a log-linear relationship between reserve demand

In the spirit of Benchimol and Fourçans (2012), Belongia and Ireland (2014), and Ireland (2014), we use the above approach to money stock determination to deviate from the traditional NK model with a Taylor-type monetary rule to include a monetary rule, equation (B.3), and a money supply condition, equation (B.4), which allows for alternative operational instruments and intermediate targets. Specifically, ν_h captures the degree of interest rate smoothing enforced by the central bank. As $\nu_h \to \infty$, the money supply schedule becomes horizontal and we enter a monetary regime of interest rate-targeting—either a "pure" peg or a strict dynamic Taylor rule (e.g., by letting $\bar{i}$ follow some monetary policy reaction function that responds to inflation and output). Money and reserves become endogenous, and the reserve-money multiplier becomes irrelevant to the determination of the money stock (Hetzel, 1986, 5-6, 13, 17-18, 20). Under this type of regime, the model reduces to the standard NK framework (Benchimol and Fourçans, 2012). As $\nu_h \to 0$, we enter into a "pure" monetary aggregate targeting regime.[8]

The bank's decision problem for free reserves (fr_t) in an interest-rate corridor or channel system is based on Woodford (2001, 31) and Whitesell (2006); see also Walsh (2010, 544)). In this framework, the net supply of settlement balances (free reserves) is zero in the steady state. As will be shown, this fact ensures that the effective federal funds rate hits the target policy rate in the steady state. In reality, as depicted in figure B.3, the "target supply" of reserves may exceed required reserves in the steady state because of uncertainty or because the model applies to *average* reserve balances over a maintenance period (Keister et al., 2008, 43-45). In addition, we do not explicitly distinguish cash from reserve balances and deposits. Total bank reserves at the central bank therefore represent the monetary base, and household deposits therefore represent the broad monetary aggregate.[9]

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schedule and reserve supply schedule.

[8]Note that the reserve-money multiplier only becomes irrelevant as a result of the modelling assumption. This assumption does not mean that the real demand for money (purchasing power) *determines* the quantity of nominal money (Tobin (1963), cited in Hetzel (1986, 19)). Empirically, the relationship depends on the degree to which monetary aggregates (or reserve-money multipliers) become interest sensitive, that is, elastic (Inagaki, 2009), or on how monetary aggregates are measured (Belongia and Ireland, 2014, 2017; Tatom, 2014): an insensitive or structurally stable monetary aggregate results in a relevant and predictable reserve-money multiplier. For historically relevant practical and technical expositions, see Brunner and Meltzer (1981) and Hetzel (1981).

[9]This simplification follows the proposition that reserves are "the fundamental numeraire and means of final payment" (Cochrane, 2014, 90-91). As of March 14, 2018, \$100 notes account for 80 percent of the value of currency in circulation (\$1.59 trillion), of which, nearly 80 percent are held outside the United States (Haasl et al., 2018). Currency accounts for 36 percent of the Federal Reserve's liabilities and under 8 percent of US GDP, of which typical transaction notes (\$20s and below) account for under 1.5 percent of GDP (Judson, 2017).

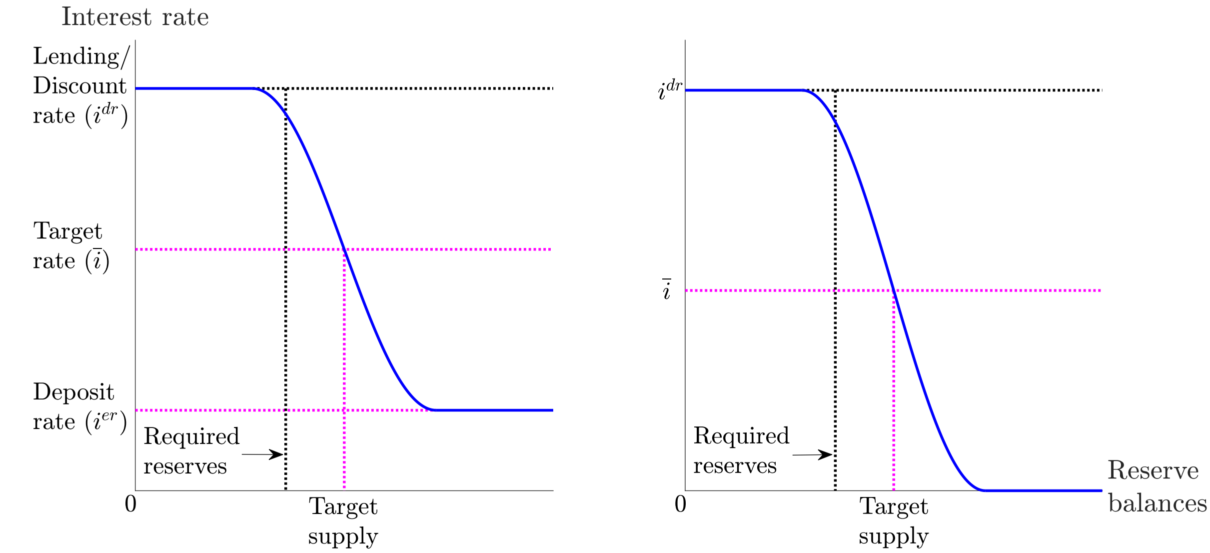

Figure B.3: Monetary Policy Implementation: corridor system (left panel); US reserve demand pre-2008 (right panel). Source: Adapted from Keister et al. (2008). See also Woodford (2001, figure 1, 33), Whitesell (2006, figure 1, 1181) and Walsh (2010, figure 11.2, 546).

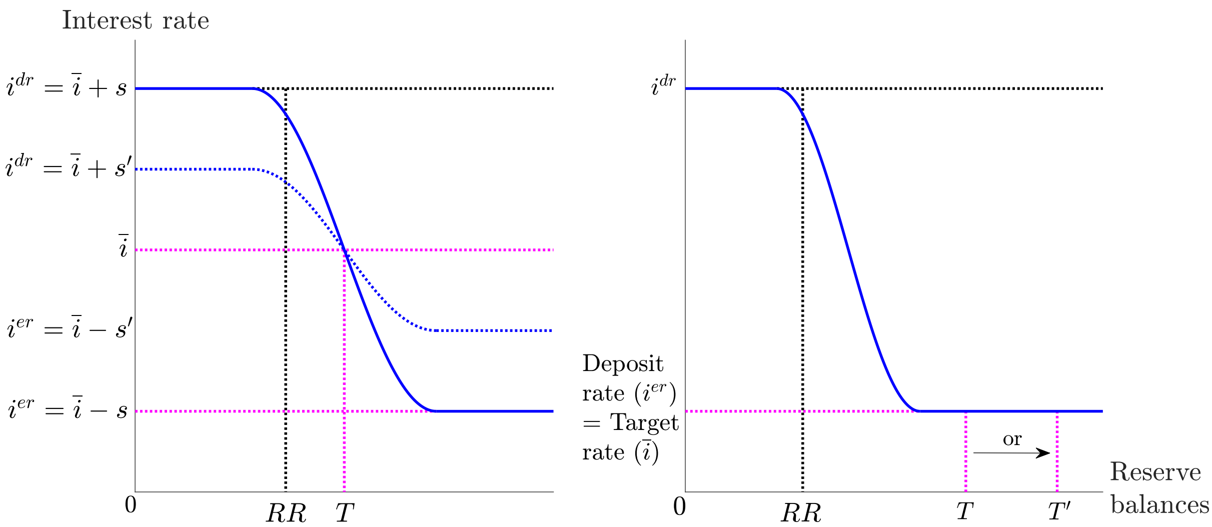

Figure B.4: Monetary Policy Implementation: narrow peg regime (left panel); US reserve demand post-2008 under floor regime (right panel). Left panel depicts narrowing of symmetrical spread $s' < s$. Right panel is equivalent to $\nu_h, \nu_f \to \infty$. Source: Adapted from Keister et al. (2008).

B.1 Households

The representative infinitely-lived household's utility is separable in consumption, money and leisure. The household maximizes its expected lifetime utility function given by:

$$E_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{a}{1-\eta_c} (C_t)^{1-\eta_c} + \frac{(1-a)\xi_{m_d,t}}{1-\eta_m} (M_t^d / P_t)^{1-\eta_m} - \frac{\Psi}{1+\eta_l} (L_t)^{1+\eta_l} \right], \tag{B.5}$$

where β^t is the discount factor. Utility depends positively on the consumption of goods C_t, and negatively on the supply of labor hours L_t. Households' financial wealth is made up of risk-free bonds B_t and nominal money balances M_t^d. Similar to Van den Heuvel (2008); Christiano et al. (2010); Benchimol and Fourçans (2012); and Ireland (2014), we assume that households derive direct utility from the liquidity services of money. This utility drives a positive wedge in the spread between the return on bonds and the own return on money (the opportunity cost of holding money). The parameter η_l measures the inverse of the elasticity of hours worked to the real wage, η_c captures the inverse of the intertemporal elasticity of substitution in consumption, and η_m measures the inverse of the interest rate semi-elasticity of money. Last, the variable $\xi_{m_d,t} = \exp(\varepsilon_t^{m_d})$ is an exogenous shock to money demand.

Equation B.6 gives the household budget constraint:

$$P_t C_t + M_t^d + Q_t B_t + P_t T_t \leq W_t L_t + B_{t-1} + M_{t-1}^d. \tag{B.6}$$

The household allocates periodic income from wages (W_t), risk-free bonds (B_{t-1}), and cash balances M_{t-1}^d to current consumption and new financial wealth holdings in the form of money and bonds. The variable Q_t is the discount on one-period bond purchases such that the pay-off at maturity is the short-term nominal interest rate ($i_t = -\log Q_t$). The variable T_t includes both lump-sum taxes net of transfers and rebated profits from firms.

The representative household's first-order conditions for bonds, money, and labor are the following:

$$U_{c,t} = \beta E_t \left[U_{c,t+1} \frac{(1+i_t)}{(1+\pi_{t+1})} \right], \tag{B.7}$$

$$U_{m,t} = U_{c,t} - \beta E_t \left[U_{c,t+1} \frac{1}{(1+\pi_{t+1})} \right], \tag{B.8}$$

$$\frac{W_t}{P_t} = \frac{U_{l,t}}{U_{c,t}}, \tag{B.9}$$

where π_t is the rate of inflation, $U_{c,t} = a(C_t)^{-\eta_c}$ is the marginal utility of consumption, $U_{m,t} = (1-$

$a)\xi_{m_d,t}(M_t^d/P_t)^{-\eta_m}$ is the liquidity services from holding real money balances, and $U_{l,t} = \Psi(L_t)^{\eta_l}$ is the marginal disutility of labor. Equation B.8 is the household's demand for real money balances. Equation B.9 gives the standard real wage equation, which states that the real wage equals the marginal rate of substitution between consumption and labor. Equation B.7 gives the consumption Euler equation, which is based on the standard asset-pricing equation for bonds.

Combining equation B.7 and equation B.8 illustrates the opportunity cost of holding money.

$$\frac{U_{m,t}}{U_{c,t}} = \frac{i_t}{(1+i_t)} \; . \tag{B.10}$$

Here equation B.10 states that the marginal utility of the liquidity services, expressed in units of consumption, equals the opportunity cost of not investing money holdings in risk-free nominal bonds.

B.2 Firms

Firms manage the goods-producing sector and are owned by households. Firms behave optimally in a monopolistically competitive environment in which their objective is to maximize profits. In each period, only a fraction of firms $(1-\theta)$ can reset their prices. The aggregate price level then evolves as

$$(P_t) = \left[\theta(P_{t-1})^{1-\varepsilon^p} + (1-\theta)(\tilde{P}_t)^{1-\varepsilon^p}\right]^{\frac{1}{1-\varepsilon^p}} \; . \tag{B.11}$$

Firms produce goods using identical technology in the form of a standard Cobb-Douglas production function:

$$Y_t = \xi_{z,t} L_t^{\alpha}, \tag{B.12}$$

where L_t is the demand of labor hours, $0 < \alpha < 1$ represents labor's decreasing returns to production, and $\xi_{z,t} = \exp(\varepsilon_t^z)$ represents the exogenous technology identical to all firms.

B.3 The banking sector

Our intention in constructing the stylized banking sector introduced below is to focus on the relationship between the demand for reserve balances and the effective (or target) policy rate. Although operational procedures in the United States before 2008 differed from the corridor (symmetric channel) systems used by several of the world's central banks (e.g., the European Central Bank and the central banks of Australia, Canada, and England), monetary policy in the United

States was implemented in much the same way as in those regions (see figure B.3).[10] Simply put, the central bank determines the quantity of reserves to achieve its target interest rate. At the same time, the aggregate stock of bank reserves (those necessary for interbank payments and required—or desired—reserves) is proportional to the broader stock of money.[11] Importantly, we take the pragmatic stance that the central bank accommodates shocks to the broader monetary aggregate (Goodhart, 2017, 33-34, 38). In other words, the central bank provides the monetary base (bank reserves), consistent with both the stock of broad money in the economy and the desired free reserves, that aligns the short-term interbank (federal funds) rate with its target. That said, the Federal Reserve has in the past systematically adjusted (and still can adjust) the monetary base to bring about changes to the stock of money used for transactional services in the broader economy (see, e.g., DeRosa and Stern, 1977; Gilbert, 1985; Chowdhury and Schabert, 2008; Tatom, 2014; Schabert, 2015). As such, our dynamic interaction between the supply of and demand for money, together with a stylized description of the banking sector, allows us to focus on the structural relationship between the market for money and macroeconomic aggregates in a conventional general equilibrium framework. (For a similar motivation, see also Chowdhury and Schabert (2008) and Ireland (2014).)[12]

B.3.1 A traditional model of the reserve market

The central bank has autonomy over the quantity of reserves supplied (see equation B.3). However, the money supply function is derived from the banking sector's demand for free reserves (see equation B.4). Free reserves (FR) represent funds available for interbank clearing and settlement, interbank loans, and the portion of excess reserves (ER) less borrowed reserves (BR) allocable to reserve requirements (RR) in the deposit (D) creation process (see also Norman et al., 2011). Assume that the central bank has a standing facility for borrowing at the discount window and that banks are required to hold reserves for a fixed reserve requirement ratio (rr). Required reserves ($RR = rrD$) and borrowed reserves (BR) are therefore not directly determined by the central bank, but the central bank directly determines nonborrowed reserves (H), the discount rate (i^{dr}), and interest on (excess) reserves (i^{er}). On the basis of this model from Tinbergen (1939, 1951), Hetzel (1986) defines the relationship between nominal money (supply), the short-term interest rate, and

[10]See Gilbert (1985) and Keister et al. (2008) for an accessible discussion on central bank operating procedures in a stylized graphical framework as depicted here. A more detailed analysis can be found in Whitesell (2006).

[11]Although highly persistent, the effective reserve ratio has not been stable over the period 1959Q1−2016Q3 (see figure D.1). In addition to the measurement and substitutability of monetary aggregates, regulatory changes and financial innovations can explain these structural changes over time. (See, e.g., Lucas and Nicolini (2015); Berentsen et al. (2015, 2018); Banerjee and Mio (2017); Bech and Keister (2017); Li et al. (2017).)

[12]It is also important to note that stochastic singularity arises if both the broad monetary aggregate and reserves are used to estimate the model.

bank reserves as follows:

$$
\begin{aligned}
FR &= H - RR = ER - BR && \text{(B.13)} \\
RR &= H - FR && \text{(B.14)} \\
RR &= rrD && \text{(B.15)} \\
FR &= f(i|i^{dr}, i^{er})\ . && \text{(B.16)}
\end{aligned}
$$

Equation B.16 shows bank demand for free reserves as a function of the short-term nominal interest rate, given the spread between the discount rate on borrowed reserves and the interest on excess reserves. Deposits D equate with the nominal money supply M^s. Substituting equation B.15 into equation B.14 gives the money supply function for period $t = 1, 2, 3, \ldots$:

$$
M_t^s = \frac{1}{rr}(H_t - FR_t)\ . \tag{B.17}
$$

Nonborrowed reserves evolve over time (t) according to the following policy rule:

$$
H_t = (H_{t-1})^{\rho_h}(\bar{H})^{(1-\rho_h)}\left(\frac{1+i_t}{1+\bar{i}}\right)^{-\nu_h}, \tag{B.18}
$$

where $\bar{H}$ is the trend rate of growth of nonborrowed reserves and ρ_h determines the degree of persistence in reserve accumulation. With the elasticity of bank reserves ν_h approaching 0, the reserve-deposit (money) multiplier ($1/rr$) determines the quantity of money stock created. If $\rho_h = 1$, equation B.18 follows a random walk, and independent changes to reserves are not offset. Furthermore, the market rate (i_t) equals the target rate ($\bar{i}$) in the steady state, which implies that any level of reserves is independent from the interest rate.

B.3.2 The banks' demand for free reserves in a corridor system

The representative bank is assumed to be risk neutral. In each period, the bank trades central bank deposit balances (free reserves) with other banks in a competitive interbank market at the market rate i. Free reserves are assumed to be subject to stochastic fluctuations ("margins of error") after the interbank market closes ($FR + \varepsilon$).

The demand for clearing balances in the interbank market follows directly from the models of Woodford (2001) and Whitesell (2006). Given the discount rate on borrowed reserves and any interest paid on excess reserves, equation B.19 expresses bank j's optimal (period t) demand for free reserves as a function of (1) the opportunity cost of holding a positive end-of-period reserve balance relative to lending that balance out in the interbank market, $i_t - i_t^{er}$, and (2) the opportunity cost of holding a negative end-of-period reserve balance (overdraft) and having to borrow from the central bank rather than from the interbank market, $i_t^{dr} - i_t^{er}$:

$$F(-FR_t) = \left(\frac{i_t - i_t^{er}}{i_t^{dr} - i_t^{er}} \right) , \tag{B.19}$$

where $F(\cdot)$ is the symmetric distribution of the reserve account shock. A symmetric distribution implies that $i^{er} = (\bar{i} - s)$ and $i^{dr} = (\bar{i} + s)$; they form a floor and a ceiling around the target interest rate $\bar{i}$ (see figure B.4). With full information, the bank sets its desired level of period reserves $FR^{*} = -\varepsilon$, where $FR - E(FR) = \varepsilon$ is the end-of-day stochastic "margin of error" and where $E(\varepsilon) = 0$.[13] As a result, net settlement balances at the central bank are zero ($FR = 0$) and $i = \bar{i}$ (Whitesell, 2006, 1180). Notice that this equation represents a strict interest rate-targeting regime in circumstances where ν_h, in equation B.18, approaches ∞: the equilibrium point where reserves become irrelevant for the determination of the money stock.

Following Woodford (2001) and Whitesell (2006), it is further assumed that $F(\cdot)$ is a cumulative standard normal distribution function $N(\cdot)$ with variance σ^2. Summing over all banks, indexed by j, gives the aggregate demand for reserves (depicted in figure B.4):

$$FR_t = \sum_j FR_t(j) = -N^{-1} \left(\frac{i_t - i_t^{er}}{i_t^{dr} - i_t^{er}} \right) \sum_j \sigma_j = H_t - RR_t \ , \tag{B.20}$$

where $\sum \sigma_j$ captures the degree of uncertainty of (private) banks. Given the spread s, the function $N^{-1}(\cdot)$ can be re-written as:

$$N^{-1} \left(\frac{1}{2} + \frac{i_t - \bar{i}_t}{2s} \right) ,$$

such that if $i_t = \bar{i}_t$, then $FR_t = -N^{-1}(1/2) = 0$ under zero aggregate uncertainty and a symmetric distribution function.

Whitesell (2006, 1181) highlights two important characteristics of greater uncertainty in the market for reserves. First, on the demand side, interbank uncertainty leads to interest rate smoothing (i.e., to a flattening of the the demand curve for reserves); second, on the supply side, central bank uncertainty in reserve supply raises the volatility of interest rates. The larger the ratio of central bank uncertainty to private bank uncertainty, the fatter the tails of the resulting distribution of overnight interest rates (ibid., 1182). We can approximate the demand for free reserves over time t according to

$$FR_t = (FR_{t-1})^{\rho_{fr}} (\bar{FR})^{(1-\rho_{fr})} \left(\frac{i_t - i_t^{er}}{i_t^{dr} - i_t^{er}} \right)^{-\nu_{fr}} , \tag{B.21}$$

[13] The bank's funding costs are therefore minimized at $-i\varepsilon$.

where ν_{fr} determines the interest elasticity of free reserves (or the degree of interest rate smoothing in the interbank market for reserves). Under a strict interest rate peg, the market rate (i_t) is the target rate ($\bar{i}$), and the central bank saturates the interbank market with reserves to narrow the width of the corridor until the elasticity of demand for reserves is infinite (ν_h and $\nu_{fr} \to \infty$). In this case, free reserves are irrelevant, as are nonborrowed reserves, to the determination of the money supply (see, e.g., figure B.4).

A higher elasticity of reserve demand (a flatter demand curve at equilibrium—near the target interest rate) occurs not only with a narrower corridor, but also with greater reserve balance uncertainty (Whitesell, 2006, 1181). And as originally indicated by Poole (1968), a higher elasticity of reserve demand essentially means a wider dispersion of reserve balances. It is important to note that ν_{fr} captures only the *sensitivity* of reserves to market rate changes. We therefore allow a degree of persistence, ρ_{fr}, to free reserve accumulation. $\rho_{fr} = 0$ implies that independent changes to free reserves are offset around some constant level of free reserves or constant trend growth. If $\rho_{fr} = 1$, free reserves follow a random walk. A degree of persistence $0 < \rho_{fr} < 1$ therefore captures the speed of mean reversion of free reserves, which acts as a proxy for precautionary adjustments of free reserves to interest rate changes. The demand for free reserves thus need not respond immediately to aggregate uncertainty implied by σ_{fr}.

As noted by Hetzel (1986, 12), any changes in reserve demand typically derive from credit expansion in a fractional reserve system.[14] Equating money supply with money demand we get the following expression for equilibrium in the market for reserves:[15]

$$\underbrace{H_t - FR_t}_{\substack{\text{reserve supply}\\ \text{schedule}}} = \underbrace{rr\left[\left(\frac{i_t}{1+i_t}\right)^{-\frac{1}{\eta_m}} (P_t C_t)^{\frac{\eta_c}{\eta_m}}\right] P_t^{\left(\frac{\eta_m - \eta_c}{\eta_m}\right)}}_{\substack{\text{reserve demand}\\ \text{schedule}}} \tag{B.22}$$

The money supply schedule slopes upward because a higher interest rate spread between i_t and i_t^{dr} produces a lower level of free reserves and a higher level of borrowed reserves (i.e., excess reserves fall). The rise in (borrowed) reserves accommodates monetary expansion. Conversely, reserve demand slopes downward and relates to households' demand for *real* money balances. The demand for nominal reserves therefore responds to changes in economic activity, and adjusts proportionally to fluctuations in the aggregate price level to be consistent with the long-run neutrality of money.

[14] This cause of changes in demand is accurate given equation (B.16) and the accounting link between assets and liabilities.

[15] $RR = rrD = rrM^s = rrM^d$.

B.4 DSGE model

The usual market-clearing conditions ensure that $Y_t = C_t$, $M_t^s = M_t^d$ and $B_t = 0$. We now can derive the Hetzel (1986) framework presented in equations (B.1) through (B.4). For simplicity, all equations are expressed as first-order Taylor approximations around the steady state.

B.4.1 Real money demand and the velocity of money

The money demand equation (B.10) can be expressed in first-order Taylor approximation form as

$$m_t^d - p_t = \frac{\eta_c}{\eta_m} c_t - \frac{1}{\eta_m} i_t \ , \tag{B.23}$$

where, for now, we have ignored the exogenous money demand shock $\xi_{m_d,t}$. Notice that after we impose market clearing conditions in equilibrium ($c_t = y_t$ and $m_t^d = m_t^s = m_t$), equation (B.23) gives equation (B.2), where $\phi_y = \eta_c/\eta_m$ and $\phi_i = 1/\eta_m$. Given the equation of exchange for velocity: $v_t = p_t + y_t - m_t$, we can re-write equation B.2 as follows:

$$\underbrace{\phi_i i_t + (1-\phi_y) y_t}_{\text{velocity:}v_t} \quad = \quad p_t + y_t - m_t \ . \tag{B.24}$$

We estimate the model for parameters ϕ_i and ϕ_y and determine the robustness of the estimates to the literature on interest and income semi-elasticities and to that of velocity of money dynamics over the business cycle.

B.4.2 The Fisher relation

The first-order condition for bonds (equation B.7) can be combined with the flexible price equilibrium to give:

$$r_t = r_t^n + \eta_c (E_t[\tilde{y}_{t+1}] - \tilde{y}_t) \ . \tag{B.25}$$

where $\tilde{y}_t = y_t - y_t^n$ is the output ga Here, y_t^n is the natural level of output commensurate with flexible prices and wages. Importantly, this version of the output gap is not the efficient level of output—markets are still imperfect (Vetlov et al., 2011, 10).[16]

The Fisher relationship equation (B.2) can then be re-written, using equation (B.25), as

$$i_t \quad = \quad E_t[\pi_{t+1}] + [r_t^n + \eta_c(E_t[\tilde{y}_{t+1}] - \tilde{y}_t)] \tag{B.26}$$

[16] This fact means that although there is no price stickiness, the steady-state markup and markup shocks are still non-zero (see also, Hetzel, 2015).

In Hetzel (1986), $r_t^n = b_0 + v_t$ and $\eta_c(E_t[\tilde{y}_{t+1}] - \tilde{y}_t)] = b_1[p_t - E(p_t|I_{t-1})]$, the latter equation representing unanticipated price realisations (analogous to output gap changes), where $b_1 < 0$. The variable v_t represents an exogenous real shock that shifts the supply curve (i.e., both output and its flexible price equivalent (natural output) change in response to technology shocks). Furthermore, in Hetzel (1986), unanticipated price changes produce the necessary short-run trade-off between inflation and unemployment. For our rational expectations model, the short-run NK Phillips curve derived from the firm's decision problem achieves the same end.

B.4.3 A monetary rule for money stock determination

The linearized nominal money supply from equation B.17 follows as

$$m_t \;=\; h_t + \frac{1}{rr}[\frac{FR}{M}(h_t - fr_t)] \;, \tag{B.27}$$

in which the monetary rule (B.3) is defined in terms of a reserve aggregate. Specifically, nonborrowed reserves (h_t) evolve according to their linearized supply schedule:

$$h_t = \rho_h h_{t-1} - \nu_h(i_t - \bar{i}_t) \;, \tag{B.28}$$

in which $\nu_h > 0$ determines the degree of interest rate smoothing. If $\bar{i}_t$ is used as the monetary authority's operational instrument ($\nu_h \to \infty$), then the reserve-money multiplier is irrelevant to the determination of the money stock. In this case, the monetary authority can peg the nominal short-term interest rate i to some constant rate $\bar{i}$, or follow a dynamic Taylor-type rule $\bar{i} = i_t^T = f(i_{t-1}^T, \tilde{y}_t, \pi_t, \varepsilon_{i,t})$. We will use this monetary rule to emulate the pre- and post-2008 global financial crisis regimes. That is, between 1984 and 2007, the effective federal funds rate closely followed a Taylor-type rule (Taylor, 1993; Orphanides, 2002, 2003; Walsh, 2010), whereas, after 2008, the effective federal funds rate was pegged in a floor system by paying interest on reserves and saturating the banking system with reserves. In this case, the zero lower bound accentuated the peg as s approaches 0 in equation (B.29).

The demand for free reserves follows from equation B.21, as:

$$fr_t = \rho_{fr} fr_{t-1} - \frac{\nu_{fr}}{s}(i_t - \bar{i}_t) \;. \tag{B.29}$$

Notice that the symmetric spread (s) serves as a "slackness" parameter in the corridor system. For example, if we assume that $\nu_h = \nu_{fr}$, a narrower (wider) spread raises (lowers) the effective elasticity of free reserves relative to nonborrowed reserves. That is, a narrower spread implies a stricter interest rate peg, a flatter demand curve for free reserves, and a wider dispersion of reserves. In 2003, $s = 0.01$ (Whitesell, 2006, 1179); August 17, 2007 $s = 0.005$ and March 18, 2008 $s = 0.0025$ (Walsh, 2010, 534).[17]

B.4.4 System of linearized equations

Equations (B.24) through (B.29), plus the NK Phillips curve, $\pi_t = \beta\pi_{t+1} + \tilde{\kappa}\tilde{y}_t$; the output gap, $\tilde{y}_t = y_t - y_t^n$; the natural (flexible price equilibrium) output, $y_t^n = (1+\eta_n)/(\eta_c+\eta_n)\xi_{z,t}$; the natural rate of interest, $r_t^n = \eta_c(E_t[y_{t+1}^n] - y_t^n)$; and a definition for inflation, $\pi_t = p_t - p_{t-1}$, form the system of equilibrium conditions. We also assume that the policy rate target follows a Taylor-type rule ($\bar{i}_t = i_t^T$), which therefore gives 12 equations and 12 endogenous variables, excluding exogenous shock processes:

$$
\begin{aligned}
\text{Fisher relation} &: \quad i_t = E_t[\pi_{t+1}] + [r_t^n + \eta_c(E_t[\tilde{y}_{t+1}] - \tilde{y}_t)] && \text{(B.30)} \\
\text{Money demand} &: \quad m_t - p_t = \frac{\eta_c}{\eta_m} y_t - \frac{1}{\eta_m} i_t + \xi_{m_d,t} && \text{(B.31)} \\
\text{Consumption Euler equation} &: \quad r_t = r_t^n + \eta_c(E_t[\tilde{y}_{t+1}] - \tilde{y}_t) && \text{(B.32)} \\
\text{Natural rate} &: \quad r_t^n = \eta_c(E_t[y_{t+1}^n] - y_t^n) && \text{(B.33)} \\
\text{Money supply} &: \quad m_t = h_t + \phi_{rr}(h_t - fr_t) + \xi_{m_s,t} && \text{(B.34)} \\
\text{Nonborrowed reserve supply} &: \quad h_t = \rho_h h_{t-1} - \nu_h(i_t - i_t^T) && \text{(B.35)} \\
\text{Free reserve demand} &: \quad fr_t = \rho_{fr} fr_{t-1} - \frac{\nu_{fr}}{s}(i_t - i_t^T) && \text{(B.36)} \\
\text{Policy target rate} &: \quad i_t^T = \rho_i i_{t-1}^T + (1-\rho_i)(\kappa_\pi \pi_t + \kappa_y \tilde{y}_t) + \epsilon_t^i && \text{(B.37)} \\
\text{NK Phillips curve} &: \quad \pi_t = \beta E_t[\pi_{t+1}] + \tilde{\kappa}\tilde{y}_t && \text{(B.38)} \\
\text{Output gap} &: \quad \tilde{y}_t = y_t - y_t^n && \text{(B.39)} \\
\text{Natural output} &: \quad y_t^n = (1+\eta_n)/(\eta_c+\eta_n)\xi_{z,t} && \text{(B.40)} \\
\text{Inflation definition} &: \quad \pi_t = p_t - p_{t-1} \ , && \text{(B.41)}
\end{aligned}
$$

where $\phi_{rr} = \frac{FR}{rrM} = \frac{FR}{RR}$.

[17] The first-order Taylor approximation yields, after imposing the symmetrical spread, an additional constant term on the right-hand side of equation B.29: $\nu_{fr} \ln 2$, which has no material affect on the results.

C Implications of the 'liquidity trap' hypothesis and the Fiscal Theory of the Price Level

In the current economic state of low interest rates and ineffective monetary policy some notable hypotheses have gained traction. One strand of literature, in particular, posits a theory of price level determination based on the interaction between fiscal policy and monetary policy. Cochrane (2014) and Leeper (2016) form the argument by identifying three basic approaches to monetary policy and price level determination: money supply and demand in the spirit of the monetarist MV≡PY tradition; interest-rate controlling New-Keynesian models; and the fiscal theory of the price level (FTPL). Their important critique, as previously raised by Sargent and Wallace (1985), is that the economy is satiated with money when the return on money (or reserves) equals the return on risk-free assets (e.g., Treasury bills). That is, any amount of money will be held at this point, and exchanging Treasuries for money has no effect on the economy—the price level is therefore indeterminate. In response to this state of the world, Cochrane (2014) and Leeper (2016) show that a determinant equilibrium necessitates an "active" fiscal policy.[18] Indeed, Cochrane (2014) correctly emphasizes that this holds *only* in the current international monetary system of fiat money and central banks. But if the price level is the price of goods in terms of nominal (government) liabilities (money plus bonds), the question then becomes: what determines the price level in a world of free banking with un-backed, de-centralized fiat money? Is there a more fundamental theory of price-level determination that precludes fiscal debt management and present discounted government deficits and surpluses?

Understanding the interaction between fiscal and monetary policy certainly needs more attention. Cochrane (2014, p. 78) emphasizes the fiscal theory of the price level as follows: "In this way, the Treasury and the Fed acting together do, in fact, institute a system in which the government as a whole sets the interest rate i_{t-1} and then sells whatever facevalue of the debt B_{t-1} that [is demanded] ... even though the Fed does not directly change the overall quantity of debt, and even though the Treasury seems to sell a fixed quantity, not at a fixed price." The model developed here could easily be extended to incorporate fiscal policy and the government budget (see, e.g., Schmitt-Grohé and Uribe, 2007), but under the assumption that fiscal policy is "passive" it is not necessary: in Leeper's (1991; 2016) "Regime M" monetary policy controls inflation and fiscal policy ensures government solvency (see also, Cochrane, 2014, p. 91). That said, Leeper's framework falls into the same trap identified by McCallum (1986, p. 156) in relation to Sargent and Wallace

[18] "The aggregate price level is a relative price: it measures how much a basket of goods is worth in terms of nominal government liabilities—money plus bonds. This relative price must be determined by the interaction of supply and demand for these government liabilities." (Leeper, 2016, p. 2)

(1982), namely that the model "neglects the medium-of-exchange role of money, thereby negating the possibility of distinguishing between monetary and non-monetary assets."

In contrast, the model developed in Belongia and Ireland (2014) and Ireland (2014), based on Barnett's (1978; 1980) user cost of money and monetary aggregation theory, emphasizes the role of the true aggregate of monetary (liquidity) services demanded. Their shopping time model maintains the core New-Keynesian (IS-LM) framework and ensures that the opportunity cost on this true monetary aggregate is always positive—provided the risk-free rate is not zero. With regards to the zero lower bound, it is not immediately evident that money demand has no satiation point. While the threshold appears to be currently rather high in the market for reserves, Ireland (2009) shows evidence of a finite satiation point for broader monetary aggregates (also illustrated in Figure A.1). As this is likely true, then even at zero nominal interest rates, the true monetary aggregate—whether currency or highly liquid, risk-free assets—commands some positive finite transactions value (Yeager, 1986). In effect, all perfectly substitutable, perfectly liquid assets will inherit this valuable attribute. In the context of macroeconomic models, the demand for fiat money depends on whether we expect it will hold its *exchange value* in the future: its discounted present value. By backward induction, money would be valueless today if we knew with certainty that money would be valueless at some given date in the future. But if money has positive value in all future periods, we can proceed.

This is basically illustrated by assuming that all wealth (assets) are in the household's utility function and that their corresponding rate of return has some implicit transactions value, no matter the illiquidity or riskiness—someone, somewhere is willing to trade for that asset. This is effectively Say's Law: the supply of any good, including fiat money and specie, generates a demand for all other goods (see, e.g., Yeager (1986)). Further, we are essentially proposing some measure of "moneyness" attached to any item of value, to which, as it approaches perfect substitutability with money, it will approach the finite value of liquidity (transactions) services.

D Descriptive statistics

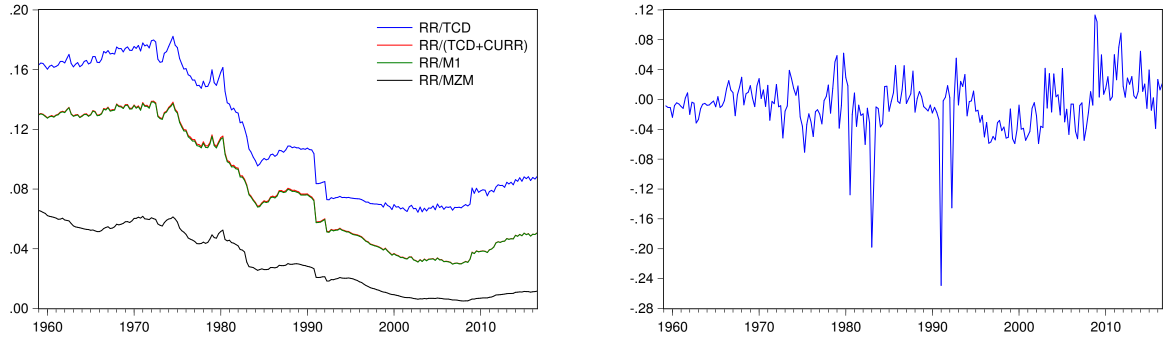

Figure D.1: Left panel: Effective reserve ratio ($RR_t/M_t = rr_t$). Right panel: Log-difference effective reserve ratio ($RR_t/MZM_t = rr_t$). Sample: 1959Q1−2016Q03.

E Estimation results

E.1 Estimation diagnostic statistics

E.2 Historical decompositions

E.3 Posterior estimations for alternative samples

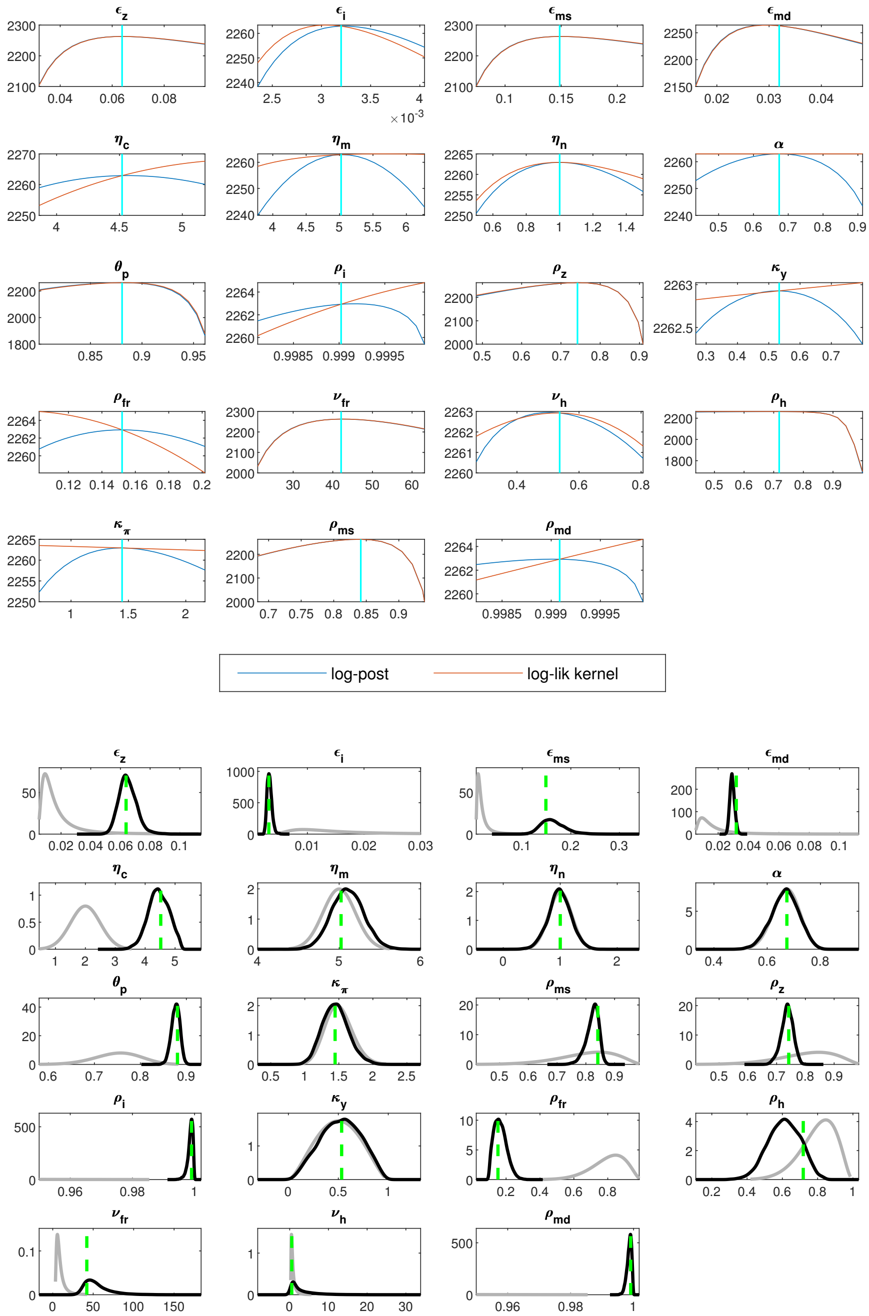

Figure E.2: Top panel: log-data density. Bottom panel: prior and posterior distributions. Estimation period: 1959Q1−2007Q3.

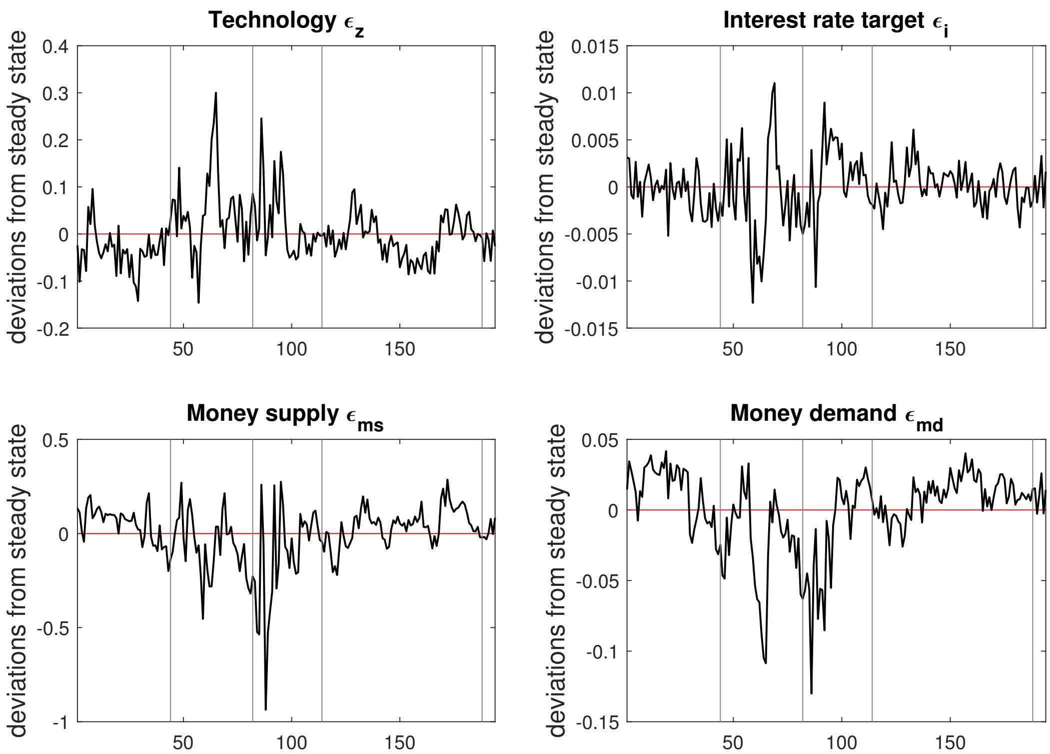

Figure E.3: Smoothed shocks.

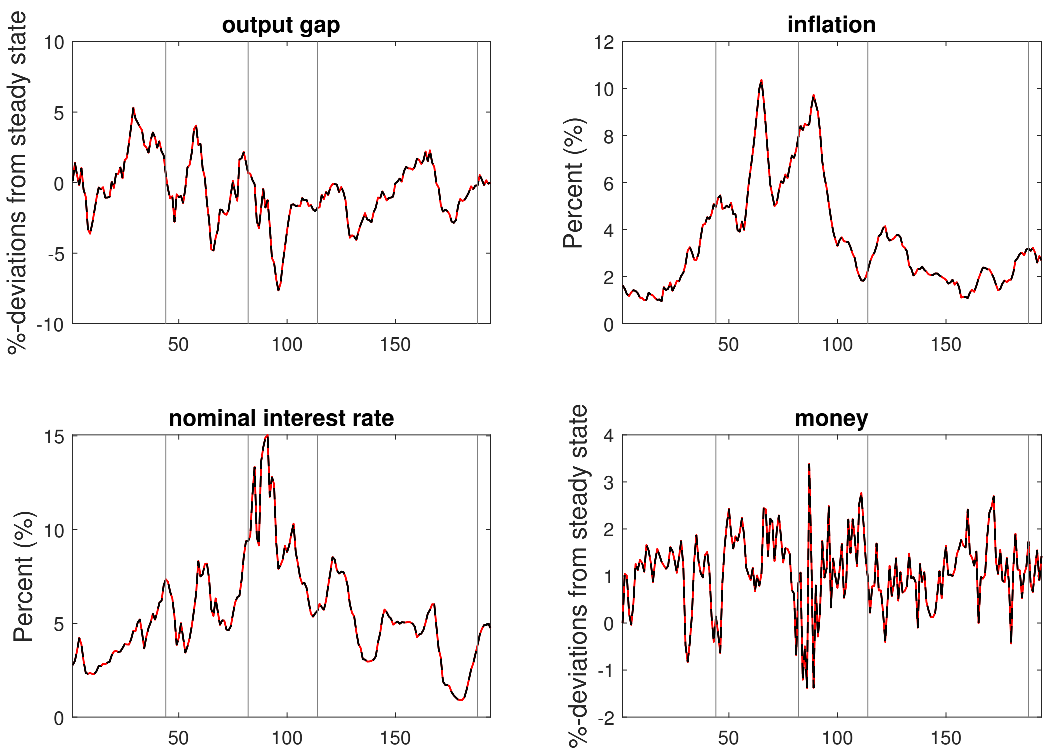

Figure E.4: Historical variables.

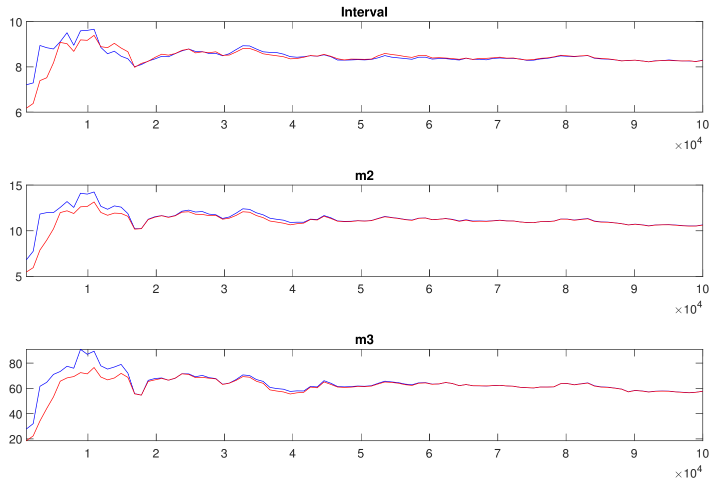

Figure E.5: Multivariate convergence diagnostic.

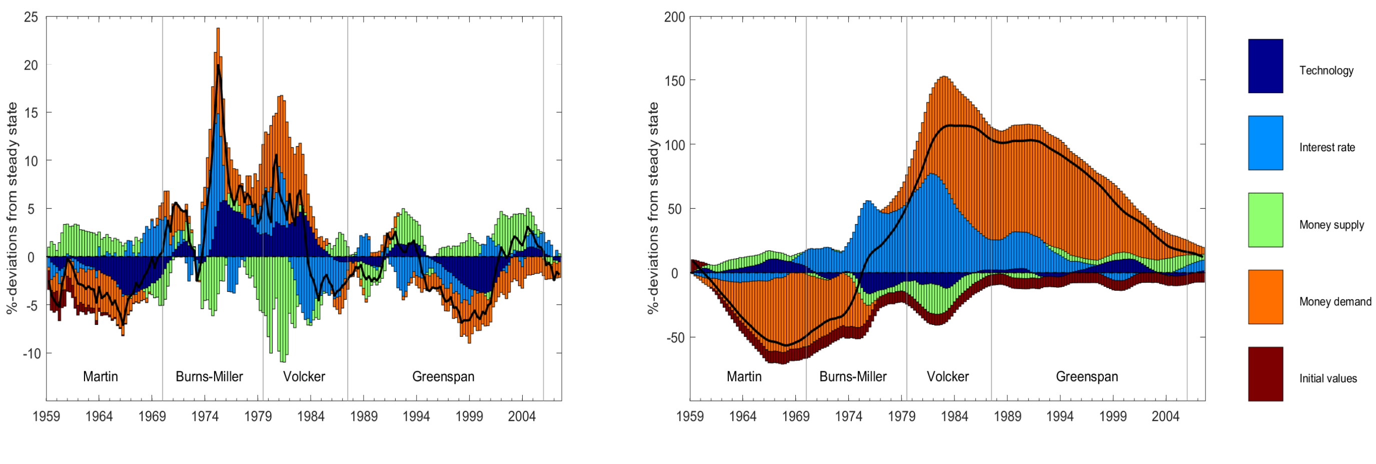

Figure E.6: Historical decomposition (1959Q1−2007Q3): Output (left panel); Price-level (right panel). Estimation period: 1959Q1−2007Q3

Table E.1: Bayesian estimation of structural parameters

					1959Q01−2007Q03 Posterior dist.			1984Q01−2007Q03 Posterior distr.			1959Q01−2019Q04 Posterior distr.		
		Prior dist.											
	Parameter	Type	Mean	Std.dev	Mean	90% HPD int.		Mean	90% HPD int.		Mean	90% HPD int.	
Households													
η_c	Relative risk aversion	Normal	2	0.50	4.443	3.895	5.022	3.390	2.777	3.984	4.843	4.515	5.180
η_m	Inv. elasticity of money demand	Normal	5	0.20	5.101	4.789	5.427	5.094	4.771	5.396	5.195	4.886	5.503
η_l	Inv. elasticity of labour supply	Normal	1	0.10	0.986	0.643	1.305	0.972	0.632	1.300	0.992	0.655	1.324
β	Discount factor		0.98										
Firms													
α	Labour's share in production	Beta	0.67	0.05	0.666	0.580	0.748	0.668	0.585	0.749	0.670	0.591	0.754
θ	Price stickiness	Beta	0.75	0.05	0.877	0.861	0.891	0.868	0.847	0.891	0.888	0.877	0.900
Monetary regime													
ν_h	Elasticity of non-borr. reserves	Inv.Gamma	1	10	3.024	0.217	7.458	11.51	1.116	20.83	8.393	0.289	16.70
ν_{fr}	Elasticity of free reserves	Inv.Gamma	10	10	54.40	32.07	77.64	11.61	4.274	18.61	84.39	44.04	123.5
ρ_h	Non-borr. reserve persistence	Beta	0.8	0.10	0.610	0.464	0.756	0.413	0.289	0.541	0.529	0.383	0.659
ρ_{fr}	Free reserves persistence	Beta	0.8	0.10	0.166	0.103	0.217	0.184	0.111	0.242	0.155	0.103	0.203
κ_π	Weight on inflation	Gamma	1.5	0.20	1.449	1.127	1.745	1.486	1.153	1.812	1.453	1.120	1.773
κ_y	Weight on output gap	Beta	0.5	0.20	0.523	0.216	0.866	0.530	0.206	0.860	0.543	0.222	0.870
$\phi_{rr} = FR/RR$	Ratio of FR to RR				0.003			0.017			0.003		
AR(1) coeff.													
ρ_z	Technology	Beta	0.8	0.10	0.736	0.703	0.771	0.756	0.712	0.796	0.750	0.721	0.779
ρ_i	Interest rate target	Beta	0.8	0.10	0.999	0.997	1.000	0.996	0.992	0.999	0.999	0.998	1.000
ρ_{m_s}	Money supply	Beta	0.8	0.10	0.823	0.787	0.856	0.759	0.706	0.814	0.819	0.780	0.860
ρ_{m_d}	Money demand	Beta	0.8	0.10	0.999	0.998	1.000	0.992	0.986	0.999	0.999	0.998	1.000
Std. dev.													
ϵ_z	Technology	Inv.Gamma	0.02	2.00	0.065	0.055	0.074	0.037	0.031	0.043	0.065	0.056	0.074
ϵ_i	Interest rate target	Inv.Gamma	0.02	2.00	0.003	0.003	0.004	0.004	0.003	0.005	0.003	0.003	0.004
ϵ_{m_s}	Money supply	Inv.Gamma	0.02	2.00	0.163	0.124	0.201	0.072	0.050	0.091	0.190	0.143	0.234
ϵ_{m_d}	Money demand	Inv.Gamma	0.02	2.00	0.029	0.027	0.032	0.014	0.012	0.015	0.028	0.026	0.030
Log-data density					2213.38			1250.33			2857.27		
Acceptance ratio range					[23%;24%]			[24%;26%]			[25%;26%]		
Observations					195			95			244		

E.4 IRFs for alternative samples

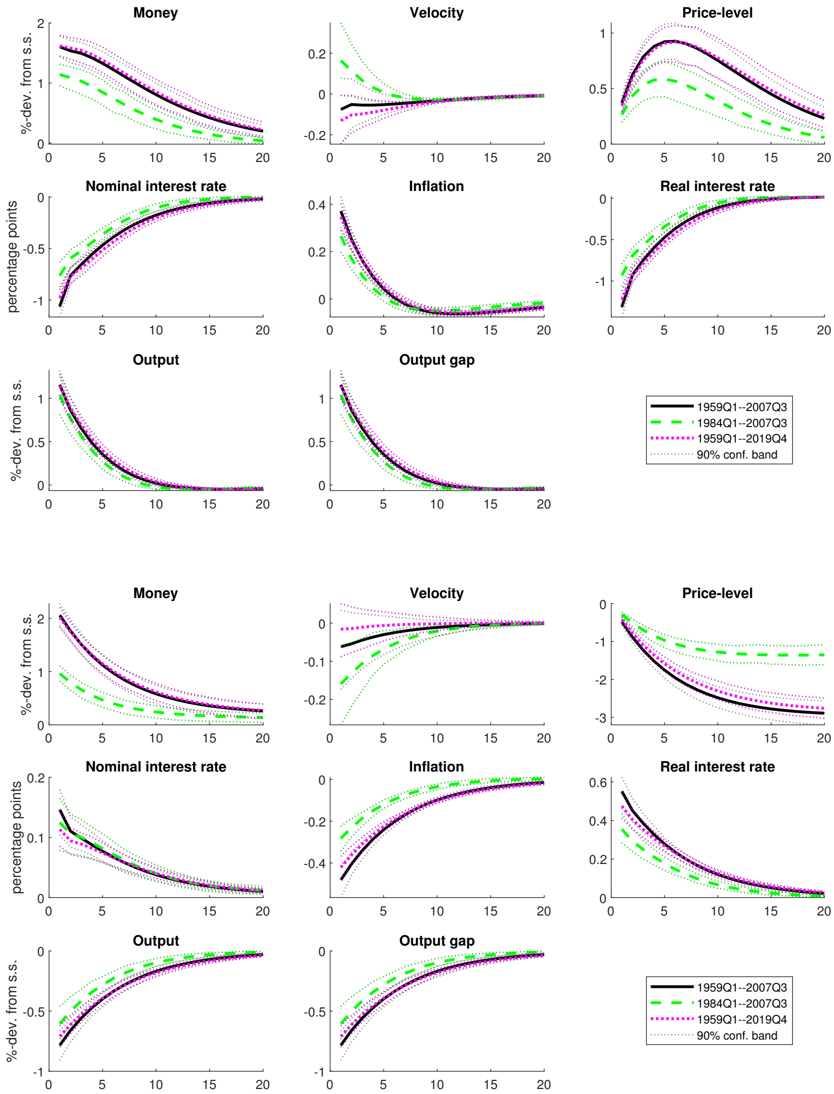

Figure E.7: Impulse response to positive money supply shock (top) and positive money demand shock (bottom). Note: s.s. = steady state.

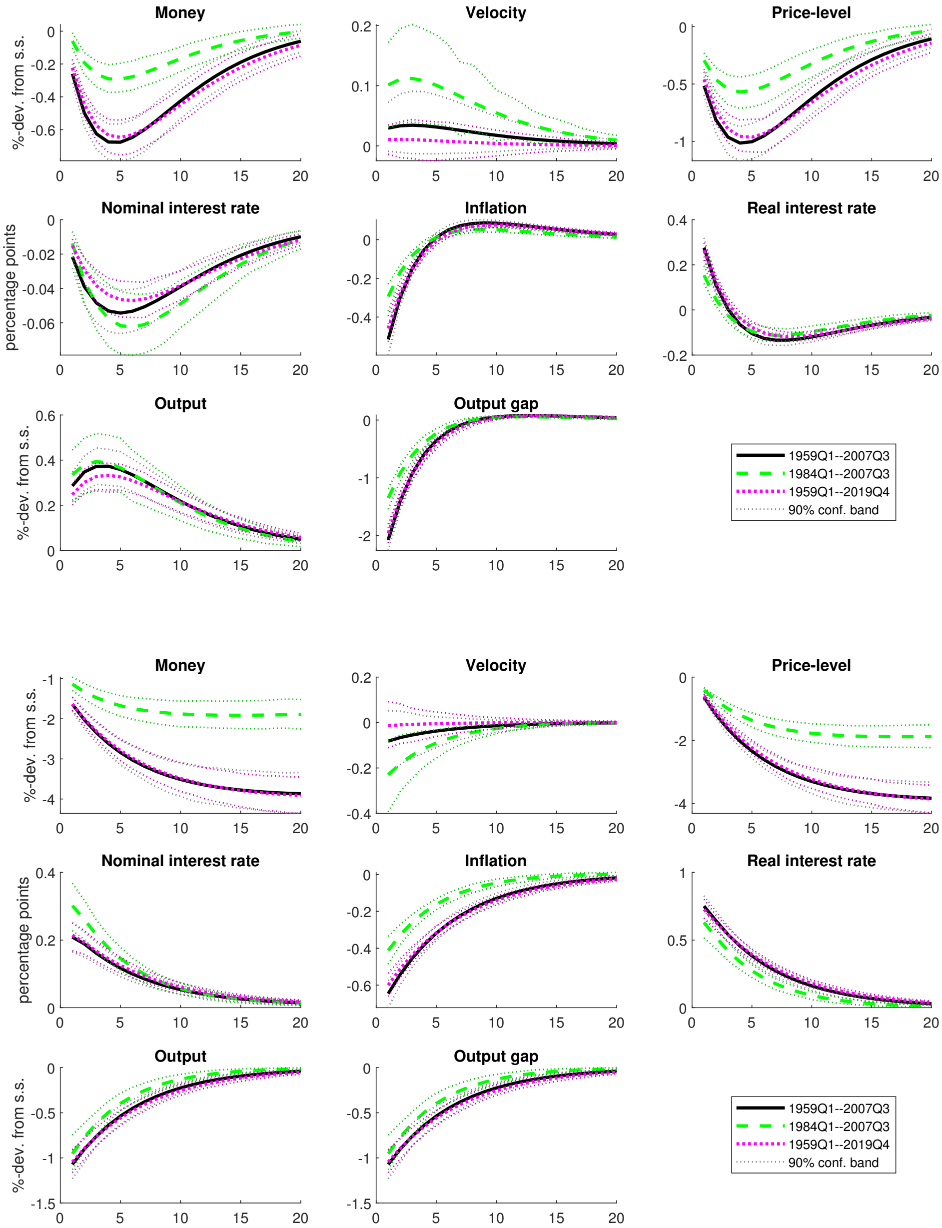

Figure E.8: Impulse response to positive technology shock (top) and positive interest rate target shock (bottom). Note: s.s. = steady state.

F Simulation IRFs

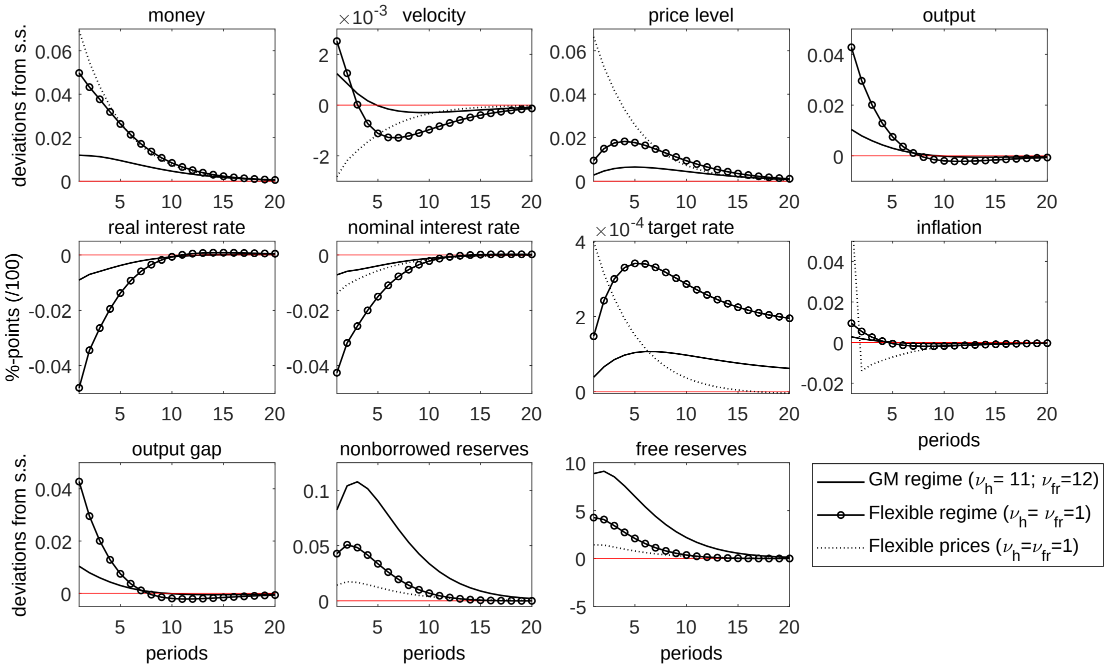

Figure F.9: Positive money supply shock.

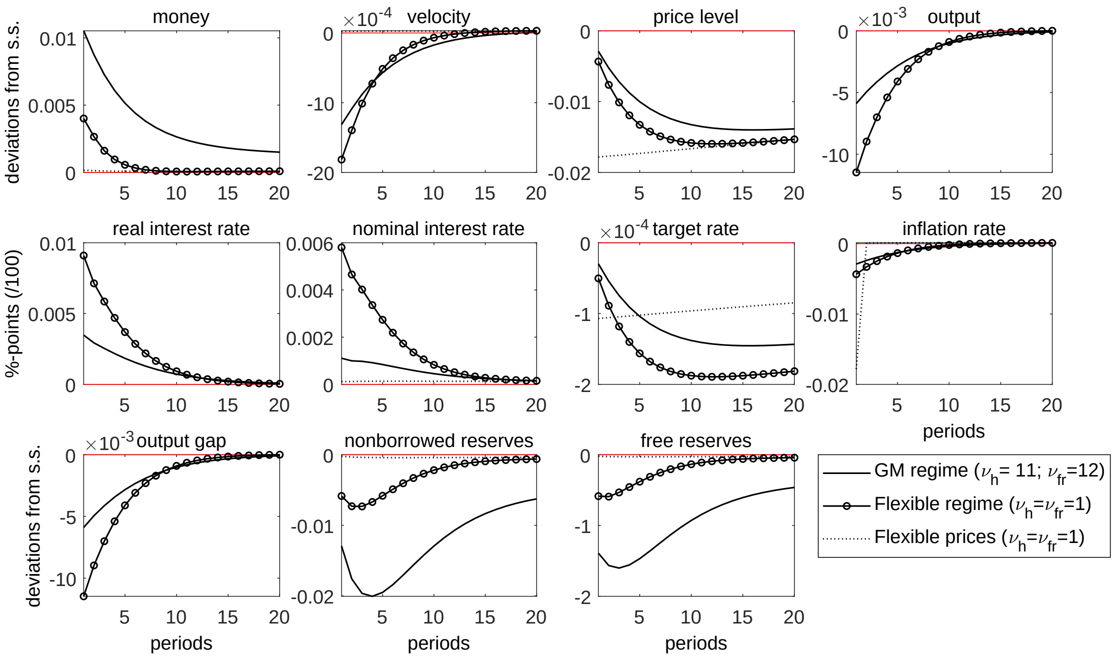

Figure F.10: Positive money demand shock.

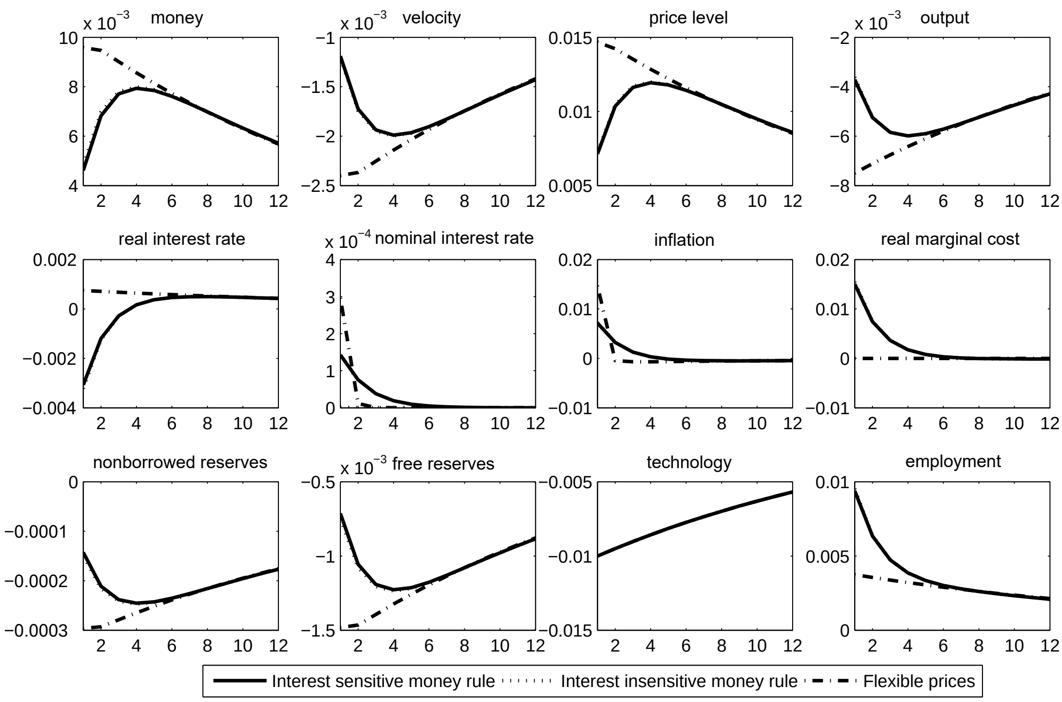

Figure F.11: Negative technology shock.

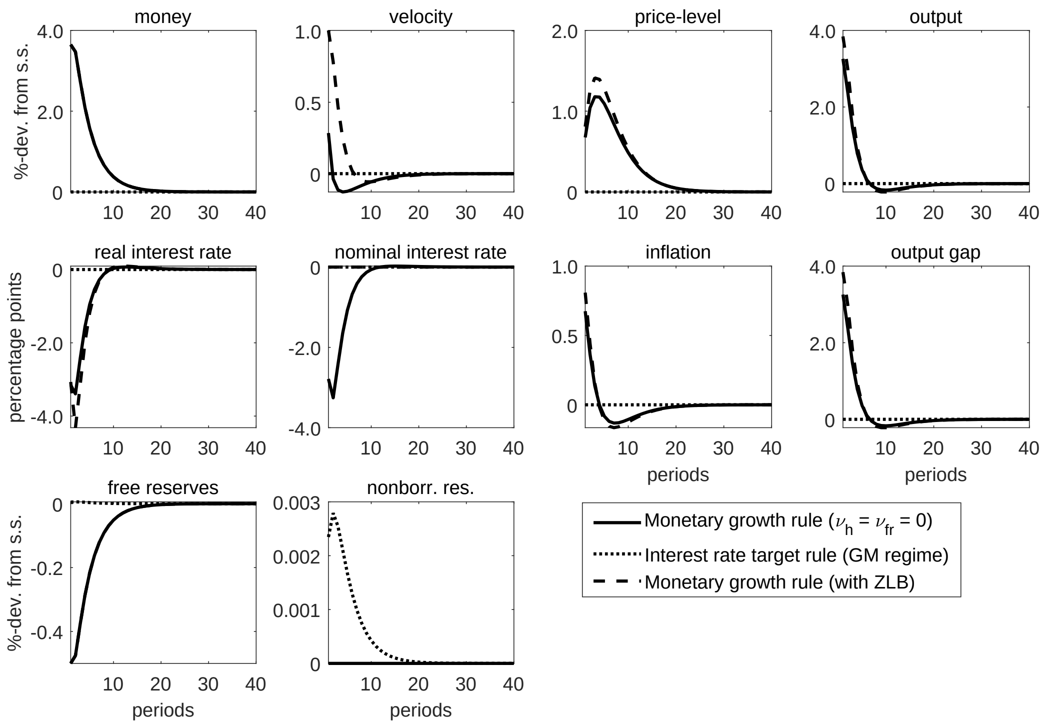

Figure F.12: Impulse responses to a negative free reserves shock.

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