Interest on Reserves and the Credit Channel of Monetary Policy

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Abstract

Since October 2008, the Fed has been paying interest on banks' required reserve and excess reserve balances. Paying interest on reserves (IOR) acts as a supplemental tool to enforce the targeted federal funds rate. This research explicitly derives the relationships between interest paid on reserves and other interest rates, and it analyzes the impact of expansionary monetary policy shocks and financial cost shocks in an IOR scheme and in a non-IOR scheme. The results indicate that paying IOR moderates the negative impact of deficient liquidity on collateral-constrained households' consumption. A non-IOR scheme generates higher expected inflation and ignites Ricardian households' intertemporal consumption allocation. Paying IOR generally stabilizes economic fluctuations and promotes welfare.

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I. Introduction

Since October 2008, the Fed has been paying interest on banks' required reserve and excess reserve balances. The reason for this is to counter the downward pressure on the federal funds rate that resulted from soaring excess reserves. Paying interest on reserves (IOR) established a lower bound for the federal funds rate. It was set roughly equal to the average target federal funds rate for reserve balances over the reserve maintenance period. A growing body of studies empirically or theoretically investigates the economic effects of paying interest on U.S. reserves (Berentsen and Monnet, 2008; Kashyap and Stein, 2012; Martin et al., 2013; Cochrane, 2014; Ireland, 2014). Kashyap and Stein (2012) propose that IOR is eligible as a policy instrument along with the federal funds rate as a policy target anchored by the Taylor rule. The Fed can adjust the IOR to achieve price stability and financial stability simultaneously. Cochrane (2014) demonstrates that in an IOR regime, monetary-fiscal policy coordination helps the Fed determine expected inflation and control the size of its balance sheet. Ireland (2014) concludes that paying IOR coordinates with open market operations to maintain a desired equilibrium in the reserves market. Paying interest on reserves dampens output and inflation variabilities, promotes banks' operation efficiency, and reinforces financial stability.

One intriguing question that arises from the discussion of paying interest on reserves concerns how the IOR rate should be determined. In Keister et al.'s (2008) graphical analysis, the IOR rate is set to the deposit rate. Intuitively, the cost of taking an additional deposit should equal the interest earned on an additional reserve, which is a fraction of the deposit. Stein (2012) defines the IOR rate as the federal funds rate minus the scarcity value of reserves, i.e., the benefit for a bank to hold additional reserves on the margin. In Stein's (2012) paper, he refers the scarcity value of reserves to the nominal interest rate, i.e., the opportunity cost of holding non-interest-bearing reserves or equivalently, the value of a permit for money creation. Ireland (2014) proposes a generalized form of IOR rate as a markup of a constant or a time-varying spread over the short-term market rate (policy rate) and assumes that it follows an AR(1) process.

The purpose of this paper is twofold. First, we explicitly lay out the relationships between IOR and other interest rates prevailing in the market, such as the rate charged on the central bank's discount loans, the rate of commercial banks' taking deposit, and the rate of commercial banks' lending. By endogenizing the interactions between these interest rates, we evaluate the macroeconomic effects of various interest rates as policy rates in the Taylor rule. The second purpose of this paper is to assess the effectiveness of paying IOR on spurring consumption as financial strain occurs. We focus on the impulse responses of paying and not paying IOR against expansionary monetary policy shocks and financial cost shocks. These two shocks describe the situations in the midst of the 2008-2009 Great Recession. An expansionary monetary policy (lowered policy rates) is usually implemented during recessions. Higher financial costs deteriorate a bank's profit and widen the borrowing-deposit interest rate spread.

This research makes two contributions to existing studies. First, previous studies rarely discuss the consequences of conducting different interest rates but choose ad hoc policy rates in the Taylor rule. The Taylor rule stipulates how the central bank should adjust the nominal interest rate in response to changes in economic conditions. The selection of an interest rate as a policy rate in the Taylor rule differs in literature. Glocker and Towbin (2012) choose the lending rate charged by a deposit bank to another bank to analyze under what circumstances reserve requirements outperform an interest rate rule in achieving financial stability. Hilberg and Hollmayr (2013) construct an interbank market with two types of banks, one of which invests in less liquid assets (risky loans to the entrepreneurs) and the other invests in liquid assets (loans fully eligible as collateral in repurchase agreements with the central bank), to evaluate the effects of unconventional monetary policy. Compared to the rate charged for the liquidity provided by the central bank being used as a policy rate, a haircut instrument can substantially stabilize economic fluctuations against asset price shocks.

Chen (2015) sets the federal funds rate, which is negatively related with the excess reserve ratio, to respond to the inflation rate as a central bank's interest rate feedback rule. Ireland (2014) and Keating et al. (2014) use the nominal interest rate of government bonds as a policy rate in the Taylor rule.

By adopting various interest rates as policy rates in the Taylor rule, our results indicate that the responses of major variables against policy shocks in a non-IOR regime are greater in magnitude than those in an IOR regime. Using the federal funds rate as a policy rate generates smaller responses in an IOR regime while using the lending rate generates smaller responses in a non-IOR regime. This reconciles with the evidence that paying interest on reserves was initiated to act as a lower bound for the federal funds rate. The combination of paying interest on reserves along with using the federal funds rate as a policy rate mildens economic fluctuations.

Second, previous studies (Kashyap and Stein, 2012; Cochrane, 2014; Ireland, 2014) suggest that the amplification effect of monetary policy is transmitted to the economy more rapidly through the credit channel when IOR is used as a policy instrument. Paying IOR stabilizes output, inflation and the financial market. In our model with two types of agents, when the credit market is tightened, lower borrower net worth incurs additional agency costs of financial capital and weakens consumption demand. In an environment with low interest rates, people tend to hold more cash and reduce bank deposits, resulting in deficient market liquidity. Whether IOR is paid affects banks' incentive to hold reserves and their lending behavior. Due to convex costs of holding reserves, banks will not hold infinite excess reserves. In an IOR scheme, banks have lower opportunity costs of holding bank reserves. Banks which lack liquidity can borrow from the central bank and extend credit to borrowers. Paying IOR helps alleviate the adverse effects of deficient liquidity on collateral-constrained households' consumption. A non-IOR policy induces banks to economize on holding reserves and restricts banks' primary source of revenue to lending. Banks are intent to engage in aggressive lending of excess reserves, which adds inflation pressure. Higher expected inflation induces Ricardian households (savers) to decrease money demand and increase tradable and housing consumption.

In related research, Canzoneri et al. (2017) assume that banks consider issuing deposits and bonds as two competing sources of funding loans. The benefits of holding reserves are to reduce transaction costs and to manage the liquidity of its deposits. In a dynamic stochastic general equilibrium framework, they argue that in the presence of price adjustment cost and bank lending externality, it is optimal to impose a tax on deposits (reserves) when the central bank aims to stabilize prices with two policy instruments of federal funds rate and interest on reserves. The interest rate on reserves would be paid less than its competitive rate. Unlike the perfectly competitive banking sector, banks in our model operate in a monopolistically competitive market. Banks maximize profits by optimizing excess reserves, loans and deposits. Paying interest on reserves alters banks' incentive to hold reserves and their asset allocation between loans and excess reserves on the margin.

With respect to welfare, the welfare generated from a non-IOR policy is initially higher than the welfare generated from an IOR policy, but it declines afterwards against expansionary monetary policy shocks. This is because a non-IOR policy produces substantially high expected inflation and ignites savers' intertemporal consumption allocation. After about five quarters, an IOR scheme outperforms a non-IOR scheme in terms of consumption-based welfare. In responses to financial cost shocks, welfare is reduced less in an IOR regime than in a non-IOR regime. In general, paying IOR stabilizes economic fluctuations and promotes welfare.

The remainder of this paper is organized as follows. Section 2 presents the model. Section 3 analyzes the calibration results and Section 4 concludes.

II. Model

Our model extends Keating et al. (2014)'s version[1] to an open-economy framework with two types of households and enables banks to convert illiquid loans

[1] Keating et al. (2014) investigate the effects of alternative policy rules: the Taylor rule and money growth rate rule in terms of the Divisia monetary aggregate on real economy during financial crises. The Divisia monetary aggregate consisting of currency and deposits was proposed by Barnett (1980).

into liquid mortgage-based securities. Our model has several characteristics. First, it is equipped with New Keynesian features, such as nominal price rigidities and monopolistic competition. Intermediate-goods firms produce in a monopolistically competitive market, so they are able to set their prices over the marginal costs. Banks also operate in a monopolistically competitive market, maximizing expected present value of profit flows subject to deposit and loan demand functions. The presence of imperfect competition creates market distortions and provides a rationale for the central bank to implement monetary policy rules.

Second, our model consists of Ricardian households (savers), collateral-constrained borrowers and a financial sector, and it reconciles with empirical observations during the most recent U.S recession. Collateral-constrained households' borrowing capacity is tied to the expected future value of their housing. In the steady state, the security rate is the reciprocal of the saver's discount factor. The loan rate is inversely related to the borrower's discount factor and is a multiplier of the collateral constraint. Changes in monetary policy rates affect the security rate, the loan rate, and households' intertemporal allocation of consumption. Similar settings have been used in discussions with respect to the collateral constraint channel of

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In Keating et al. (2014)'s paper, currency and deposits are imperfect substitutable assets and have time-varying shares in Divisia monetary aggregate. The growth rate rule of the Divisia monetary aggregate targets the previous period's growth rate, current inflation, and current output gap.

monetary policy transmission (Kiyotaki and Moore, 1997; Aoki et al., 2004; Calza et al., 2007, 2013; Iacoviello, 2005; Monacelli, 2009).

Third, we assume that commercial banks can transform mortgage loans into securities and sell them to domestic and foreign savers. Through securitization, banks are able to receive funds abroad. The effects of securitization have also been documented in several studies (Estrella, 2002; Jiangli et al., 2007; Adrian and Shin, 2008, 2009, 2010; Loutskina and Strahan, 2009; Loutskina, 2011; Marques-Ibanez et al., 2014). Securitization improves banks' profitability, reduces the risk of bank insolvency, amplifies the propagation of the monetary transmission mechanism, and may disrupt financial stability.

The domestic economy consists of seven agents: patient households (savers), impatient households (borrowers), final goods producers (retailers), intermediate goods producers, financial intermediaries (commercial banks), fiscal authority and the central bank. There are equal numbers of borrowers and savers. Households share the same preferences, consuming a CES composite of home tradable goods, foreign tradable goods, and services from housing. Impatient households face an optimization problem that includes a budget constraint and a collateral constraint. Patient households have accumulated sufficient wealth and are not credit-constrained. Housing is pledged for loans. Labor is immobile between countries. Domestic firms in the tradable goods and housing sectors produce intermediate goods with labor in a monopolistically competitive market. The final goods market is assumed to be perfectly competitive. Commercial banks take deposits from domestic savers, receive funds from domestic and foreign savers through sales of mortgaged-backed securities, borrow from the central bank, and also provide loans to domestic and foreign borrowers. The central bank adjusts the level of reserve balances in the banking system by making loans to commercial banks.

2.1 **Borrowers in the Home Country**

The preferences of the representative borrowers are defined over a composite consumption X_t^B of tradable goods C_t^B and housing D_t^B, real money balance m_t^B and disutility of employment, N_t^B.

$$Max \quad E_0 \left\{ \sum_{t=0}^{\infty} \beta^t \left[\ln X_t^B + \frac{\mu_t \left(m_t^B\right)^{1-\iota}}{1-\iota} - \frac{\left(N_t^B\right)^{1+\varsigma}}{1+\varsigma} \right] \right\} \tag{1}$$

$$X_t^B = \left[(1-\alpha)^{\frac{1}{\eta}} \left(C_t^B\right)^{\frac{\eta-1}{\eta}} + \alpha^{\frac{1}{\eta}} \left(D_t^B\right)^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}} \tag{2}$$

$$C_t^B = \left[(1-\alpha_C)^{\frac{1}{\varepsilon}} \left(C_{H,t}^B\right)^{\frac{\varepsilon-1}{\varepsilon}} + (\alpha_C)^{\frac{1}{\varepsilon}} \left(C_{F,t}^B\right)^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}} \tag{3}$$

st.

$$C_t^B + Q_t\left(D_t^B - (1-\delta)D_{t-1}^B\right) + \left(1+r_{t-1}^B\right)\frac{b_{t-1}^P}{\pi_{C,t}} + \left(1+r_{t-1}^{B*}\right)\frac{S_t b_{t-1}^{P*}}{\pi_{C,t}} + m_t^B + T_t^B$$
$$= b_t^P + S_t b_t^{P*} + w_t N_t^B + \frac{1}{\pi_{C,t}} m_{t-1}^B \qquad (4)$$

$$\left(1+r_t^B\right)b_t^P + \left(1+r_t^{B*}\right)S_t b_t^{P*} = (1-\chi)(1-\delta)E_t\left\{D_t^B Q_{t+1}\pi_{C,t+1}\right\} \qquad (5)$$

Here β is the discount factor and ς is the elasticity of marginal disutility with respect to labor supply. ι is the elasticity of marginal utility with respect to money demand. μ_t serves as a money demand shock. η is the elasticity of substitution between tradable goods and housing. ε is the elasticity of substitution between domestic goods $C_{H,t}^B$ and foreign goods $C_{F,t}^B$. α determines the steady-state share of housing in total consumption. α_C is the steady-state share of foreign goods in tradable goods consumption.

The objective of the representative borrower is to maximize the expected present discounted utility (1) subject to the budget constraint (4) and the collateral constraint (5) in real terms. δ is the depreciation rate of housing. Q_t is the relative price of housing, defined as $P_{D,t}/P_{C,t}$. Housing is used as collateral for loans. We assume a financial intermediary transforms the collateralized mortgage into securities at no cost and sells them to foreign savers. An asterisk represents the foreign country. Households hold domestic borrowing from banks $b_t^P \equiv B_t^P/P_{C,t}$ and foreign borrowing $b_t^{P*} \equiv B_t^{P*}/P_{C,t}$. r_t^B represents the cost of borrowing. $w_t = W_t/P_{C,t}$

represents the real wage.[2] T_t^B is the lump-sum tax paid to the government by borrowers. S_t represents the price of foreign currency in units of domestic currency. An increase in S_t represents the depreciation of domestic currency. χ represents the fraction of the value of housing that cannot be used as collateral for a loan. $\pi_{C,t} \equiv P_{C,t}/P_{C,t-1}$ is the domestic inflation rate of tradable goods. λ_t and $\gamma_t\lambda_t$ are multipliers for budget constraint and collateral constraint, respectively. The first order conditions are defined as equations (6)-(11).

$$\frac{\beta^t (1-\alpha)^{\frac{1}{\eta}}}{\left(X_t^B\right)^{\frac{\eta-1}{\eta}} \left(C_t^B\right)^{\frac{1}{\eta}}} = \lambda_t \tag{6}$$

$$\left(N_t^B\right)^{\zeta} = \frac{(1-\alpha)^{\frac{1}{\eta}} w_t}{\left(X_t^B\right)^{\frac{\eta-1}{\eta}} \left(C_t^B\right)^{\frac{1}{\eta}}} \tag{7}$$

$$\frac{\left(X_t^B\right)^{\frac{\eta-1}{\eta}} \left(C_t^B\right)^{\frac{1}{\eta}} \mu_t}{(1-\alpha)^{\frac{1}{\eta}} \left(m_t^B\right)^{\iota}} + \frac{\beta \left(X_t^B\right)^{\frac{\eta-1}{\eta}} \left(C_t^B\right)^{\frac{1}{\eta}}}{\left(X_{t+1}^B\right)^{\frac{\eta-1}{\eta}} \left(C_{t+1}^B\right)^{\frac{1}{\eta}} \pi_{C,t+1}} = 1 \tag{8}$$

$$\left(1+r_t^B\right)\left(\gamma_t + E_t\left\{\frac{\left(X_t^B\right)^{\frac{\eta-1}{\eta}} \left(C_t^B\right)^{\frac{1}{\eta}} \beta}{\left(X_{t+1}^B\right)^{\frac{\eta-1}{\eta}} \left(C_{t+1}^B\right)^{\frac{1}{\eta}} \pi_{C,t+1}}\right\}\right) = 1 \tag{9}$$

$$\left(1+r_t^{B*}\right)\cdot\left[\gamma_t + E_t \frac{\left(X_t^B\right)^{\frac{\eta-1}{\eta}} \left(C_t^B\right)^{\frac{1}{\eta}} \beta}{\left(X_{t+1}^B\right)^{\frac{\eta-1}{\eta}} \left(C_{t+1}^B\right)^{\frac{1}{\eta}}} \frac{1}{\pi_{C,t+1}} \cdot \frac{S_{t+1}}{S_t}\right] = 1 \tag{10}$$

$$\frac{Q_t}{\left(X_t^B\right)^{\frac{\eta-1}{\eta}} \left(C_t^B\right)^{\frac{1}{\eta}}} = \frac{\alpha^{\frac{1}{\eta}}}{(1-\alpha)^{\frac{1}{\eta}} \left(X_t^B\right)^{\frac{\eta-1}{\eta}} \left(D_t^B\right)^{\frac{1}{\eta}}} + \frac{\beta\, Q_{t+1}(1-\delta)}{\left(X_{t+1}^B\right)^{\frac{\eta-1}{\eta}} \left(C_{t+1}^B\right)^{\frac{1}{\eta}}}$$

[2] Here we suppress the superscript "*B*" for wage since we assume that the wages faced by borrowers and savers are the same.

$$+\frac{1}{\left(X_t^B\right)^{\frac{\eta-1}{\eta}}\left(C_t^B\right)^{\frac{1}{\eta}}}\gamma_t\left(1-\chi\right)\left(1-\delta\right)E_tQ_{t+1}\pi_{C,t+1} \tag{11}$$

Equation (7) shows the trade-off between consumption and labor choice. Equation (8) shows the trade-off between consumption and money balances. The right-hand side of equation (8) presents the marginal utility of consumption at period t, which is normalized as 1. The left-hand side of equation (8) consists of the marginal utility of holding money at period t and the marginal utility of converting money into consumption at period $t+1$. Equation (9) is the intertemporal Euler equation. In the steady state, $\gamma+\beta=1/\left(1+\bar{r}^B\right)$. Equations (9) and (10) derive the uncovered interest parity. Equation (11) states that the marginal benefit of increasing an additional unit of housing at time t must equal the marginal utility of tradable goods consumption at time t. The former consists of the direct utility from housing services, the utility of future tradable goods consumption from selling the housing at $t+1$, and the utility obtained from borrowing against housing equity.

2.2 Savers in the Home Country

The objective of the savers is to maximize the expected present discounted utility (12) subject to the budget constraint (13) in real terms. Money aggregate m_t^A enters patient households' utility function as a CES form of currency m_t^S and deposit k_t^S.

ν represents the steady-state share of currency in money aggregate. μ_t serves as a money demand shock. ω is the elasticity of substitution between currency and deposit. $\tilde{b}_t^P \equiv \tilde{B}_t^P / P_{C,t}$ and $\tilde{b}_t^{P*} \equiv \tilde{B}_t^{P*} / P_{C,t}$ are purchases of domestic and foreign mortgage-based securities with rates of return r_t^S and r_t^{S*}, respectively. Savers also receive nominal profits Π_t from the goods-producing sector and the banking sector. T_t^S is the lump-sum tax paid to the government by savers.

$$Max \quad E_0 \left\{ \sum_{t=0}^{\infty} \beta^t \left[\ln X_t^S + \frac{\mu_t \left(m_t^A\right)^{1-\iota}}{1-\iota} - \frac{\left(N_t^S\right)^{1+\varsigma}}{1+\varsigma} \right] \right\} \tag{12}$$

$$m_t^A = \left[\nu^{\frac{1}{\omega}} \left(m_t^S\right)^{\frac{(\omega-1)}{\omega}} + (1-\nu)^{\frac{1}{\omega}} \left(k_t^S\right)^{\frac{(\omega-1)}{\omega}} \right]^{\frac{\omega}{\omega-1}}$$

st.

$$\begin{aligned} & C_t^S + Q_t \left(D_t^S - (1-\delta) D_{t-1}^S \right) + \tilde{b}_t^P + S_t \tilde{b}_t^{P*} + k_t^S + m_t^S + T_t^S \\ & = \frac{1}{\pi_{C,t}} \left[m_{t-1}^S + (1+r_{t-1}^k) k_{t-1}^S \right] + w_t N_t^S + \left(1+r_{t-1}^S\right) \frac{\tilde{b}_{t-1}^P}{\pi_{C,t}} + \left(1+r_{t-1}^{S*}\right) \frac{S_t \tilde{b}_{t-1}^{P*}}{\pi_{C,t}} + \Pi_t \end{aligned} \tag{13}$$

The first order conditions for savers are defined in equations (14)-(19). $\tilde{\beta}$ is the saver's discount rate. r_t^K defines the rate of return for deposits. Equation (15) shows the trade-off between consumption and labor choice for savers. Equation (16) shows the trade-off between consumption and holding money. Equation (17) shows the trade-off between consumption and holding deposits. The right-hand side of equation (17) presents the marginal utility of consumption at period t, which is normalized as 1. The left-hand side of equation (17) consists of the marginal utility of holding deposits at period t and the marginal utility of converting a deposit into consumption at period $t+1$. Equation (18) is the conventional uncovered interest rate parity condition. The condition for a tradeoff between tradable goods and housing, expressed as equation (19), is the same as equation (11) except for the lack of the availability of borrowing against housing.

$$\frac{\tilde{\beta}^t (1-\alpha)^{\frac{1}{\eta}}}{\left(X_t^S\right)^{\frac{\eta-1}{\eta}} \left(C_t^S\right)^{\frac{1}{\eta}}} = \lambda_t \tag{14}$$

$$\left(N_t^S\right)^{\zeta} = \frac{(1-\alpha)^{\frac{1}{\eta}} w_t}{\left(X_t^S\right)^{\frac{\eta-1}{\eta}} \left(C_t^S\right)^{\frac{1}{\eta}}} \tag{15}$$

$$\frac{\left(X_t^S\right)^{\frac{\eta-1}{\eta}} \left(C_t^S\right)^{\frac{1}{\eta}} \mu_t v^{\frac{1}{\omega}}}{(1-\alpha)^{\frac{1}{\eta}} \left(m_t^A\right)^{\frac{\omega\eta-1}{\omega}} \left(m_t^S\right)^{\frac{1}{\omega}}} + \frac{\tilde{\beta} \left(X_t^S\right)^{\frac{\eta-1}{\eta}} \left(C_t^S\right)^{\frac{1}{\eta}}}{\left(X_{t+1}^S\right)^{\frac{\eta-1}{\eta}} \left(C_{t+1}^S\right)^{\frac{1}{\eta}} \pi_{C,t+1}} = 1 \tag{16}$$

$$\frac{\left(X_t^S\right)^{\frac{\eta-1}{\eta}} \left(C_t^S\right)^{\frac{1}{\eta}} \mu_t (1-v)^{\frac{1}{\omega}}}{(1-\alpha)^{\frac{1}{\eta}} \left(m_t^A\right)^{\frac{\omega\eta-1}{\omega}} \left(k_t^S\right)^{\frac{1}{\omega}}} + \frac{\tilde{\beta} r_t^K \left(X_t^S\right)^{\frac{\eta-1}{\eta}} \left(C_t^S\right)^{\frac{1}{\eta}}}{\left(X_{t+1}^S\right)^{\frac{\eta-1}{\eta}} \left(C_{t+1}^S\right)^{\frac{1}{\eta}} \pi_{C,t+1}} = 1 \tag{17}$$

$$\left(1+r_t^S\right) S_t = \left(1+r_t^{S*}\right) E_t S_{t+1} \tag{18}$$

$$\frac{(1-\alpha)^{\frac{1}{\eta}} Q_t}{\left(X_t^S\right)^{\frac{\eta-1}{\eta}} \left(C_t^S\right)^{\frac{1}{\eta}}} = \frac{\alpha^{\frac{1}{\eta}}}{\left(X_t^S\right)^{\frac{\eta-1}{\eta}} \left(D_t^S\right)^{\frac{1}{\eta}}} + \frac{\tilde{\beta} (1-\alpha)^{\frac{1}{\eta}} Q_{t+1} (1-\delta)}{\left(X_{t+1}^S\right)^{\frac{\eta-1}{\eta}} \left(C_{t+1}^S\right)^{\frac{1}{\eta}}} \tag{19}$$

2.3 Domestic Retailers and Intermediate Goods Producers

Retailers aggregate intermediate goods into final goods and sell them to consumers in a perfectly competitive market. There is a continuum of intermediate goods producers indexed by j, $j \in (0,1)$. The production function for domestic retailers in tradable goods sector C and housing sector D is defined as

$$Y_{l,t} = \left[\int_0^1 \left(Y_{l,t}^j \right)^{1-\theta_l} \right]^{\frac{1}{1-\theta_l}}, \quad l = C, D. \tag{20}$$

where θ_l refers to the elasticity of substitution between any two differentiated goods. The production function for an individual intermediate goods firm is defined in equation (17). $Z_{l,t}$ is the productivity shock.

$$Y_{l,t}^j = Z_{l,t} N_{l,t}^j, \quad l = C, D. \tag{21}$$

Intermediate goods producers operate in a monopolistically competitive market. Each period only a fraction $1-\psi$ of all firms can adjust their prices. ψ is a measure of the degree of nominal rigidity. Each firm faces a constant elasticity demand curve and identical marginal costs. Equations (22) and (23) represent the marginal costs in both sectors. In the steady state, firms will choose an optimal price with a fixed markup over the nominal marginal cost.

Let a lower case variable with a hat denote the percentage deviation of a variable around its steady state. Being approximated around a zero inflation steady state, the inflation-adjustment equations for the tradable goods sector and the housing sector are expressed as equations (24) and (25).[3]

[3] Here we assume that the domestic consumer price index for the tradable goods sector equals the producer price index for the tradable goods sector, that is, $P_{C,t} = P_{H,t}$.

$$MC_{C,t} = W_t / (Z_{C,t} P_{C,t}) \tag{22}$$

$$MC_{D,t} = W_t / (Z_{D,t} Q_t P_{D,t}) \tag{23}$$

$$\hat{\pi}_{C,t} = \beta E_t \hat{\pi}_{C,t+1} + (1-\psi)\cdot(1-\beta\psi)\cdot(\hat{w}_t - \hat{z}_{C,t})/\psi \tag{24}$$

$$\hat{\pi}_{D,t} = \beta E_t \hat{\pi}_{D,t+1} + (1-\psi)\cdot(1-\beta\psi)\cdot(\hat{w}_t - \hat{z}_{D,t} - \hat{q}_t)/\psi \tag{25}$$

2.4 Banking Sector in the Home Country

The banking sector is assumed to operate in a standard Dixit-Stiglitz monopolistically competitive market. We assume that banks can transform mortgage loans into securities with a constant-return technology. These mortgage-based securities will be sold to domestic savers and foreign savers for banks' funding sources besides deposits. An individual bank consequently faces a deposit function (26), a loan demand function (27), and a security demand function (28).

$$k_{j,t}^S = \left(\frac{r_{j,t}^K}{r_t^K} \right)^{\mu_K} k_t^S \tag{26}$$

$$b_{j,t}^P + S_t b_{j,t}^{P*} = \left(\frac{r_{j,t}^B}{r_t^B} \right)^{-\mu_B} (b_t^P + S_t b_t^{P*}) \tag{27}$$

$$\tilde{b}_{j,t}^P + S_t \tilde{b}_{j,t}^{P*} = \left(\frac{r_{j,t}^S}{r_t^S} \right)^{\mu_S} (\tilde{b}_t^P + S_t \tilde{b}_t^{P*}) \tag{28}$$

where $r_{j,t}^K$, $r_{j,t}^S$ and $r_{j,t}^B$ are the interest rates offered by bank j on deposits, mortgage-based securities and borrowing, respectively. $b_{j,t} + S_t b_{j,t}^*$ is the total borrowing (domestic and foreign) issued by bank j, and $\tilde{b}_{j,t} + S_t \tilde{b}_{j,t}^*$ is the total sales of mortgage-based securities (domestic and foreign) by bank j. Both are in real terms. μ_K, μ_S and μ_B represent the interest rate elasticities of demand for deposits, securities and loans. These three parameters also measure the stability of the relationship between customers and differentiated banks (Hüelsewig et al., 2006). Higher μ_K, μ_S and μ_B increase the substitutability among various deposit, mortgage-based security and loan institutions, resulting in a more competitive financial market.

Each bank's real profit flow is composed of revenues from providing loans and interest from holding interest-paid (required and excess) reserves, minus interest payments to security holders and depositors, interest paid to the central bank, and costs of holding excess reserves. In case of financial strains, banks can borrow $b_{j,t}^{G}$ from the central bank at the discount rate $r_{j,t}^{G}$ and keep it as excess reserves. This setting enables us to illustrate the relationship between the discount rate, the federal funds rate and the interest rate paid on reserves. In normal times, the discount rate acts as an upper bound and the interest rate on reserves determines the lower bound. $\tau_{j,t}^{K}$ and $\tau_{j,t}^{ER}$ are the fraction of deposits that are kept as required and excess reserves, respectively. The former is determined by the central bank while the latter is optimally chosen by the commercial bank. $r_{j,t}^{M}$ is the interest rate paid on required and excess reserves.

We follow Glocker and Towbin (2012) by assuming that banks undertake convex costs of holding excess reserves. Banks are willing to hold excess reserves for liquidity purposes with a cost saving of $\Phi_1 \tau_{j,t}^{ER} k_{j,t}^{S}$. Meanwhile, the marginal cost of holding reserves increases with a quadratic term of cost $\frac{\Phi_2}{2}\left(\tau_{j,t}^{ER}\right)^2 k_{j,t}^{S}$. Φ_1 and Φ_2 are cost function parameters and are assumed to be positive values. The restriction $\Phi_1 \geq \Phi_2 \tau_{j,t}^{ER}$ implies that holding reserves generates a nonnegative marginal benefit. This composite cost term ensures that banks will not hold infinite excess reserves when the interest rate paid on excess reserves equals the federal funds rate (Ireland, 2014). x_t represents a cost shock to the banking sector.

Equation (31) represents each bank's balance sheet constraint. On the asset side, the uses of funds include loans, mortgage-based securities, and reserves; while deposits and discount loans from the central bank are on the liability side. Without loss of generality, we assume that a fraction ϕ of mortgage-based securities is sold to domestic savers and foreign savers, as expressed in (32). ϕ measures the ratio of converting illiquid loans $b_t^P + S_t b_t^{P*}$ of banks into liquid securities $\tilde{b}_t^P + S_t \tilde{b}_t^{P*}$. A greater ϕ exposes banks to higher credit risks and a larger external finance premium.

$$E_t \sum_{i=0}^{\infty} \tilde{\beta} \left(\frac{C_t^S}{C_{t+i}^S} \right) \Pi_{j,t+i} \tag{29}$$

$$\begin{aligned} \Pi_{j,t+1} = {} & r_{j,t}^B (b_{j,t}^P + S_t b_{j,t}^{P*}) + r_{j,t}^M \left(\tau_{j,t}^K + \tau_{j,t}^{ER} \right) k_{j,t}^S - r_{j,t}^S \left(\tilde{b}_{j,t}^P + S_t \tilde{b}_{j,t}^{P*} \right) - r_{j,t}^G b_{j,t}^G - r_{j,t}^K k_{j,t}^S \\ & - \left[-\Phi_1 \tau_{j,t}^{ER} + \frac{\Phi_2}{2} \left(\tau_{j,t}^{ER} \right)^2 \right] k_{j,t}^S - x_t \, k_{j,t}^S \end{aligned} \tag{30}$$

$$k_{j,t}^{S}+b_{j,t}^{G}+\tilde{b}_{j,t}^{P}+S_t\tilde{b}_{j,t}^{P*}=\tau_{j,t}^{K}k_{j,t}^{S}+\tau_{j,t}^{ER}k_{j,t}^{S}+b_{j,t}^{P}+S_t b_{j,t}^{P*} \tag{31}$$

$$\tilde{b}_{j,t}^{P}+S_t\tilde{b}_{j,t}^{P*}=\phi_j\left(b_{j,t}^{P}+S_t b_{j,t}^{P*}\right) \tag{32}$$

We assume all banks make the same decisions. Each bank maximizes its expected present value of profit flows (29) and (30) subject to deposit and loan demand functions. After substituting the bank's balance sheet into the profit function and imposing the symmetric conditions, we obtain equations (33), (34) and (35).

$$\tau_t^{ER}=\frac{\Phi_1+r_t^M-r_t^G}{\Phi_2} \tag{33}$$

$$r_t^B=\frac{\mu_B}{\mu_B-1}\left[\phi r_t^S+\left(1-\phi\right)r_t^G\right] \tag{34}$$

$$\left(1+\mu_K\right)r_t^K+\mu_K\left[x_t-\Phi_1\tau_t^{ER}+\frac{\Phi_2}{2}\left(\tau_t^{ER}\right)^2\right]=\mu_K\left[r_t^M\left(\tau_t^K+\tau_t^{ER}\right)+r_t^G\left(1-\tau_t^K-\tau_t^{ER}\right)\right] \tag{35}$$

Equation (33) indicates that the optimal excess reserve ratio is determined by the marginal benefits of holding excess reserves relative to its marginal cost as excess reserves are accumulated. An excess reserve ratio is positively related with an IOR and negatively related with a discount rate. By rearranging equation (33), we obtain that IOR is explicitly related to the discount rate, excess reserve ratio and the cost parameters. Equation (34) shows that the benefit of providing additional loans (borrowing rate) equals the cost paid to savers from purchasing additional mortgage-based securities plus the cost of additional borrowing from the government. When securitization is complete ($\phi=1$), banks generate mortgages and securitize all of them with a constant-return-to-scale technology. The interest rate charged to borrowers will equal the interest rate promised to savers, that it, $r_t^B = r_t^S$.

When securitization is perfectly incomplete ($\phi = 0$), the interest rate charged to borrowers will equal the interest rate of discount loans from the central bank, that is, $r_t^B = r_t^G$. Equation (35) indicates that the marginal costs and marginal benefits of taking deposits should be equalized. The former includes the deposit rate paid to savers and costs of holding excess reserve; while the latter consists of the interest rate earned from holding reserves and the interest saved from not borrowing from the central bank. During recessions, the interest rate spread between a loan rate and deposit rate widens because banks suffer higher operating costs of monitoring loans and tend to hold more reserves. Since savers can obtain interest either from deposits or mortgage-based securities, in the steady state the deposit rate should be equal to the interest rate earned from buying securities for no-arbitrage reasons.

2.5 Monetary and Fiscal Authority

Equation (36) represents the central bank’s balance sheet constraint. Its asset side includes the loans made to the commercial banks, and its liability side is comprised of issued currency and reserves that commercial banks deposited at the central bank. We assume that the central bank operates the interest rate responding to the lagged interest rate, output gap and aggregate inflation. A log-linear approximation of interest rate rule around zero inflation is expressed as equation (37). r_t is any interest rate in the model. ρ_R is the weight imposed on lagged policy rates. κ_π is the coefficient of inflation in the Taylor rule and κ_Y is the coefficient of the output gap in the Taylor rule. $u_{R,t}$ represents policy shocks.

$$b_t^G = m_t^B + m_t^S + \left(\tau_t^K + \tau_t^{ER}\right)k_t^S \tag{36}$$

$$\hat{r}_t = \rho_R \cdot \hat{r}_{t-1} + (1-\rho_R) \cdot \left[\kappa_\pi \left[\left(1-\alpha\right)\hat{\pi}_{C,t} + \alpha\hat{\pi}_{D,t}\right] + \kappa_Y \hat{y}_t\right] + u_{R,t} \tag{37}$$

In normal times, the federal funds rate r_t^F is bounded by the discount rate r_t^G and interest rate on reserves r_t^M. The discount rate serves as an upper bound since banks simply borrow from the Fed when the federal funds rate is above the rate. The IOR serves as a lower bound since banks would prefer holding the reserves to lending them out when the federal funds rate is below the rate. Within the band, the demand for reserves balances moves inversely with the market interest rates. With sufficient excess reserves (on the flat part of the demand curve), the marginal benefit of holding reserves declines to zero or very close to zero. The federal funds rate will be solely determined by the IOR and disconnected from the quantity of reserves.[4]

The relationship between a discount rate and IOR is expressed as equation (38). α_ρ measures the availability of reserves in the banking system and a greater α_ρ signals sufficiency of reserves.

[4] Keister, Martin, and McAndrews (2008) refer to this as a divorce of money (quantity of reserves) from the monetary policy (targeted federal funds rate).

$$r_t^F = \alpha_\rho r_t^M + \left(1-\alpha_\rho\right) r_t^G \tag{38}$$

$$r_t^F - r_t^M = \left(1-\alpha_\rho\right)\left(r_t^G - r_t^M\right) \tag{39}$$

After writing equation (38) as equation (39), the difference between the federal funds rate r_t^F and the interest rate on reserves r_t^M is referred to as the marginal liquidity services yield on reserves in Goodfriend (2002) and the scarcity value of reserves in Kashyap and Stein (2012). If the balances of excess reserves are paid with no interest, that is, $r_t^M = 0$, the federal funds rate is just a fraction of the discount rate given that r_t^F and r_t^G are nonnegative values.

The proceeds from the central bank's lending to the commercial banks, the seigniorage from issuing currency, and the tax revenue collected from households are used to finance the interest paid on required and excess reserve balances and non-productive real government purchases. The government's real budget constraint is expressed as equation (40) in which g_t represents real government purchases, b_{t-1}^G represents central bank lending to commercial banks in real terms, and k_{t-1}^S represents savers' deposits in real terms.

$$\frac{b_{t-1}^G}{\pi_t^C} r_{t-1}^G + m_t^B - \frac{m_{t-1}^B}{\pi_{C,t}} + m_t^S - \frac{m_{t-1}^S}{\pi_{C,t}} + T_t^B + T_t^S = r_{t-1}^M \left(\tau_t^K + \tau_t^{ER}\right) \frac{k_{t-1}^S}{\pi_t^C} + g_t \tag{40}$$

2.6 Households in the Foreign Country

Foreign households are assumed to have the same preferences as domestic households. An individual intermediate goods producer's production function in the foreign country is assumed to take the same form as that in the domestic country. Equation (41) defines the terms of trade condition. With complete exchange rate pass–through, the imported price of foreign goods equals the foreign currency price denominated in domestic currency, that is, $P_{F,t} = S_t P^*_{H,t}$. We assume that the consumer price inflation and domestic producer price inflation in the foreign country are the same, so that $P^*_{C,t} = P^*_{H,t}$.

$$\mathrm{O}_t = \frac{P_{F,t}}{P_{H,t}} = \frac{S_t P^*_{H,t}}{P_{H,t}} = \frac{S_t P^*_{C,t}}{P_{H,t}} \tag{41}$$

2.7 Equilibrium

Market clearing requires that production equals consumption. In equation (42), domestic production Y_t equals exports of domestically produced goods, domestic consumption of tradable goods and housing, government purchases and resource costs. Domestic exports are assumed to be proportionate to a foreign country's tradable goods consumption $Y^*_{C,t}$. Equations (43), (44) and (45) represent the equilibrium conditions in the labor market, in the lending market and in the money market, respectively. Equation (46) represents the equilibrium condition of world production.

$$\begin{aligned} Y_t &= (1-\alpha_C)\left[C^B_t + C^S_t\right] + D^B_t - (1-\delta)D^B_{t-1} + D^S_t - (1-\delta)D^S_{t-1} + \alpha_C \mathrm{O}_t Y^*_{C,t} + \\ &+ G_t + \left[\frac{\Phi_2}{2}\left(\tau^{ER}_t\right)^2 - \Phi_1 \tau^{ER}_t\right] k^S_t \end{aligned} \tag{42}$$

$$\sum_l N_{l,t} = N^B_{l,t} + N^S_{l,t}, \quad l = C, D \tag{43}$$

$$\left(b_t^P + S_t b_t^{P*}\right) = \left(\tilde{b}_t^P + S_t \tilde{b}_t^{P*}\right) \tag{44}$$

$$m_t^B + m_t^S = m_{t-1}^B + m_{t-1}^S \tag{45}$$

$$Y_t + Y_t^* = Y_t^W \tag{46}$$

The welfare is computed as the infinite discounted sum of per period consumption for borrowers and savers and is defined as equation (47).

$$C_t^A = \Sigma_{t=0}^{\infty} \left[\beta^t \left(\ln X_t^B \right) + \tilde{\beta}^t \left(\ln X_t^S \right) \right] \tag{47}$$

We evaluate our model with productivity shocks, money demand shocks, policy shocks, cost shocks to the financial sector and exchange rate shocks. Each shock follows an exogenous first order autoregressive process as in equations (48)-(53). Each innovation is assumed to be a serially uncorrelated process with a zero mean and a constant variance.

$$\ln Z_{C,t} = \rho_1 \ln Z_{C,t-1} + \varepsilon_{1,t} \tag{48}$$

$$\ln Z_{D,t} = \rho_2 \ln Z_{D,t-1} + \varepsilon_{2,t} \tag{49}$$

$$\ln \mu_t = \rho_3 \ln \mu_{t-1} + \varepsilon_{3,t} \tag{50}$$

$$\ln u_{R,t} = \rho_4 \ln u_{R,t-1} + \varepsilon_{4,t} \tag{51}$$

$$\ln x_t = \rho_5 \ln x_{t-1} + \varepsilon_{5,t} \tag{52}$$

$$\ln S_t = \rho_6 \ln S_{t-1} + \varepsilon_{6,t} \tag{53}$$

III. Calibration Results

The model is calibrated for the U.S. economy. The ratios of U.S. currency in circulation over M2 during 1980Q1-2008Q3 have been very stable on average, so the share of currency in money aggregate is set to be 0.10. The steady-state excess reserve ratio is set to be 0.40 based on the average ratios of excess reserves on the deposits by all commercial banks during 1984Q2-2008Q3.[5] The steady-state required reserve ratio is set to be 0.10. The fraction of mortgage-based securities sold to savers is set to be 0.7 in the benchmark case in accordance with Jiangli et al. (2007).

The discount rates in the United States were about 5.78% on average during 1980Q1- 2008Q3. Hence, we set the steady-state discount rate to be 5%. The steady-state interest rate paid on required and excess reserves is set to be 0.25%, in line with U.S. data from 2009Q1-2013Q2. The three-month certificate of deposit rates for the United States were 6.365% on average during 1980Q1-2008Q3, so the deposit rate is set to be 6%. The lending rate is set to be 8% since the bank prime loan rate was 8% on average during 1980Q1-2008Q3. The aforementioned interest rates pin down values of several parameters. First, the discount factors β and $\tilde{\beta}$ for the borrower and the saver are 0.9159 and 0.9433, respectively. Second, the cost parameters of holding excess reserves Φ_1 and Φ_2 are 0.5475 and 1.25, respectively. Third, the interest rate elasticities of demand for deposits and the interest rate elasticities of demand for loans are 3.0816 and 3.4783, respectively. Fourth, the

[5] Excess reserves have dramatically increased since 2008Q4. The ratio of excess reserves to deposits was 173 on average during 2008Q4-2015Q4.

steady-state value of the collateral constraint multiplier is set to be 0.1.

We follow Ireland (2014) by setting the elasticity of substitution between any two differentiated goods in the traded goods sector to be 6, implying that the steady-state price markup over marginal cost equals 20 percent. Housing is not traded and presumed to be less competitive. The elasticity of substitution between any two differentiated in the housing sector is set to be 4. The depreciation rate is set to be 0.025 per quarter. The fraction of the value of housing that cannot be used as collateral is 0.25. The share of housing in total consumption and the share of foreign goods in tradable goods consumption are both 0.20. The elasticity of substitution between tradable goods and housing and the elasticity of substitution between domestic goods and foreign goods are set to be 1. The elasticity of marginal utility with respect to real money balance is set to be 2, and the elasticity of marginal disutility with respect to labor supply is set to be 4. A larger value makes labor supply more responsive to real wages. The real wage is pinned down to be 0.9170. The labor hours for each agent in each sector are normalized to be 0.33. The degree of nominal rigidity is set equal to 0.75, implying that the expected time between price adjustments is one year. The steady-state ratio of government purchases is 0.2062, which contributes to roughly 16% of output. All the steady-state prices are set to be 1. We also assume that the steady state log-deviations of domestic producer price and foreign producer price are the same, so that $\hat{O}_t = \hat{S}_t$. The percent change from quarter one year ago in real personal consumption expenditure during 2008Q4-2016Q3 was about 0.016. To match the data, the persistence of financial cost is set to be 0.985. The estimated degree of exchange rate shock persistence is 0.9742, based on U.S. dollar-Euro foreign exchange rate data during 2008Q4-2016Q3. The other degrees of shock persistence are set according to Keating et al. (2014).

As specified in equation (39), the federal funds rate is a linear combination of IOR and the discount rate. By regressing U.S. data of federal funds rate, interest rate paid on required and excess reserves, and discount rates from 2008M10 to 2016M1 via ordinary least squares, we obtain that $\alpha_\rho = 0.93$. We regressed the U.S. effective federal funds rate on its lagged-one-period term, lagged-one-period inflation rates measured by the CPI, and lagged-one-period real GDP growth rates during 1980Q2-2008Q3. All the values are log-transformed. The results suggest that the weight imposed on the lagged policy rate, ρ_R, is 0.96, the coefficient of inflation in the Taylor rule, κ_π, is 1.40, and the coefficient of the output gap in the Taylor rule, κ_Y, is 0.02. Table 1 presents the baseline parameters and Table 2 summarizes the calibrated steady-state values.

We consider various interest rates as a policy rate in the Taylor rule and report the most salient results. Figures 1 and 2 show the dynamics of major variables in response to a 10 percent standard deviation interest rate shock when excess reserves are paid with and without interest, respectively. Tradable consumption co-moves with housing consumption for both savers and borrowers. Reduced policy rates stimulate excess reserve ratios and welfare in both regimes. Paying interest on reserves generates dynamics at a smaller scale.

Using the federal funds rate as a policy rate generates smaller responses in an IOR regime while using the lending rate generates smaller responses in a non-IOR regime. When reserves are paid with interest, the federal funds rate is bounded with the interest rate on reserves and discount rate according to equation (38). Using the federal funds rate as a policy instrument instantly narrows the spread and tampers other interest rates in responses to monetary expansionary shocks. The lending rate and security rate play an important role of facilitating borrowers' and savers' intertemporal allocation of consumption. When reserves are not paid with interest, the federal funds rate simply becomes a fraction of the discount rate. The lending rate, however, is bounded between the security rate and discount rate according to equation (34). Accordingly, using the lending rate as a policy instrument in the Taylor rule effectively moderates the impulse responses.

Figure 3 compares the dynamics of major variables responding to a 10 percent standard deviation interest rate shock using the federal funds rate as a policy rate in an

IOR scheme and a non-IOR scheme. In response to monetary expansion, a non-IOR policy produces a bigger spike in expected inflation than an IOR policy. Intuitively, paying no interest on reserves increases banks' opportunity costs of holding excess reserves. Banks economize on holding reserves and restrict banks' primary source of revenue to lending. Banks engage in aggressive lending and add inflation pressure. Higher expected inflation induces savers to decrease money holding, increase consumption and provide less funding to collateral-constrained households. Borrowers' tradable and housing consumption accordingly decrease. A non-IOR policy initially generates higher welfare than an IOR policy and declines afterwards against expansionary monetary policy shocks. This is because a non-IOR policy produces substantially high expected inflation and ignites savers' intertemporal consumption allocation. After about five quarters, an IOR scheme outperforms a non-IOR scheme in terms of consumption-based welfare.

The reason why the security rate and other interest rates respond oppositely against interest rate shocks lies in the degree of banks' converting illiquid loans to mortgage-based securities. When securitization is complete ($\phi = 1$), the borrowing rate and security rate will be the same. A greater degree of securitization boosts the demand of mortgage-based securities for savers and provides borrowers more funding.

Figure 4 shows the dynamics of major variables in response to a 10 percent standard deviation financial cost shock using the federal funds rate as a policy rate. The results show that increased financial costs instantly reduce the deposit rates along with other interest rates, allotting savers' resources from demand deposit to consumption. When banks encounter rising costs and limited funding availability, they seek funding from the central bank. Since the discount rate is below its steady-state value, banks have an incentive to borrow from the central bank. Compared to a non-IOR scheme, an IOR scheme more effectively subdues the reduction in funding availability and the dynamics of borrowers' consumption. The welfare against financial cost shocks is lowered more in a non-IOR regime than in an IOR regime.

IV. Conclusions

The advantages of using the interest rate on reserves as a policy tool has been acknowledged in several studies (Goodfriend, 2002; Keister et al., 2008; Kashyap and Stein, 2012; Stein, 2012; Williamson, 2015). It reduces banks' opportunity cost of holding reserves, the so-called reserve tax. It is used as a supplement to enforce the targeted federal funds rate, which has declined since July 2008 and stayed near zero during 2008-2015. It helps increase broad liquidity[6] in the economic downturn. An IOR scheme also provides the central bank the policy flexibility of addressing macroeconomic stability via an interest rate rule while stabilizing financial markets through bank reserves.

This research explicitly derives the relationship between IOR and other interest rates, and it analyzes the impact of expansionary monetary policy shocks and financial cost shocks in an IOR scheme and in a non-IOR scheme. In responses to expansionary monetary policy shocks and financial cost shocks, paying IOR moderates the negative impact of deficient liquidity on collateral-constrained households' consumption. A non-IOR scheme generates higher expected inflation and ignites savers' intertemporal consumption allocation. Paying interest on reserves generally stabilizes economic fluctuations and promotes welfare.

Our research has two limitations. First, the federal funds rate in our model is bounded between a discount rate and an interest rate paid on reserves. With sufficient excess reserves, the federal funds rate could possibly be pinned down by the interest rate on reserves. Bech and Klee (2011) document that government-sponsored enterprises (GSEs) do not receive interest on their reserves deposited at the Fed and are more likely to sell funds at rates below the IOR. With a growing share of GSEs in

[6] Goodfriend (2002) defines broad liquidity as a service that households or firms can obtain cash through collateralization of assets.

the federal funds market, a mismatch of the targeted federal funds rate and IOR consequently occurs. Future research can be extended to include an interbank lending market and discuss the liquidity issue via the effective federal funds rate.

Second, our model incorporates the reserves that banks voluntarily borrow from the central bank but neglects any reserves injected from the central bank through asset purchase programs. Several studies empirically document that drastically increased reserves by the Fed's quantitative easing policies create a banking system's total liquidity. A banking system with more excess reserve accumulation can potentially expand lending quickly depending on the quality of lending opportunities (Ennis and Wolman, 2015), stimulate banks' risk-taking activities (Kandrac and Schlusche, 2017), and lower banks' lending standards (Kurtzman et al. 2017). The effect of paying IOR on banks' lending behavior under a central bank's large scale asset purchases is another direction for future research.

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Table 1 Baseline Parameters

Baseline Parameters	Values	Description
$\tilde{\beta}$	0.9433	Discount factor for savers
β	0.9159	Discount factor for borrowers
δ	0.025	Depreciation rate of housing (quarterly)
χ	0.25	Fraction of the value of housing that cannot be used as collateral
α	0.2	The share of housing in total consumption
α_c	0.2	The share of foreign goods in tradable goods consumption
α_ρ	0.93	The measure of availability of reserves in the banking system
η	1	The elasticity of substitution between tradable goods and housing
ε	1	The elasticity of substitution between domestic goods and foreign goods
ι	2	The elasticity of marginal utility with respect to real money balance
ς	4	The elasticity of marginal disutility with respect to labor supply
θ_C	6	The elasticity of substitution between any two differentiated goods in the tradeable goods sector
θ_D	4	The elasticity of substitution between any two differentiated goods in the housing sector
ν	0.10	The steady-state share of currency in money aggregate
ω	0.5	The elasticity of substitution between currency and deposit
μ_K	3.0816	The interest rate elasticities of demand for deposits
μ_B	3.4783	The interest rate elasticities of demand for loans
ψ	0.75	The degree of nominal rigidity
ϕ	0.70	The fraction of mortgage-based securities sold to savers
Φ_1	0.5475	Cost function parameter
Φ_2	1.25	Cost function parameter
ρ_1	0.9853	The persistence of the technology shock in the traded goods sector
ρ_2	0.9853	The persistence of the technology shock in the housing sector
ρ_3	0.9579	The persistence of the preference shock
ρ_4	0.9853	The persistence of the interest rate shock
ρ_5	0.985	The persistence of the financial cost shock
ρ_6	0.9742	The persistence of the exchange rate shock
ρ_R	0.96	The weight imposed on the lagged policy rate
κ_π	1.40	Coefficient of inflation in the Taylor rule
κ_Y	0.02	Coefficient of the output gap in the Taylor rule

Table 2 Calibrated Steady-State Values

Baseline Parameters	Steady-State Values	Description
$\bar{\gamma}$	0.01	The multiplier on collateral constraint
$\bar{N}^B = \bar{N}^S$	0.66	Steady-state level of hours worked for each agent
$\bar{\pi}_C = \bar{\pi}_C^*$	1	Inflation rate of tradable goods
$\bar{Q}$	1	Relative price of housing
$\bar{O}$	1	Terms of trade
$\bar{S}$	1	Exchange rate
$\bar{r}^B = \bar{r}^{B*}$	0.08	Borrowing rate or lending rate
$\bar{r}^S = \bar{r}^{S*}$	0.06	Rate of return on securities
$\bar{r}^K$	0.06	Deposit rate
$\bar{r}^G$	0.05	Discount rate
$\bar{r}^M$	0.0025	Interest rate paid on reserves (IOR)
$\bar{C}^B$	0.5050	Tradable goods consumption for borrowers
$\bar{C}^S$	0.5050	Tradable goods consumption for savers
$\bar{D}^B$	1.2662	Housing consumption for borrowers
$\bar{D}^S$	1.5707	Housing consumption for savers
$\bar{w}$	0.9170	Real wage
$\bar{m}^B$	2.7396	Real money balance for borrowers
$\bar{k}^S/\bar{m}^S$	0.244948	Deposit relative to cash holding for savers
$\bar{k}^S/\bar{m}^A$	0.8124	Deposit relative to aggregate money balance for savers
$\bar{b}^G/\bar{m}^S$	0.1224	Government discount loan relative to cash holding for savers
$\frac{\bar{b}^P + \bar{b}^{P*}}{\bar{m}^S}$	0.8160	Domestic borrowing and foreign borrowing relative to cash holding for savers
$\bar{G}/\bar{P}_C$	0.2062	Real government purchase
$\bar{Y} = \bar{Y}^*$	1.32	Total production
$\bar{Y}^C$	0.66	Production in the tradable goods sector
$\bar{Y}^D$	0.8052	Production in the housing sector
$\bar{x}$	0.12	Steady-state value of a bank's operation costs
$\bar{Z}^C$	1	Steady-state value of a productivity shock in the tradable goods sector
$\bar{Z}^D$	1.22	Steady-state value of a productivity shock in the housing sector
τ^K	0.10	The fraction of deposits that are kept as required reserves
τ^{ER}	0.40	The fraction of deposits that are kept as excess reserves

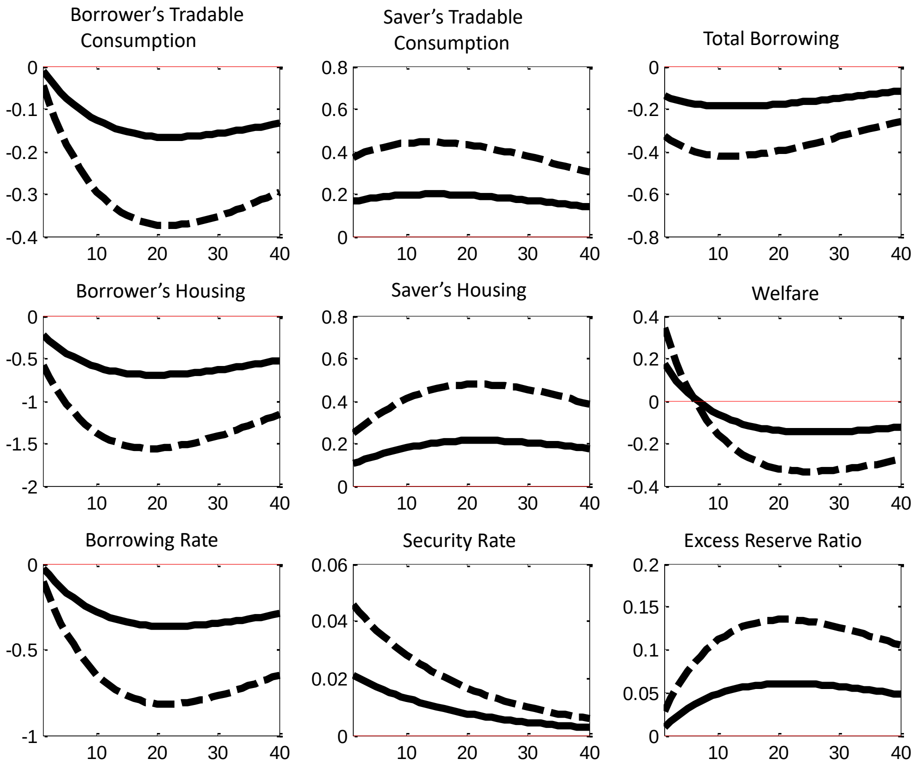

Figure 1 Impulse responses to a 10-percent-standard-deviation interest rate shock (monetary expansion) in an IOR regime Solid line represents using the federal funds rate as a policy rate. Dashed line represents using the lending rate as a policy rate.

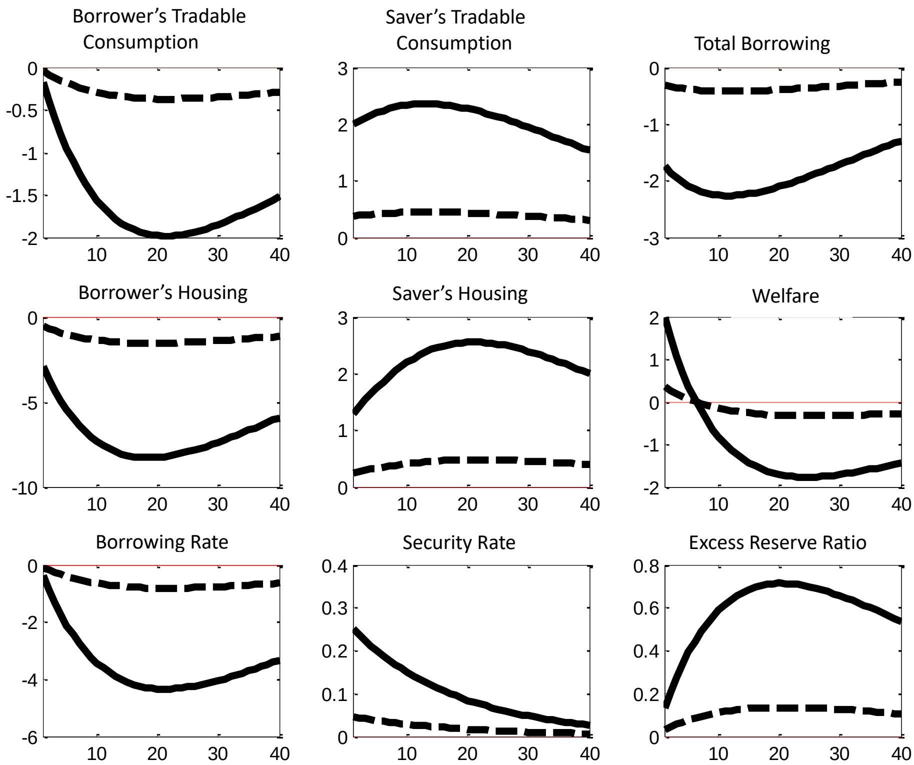

Figure 2 Impulse responses to a 10-percent-standard-deviation interest rate shock (monetary expansion) in a non-IOR regime Solid line represents using the federal funds rate as a policy rate. Dashed line represents using the lending rate as a policy rate.

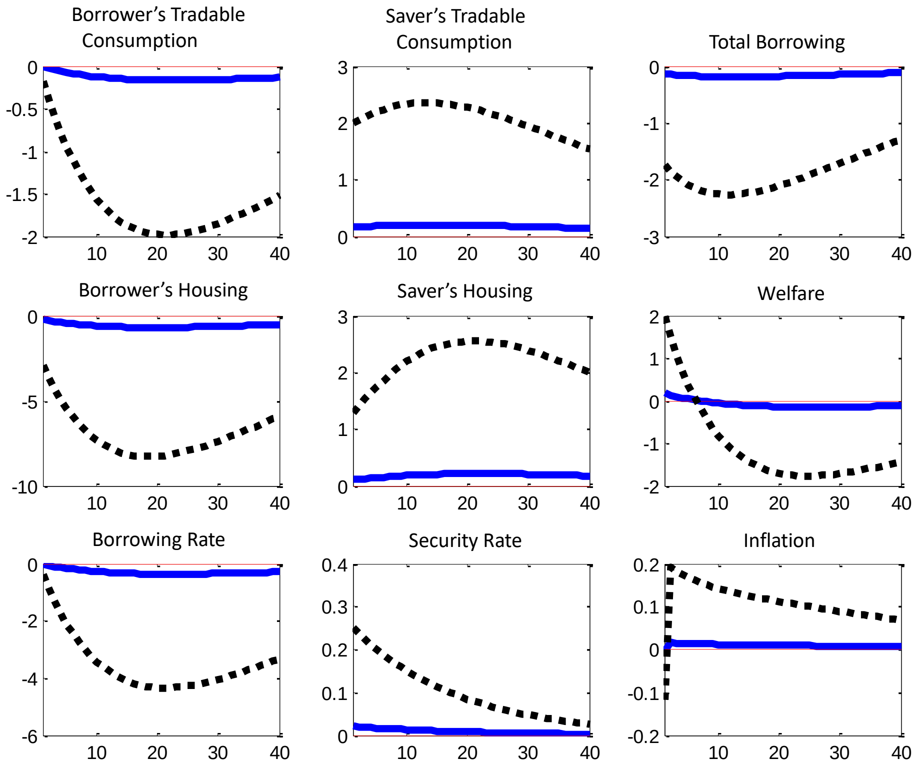

Figure 3 Impulse responses to a 10-percent-standard-deviation interest rate shock Solid line represents interest is paid on reserves. Dotted line represents interest is not paid on reserves. The federal funds rate is used as a policy rate.

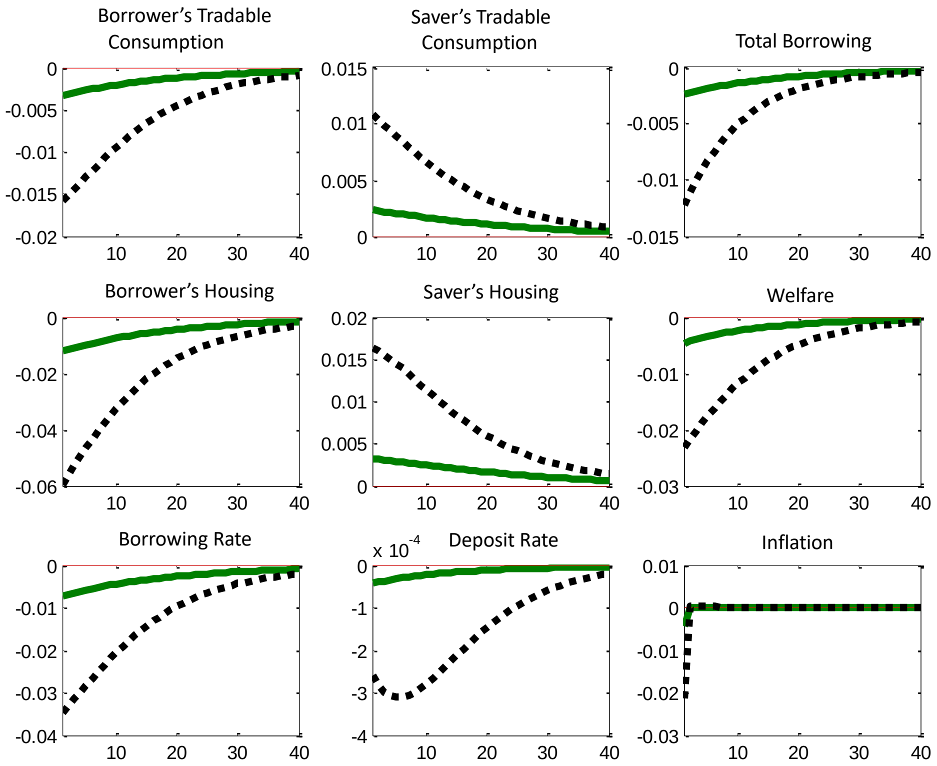

Figure 4 Impulse responses to a 10-percent-standard-deviation financial cost shock

Solid line represents interest is paid on reserves. Dotted line represents interest is not paid on reserves. The federal funds rate is used as a policy rate.