Interest on Reserves, Business Cycles and the Zero Lower Bound*

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Abstract

We argue that state-contingent interest on reserves (IOR) policies significantly increase welfare, alter the monetary policy transmission mechanism and insure against a liquidity trap. These findings are explained by an endogenous association amongst IOR, the deposit rate, the inflationary output gap and credit spreads. Such link operates via a working-capital cost channel, and affords the central bank an additional degree of freedom in stabilizing the economy. This is particularly beneficial when the refinance rate strikes the zero lower bound. Our policy prescriptions echo the Fed's actions in 2008, and the ECB's decision to pay negative rates on reserves since 2015.

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1 Introduction

Since October 2008 and following the enactment of the Emergency Economic Stabilization Act (2008) in the United States (U.S.), the U.S. Federal Reserve (Fed) has been paying interest on balances in both required and excess reserves. At that time, deep turmoil in global finance gave rise to unprecedented injections of liquidity into the credit markets, as well as to the implementation of other unconventional policy tools, such as quantitative easing, forward guidance and, importantly for our purposes, the payment of interest on reserves. By varying the rate on reserves during (and after) the peak of the financial crisis, the Fed's aims have been to offset the implicit tax that required reserves impose on the banking system, to maintain the federal funds rate close to its target, and to address the deteriorating conditions in the financial markets. With the introduction of interest on reserves, the Fed has essentially instituted a corridor system in which the main policy rate is ideally traded between the rate charged on borrowed balances and the rate paid on reserves held at the central bank (similar to the European Central Bank system). In this way, interest on reserves is set as a positive lower bound for the policy rate, potentially allowing the central bank to keep the latter under control (see Goodfriend (2002, 2011) and Bech and Klee (2011)). More recently, since 2015, and in the aftermath of the Great Recession, the European Central Bank (ECB) and the Bank of Japan (BoJ) have started paying zero interest rate on required reserves and a negative rate on any excess reserves, thereby effectively taxing banks for exceeding the mandatory reserve requirements. These drastic moves were made in light of the persistent deflationary pressures experienced in these regions, and following the exhaustion of the standard refinance rate policy tool, which had already been hovering around the zero lower bound (ZLB).

These events imply no clear view on how and when central banks should set interest on reserves, nor how this tool interacts with more conventional monetary policy instruments during normal times and in periods of liquidity traps. Motivated by these observations and the implementation of the interest on reserves facility by central banks in advanced economies, this paper attempts to answer the following questions: i) what are the macroeconomic and welfare implications of an interest on reserves policy rule in a model with endogenous credit spreads?; ii) how should interest on reserves *optimally* adjust during business and financial cycles, and in response to various shocks?; iii) how does the interest on reserves alter the transmission mechanism of standard monetary policy rules in normal times, and what are the consequences of this less-conventional tool when the ZLB on the policy rate becomes binding?

To answer these questions, we build a Dynamic Stochastic General Equilibrium (DSGE) model with nominal price rigidities and a credit cost channel, where firms have to borrow in advance to finance their working-capital needs, as in Ravenna and Walsh (2006).[1] Compared to their model, the loan rate at which firms borrow from the lending bank not only depends on the interbank policy rate set by the central bank, but also on an endogenous risk premium charged by the lender due to the possibility of firm default. We prove that default risk, the risk premium and consequently the lending rate are *positively* related to the inflationary marginal production costs proxied by the output gap, which, in turn, is *negatively* linked to the deposit rate due to an intertemporal substitution effect. The deposit rate is set as a weighted average of the policy rate and the interest on reserves, with the relative weight on the latter equal to the constant required reserves ratio set by the central bank.[2] Put differently, *endogenous* credit spreads, that depend directly on the output gap, provide an additional policy lever through which the central bank can influence real economic activity by fluctuating the rate on reserves. This additional risk premium channel is particularly important when the nominal policy rate strikes the ZLB and becomes largely impotent.

We identify various transmission channels through which an interest on reserves policy rule, that reacts to a reliable financial stability indicator (measured in terms of variations in credit or the credit to GDP ratio), can influence the real economy, as well as modify the optimal refinance rate setting behaviour. We first show that a rise in interest paid on reserves acts as a subsidy to the banking system, thereby raising the deposit rate. A higher deposit rate alters the intertemporal consumption-savings decision of the household, and a-priori triggers a fall in the output gap and in price inflation. Second, we demonstrate that the decline in the output gap exerts downward pressure on the cost of borrowing, which, in turn, offsets to a degree stagnating lending conditions during economic downturns, while bringing about a further reduction in the price level via the credit cost channel. The effect of *higher* interest on reserves on inflation is therefore *negative*, whereas the impact of this policy on lending and output is *ambiguous* and depends on the source of the shock

[1] On the importance of the working-capital (credit cost) channel in explaining business cycle fluctuations, and the 'missing deflation' phenomenon observed during the Great Recession, see Christiano, Eichenbaum and Trabandt (2015).

[2] Throughout the text, we interchangeably use the refinance rate and the interbank rate to describe the standard monetary policy rate set by the central bank. This policy rate may potentially *differ* from the rate paid on reserves. In the United Kingdom, for example, where banks are *not* subject to regulatory reserve requirements, the interest on reserves is defined as the standard monetary policy rate. Our model is therefore more applicable to economies where reserve requirements are mandatory such as in the United States, the Eurozone, Japan and Switzerland.

distorting the economy.

Specifically, following negative financial shocks that drive output and inflation in *opposite* directions, as was also observed at the start of the financial crisis (see Gilchrist, Schoenle, Sim and Zakrajsek (2016)), *raising* interest on reserves mitigates the rise in the cost of borrowing, curbs inflationary pressures and attenuates output volatility through the credit cost channel. Under these conditions, we also find that a *more hawkish* response to price fluctuations in the Taylor (1993) monetary policy rule contributes further to macroeconomic and financial stability, but at the cost of stronger dis-inflation. This state-contingent, welfare enhancing policy mix is therefore consistent with the aforementioned actions pursued by the Fed in October 2008, when borrowing costs skyrocketed and the financial markets froze. In contrast, following adverse demand shocks that push prices and output in the *same* direction, an increase in interest on reserves only acts to amplify price dis-inflation, driving the policy rate further down towards the ZLB, and placing upward pressure on the real deposit rate. Under this scenario, we find that *lowering* interest on reserves can be a very powerful force in enhancing welfare. In this vein, the recent cuts in interest on reserves undertaken by the ECB and BoJ in 2015-2016 are endorsed by the model, especially in situations when the economy is subject to shocks that produce deflationary pressures associated with a crippling recession.[3]

Indeed, following a sizeable adverse demand disturbance that constrains the nominal policy rate to the ZLB, we find that an interest on reserves policy rule largely insures against a liquidity trap, brings the policy rate back to its equilibrium level at a quicker pace, and overall promotes economic and price stability. We argue that the risk premium channel, endogenously driven by the output gap, renders the central bank an extra degree of freedom to use interest on reserves in order to stabilize the economy, as well as to largely prevent it from descending into a liquidity trap. This channel is a key determinant in our model, and one which we believe is a novel feature that highlights and imparts an alternative justification for the recent policy practices conducted by central banks. To the best of our knowledge, the welfare and business cycle implications of an optimal interest on reserves policy *rule*, and its interaction with standard monetary policy rules during normal *and* abnormal times, have not been fully addressed in the literature; especially regarding the impact of this tool on the *endogenous* banking sector's multiple interest rates decisions within a New

[3] Indeed, Conti, Neri and Nobili (2016) find that adverse aggregate demand shocks have been the most important contributors to the dis-inflation and the lower real GDP growth experienced in the Eurozone since 2014.

Keynesian setup.[4]

Our paper is related to several strands of literature. First, there is a literature examining the use of interest on reserves as an independent policy instrument that can free standard monetary policy from financial stability concerns. Goodfriend (2002, 2011), Cúrdia and Woodford (2011), Ireland (2012) and Kashyap and Stein (2012) show that the ability to manipulate the spread between the policy rate and the interest on reserves provides the central bank an additional degree of freedom to pursue its policymaking objectives; namely macro and financial stability. Our contribution to this strand of literature is linking interest on reserves policy rules directly to economic welfare, rather than relating such non-conventional policies to the central bank's balance sheet position (Cúrdia and Woodford (2011) and Cochrane (2014)), or to the regulation of lending externalities (Kashyap and Stein (2012)). Put differently, we argue that a state-contingent interest on reserves policy can go beyond its' remit of financial stability and more significantly foster macroeconomic and price stability through both the standard demand channel of monetary policy and the risk premium channel described above.[5] This upshot comes in contrast to Ireland (2014), for example, who finds that interest on reserves has only a modest impact on inflation and GDP in normal times. Our paper therefore is more in line with Hall (2002) and with the recent contribution by Hall and Reis (2016), who demonstrate that interest on reserves can be used to control the price level as a mechanism to implement monetary policy. However, instead of indexing interest on reserves to the market interest rate, the price level and the target price level, we study optimal policy rules that minimize welfare losses. Overall, our results point out to interesting and non-trivial policy interactions between interest on reserves and standard monetary policy when the credit cost channel matters.

Second, our paper also relates to the theoretical literature examining macroeconomic policies at the ZLB. Christiano, Eichenbaum and Rebelo (2011) and Eggertsson (2011) show that increased government spending yields a high fiscal multiplier and thus become extremely efficient in releasing the economy from a liquidity trap. Carrillo and Poilly (2013) reinforce this point by proving that credit market frictions considerably magnify the government-spending multiplier during a spell in

[4] Goodfriend and McCallum (2007) and Cúrdia and Woodford (2011, 2016), for example, posit a reduced-form intermediation technology to justify the existence of credit spreads.

[5] We abstract from excess reserves for the purpose of our paper. See Güntner (2015) and Dressler and Kersting (2015), who examine the impact of excess reserves and liquidity injections on the economic activity. These papers also briefly touch upon the consequences of interest on reserves, but do not study the welfare implications of this tool at the ZLB nor its optimal interaction with standard monetary policy rules.

a liquidity trap. As for unconventional monetary policy at the ZLB, Cúrdia and Woodford (2011) and Gertler and Karadi (2011) find a role for direct central bank liquidity injections, particularly in situations when the financial markets are sufficiently impaired.[6] Compared to these models that focus on the impact of fiscal policy and unconventional central bank credit policies in a liquidity trap, we show that adding another dimension to monetary policy in the form of a fairly simple interest on reserves rule, can achieve superior welfare gains, as well as minimize the duration and probability of the policy rate hitting the ZLB. Altogether, we argue for routinely adjusting the rate on reserves based on the nature of the business cycle, both in normal times and when the economy is mired in a deep recession.[7]

The remainder of the paper proceeds as follows. Section 2 describes the model and its equilibrium properties. Section 3 details the main transmission mechanisms linking interest on reserves to standard monetary policy and to the cost of borrowing in an analytically tractable way. In Section 4 we explain the parameterization of the model and its fit with the U.S. data. Section 5 examines simple and implementable optimal policy rules that minimize a micro-founded welfare loss function following financial and demand shocks that do not drag the policy rate to the ZLB. In Section 6 we study the effects of interest on reserves policy in response to a sizeable negative demand shock that pushes the economy into a liquidity trap. Section 7 concludes.

2 The Model

Our framework builds on a New Keynesian model with a credit cost channel, à la Ravenna and Walsh (2006), enriched by financial frictions in the form of a banking sector subject to reserve requirements, and endogenous credit spreads. Two additional features are added. First, the zero lower bound (ZLB) constraint is imposed on the nominal interest rate to study the effects of a liquidity trap. Second, interest on reserves (IOR) policy is examined alongside standard monetary policy rules, both outside of and at the ZLB. The model economy consists of households, a final good

[6] Gertler and Karadi (2011) also find that unconventional monetary policy in the form of a direct intermediation of credit by the central bank may produce significant benefits *even if* the zero lower bound constraint on the nominal interest rate is *not* binding.

[7] Canzoneri, Cumby and Diba (2016) also find a role for fluctuating interest on reserves (or the tax on reserves) in response to various shocks, as well as imposing a tax on reserves in steady state. Contributing to their paper, we examine the implications of a *simple implementable rule* governing the rate on reserves *also* in a *liquidity trap environment*, and derive an *endogenous* risk premium that highlights the welfare benefits of this tool in *both* normal and abnormal times.

(FG) firm, a continuum of intermediate good (IG) firms, a competitive banking sector comprised of a deposit bank and a lending bank, and a central bank. At the beginning of the period and following the realization of aggregate shocks, the deposit bank receives deposits from households, and lends part of these deposits to the lending bank, with the other fraction kept at the central bank as reserve requirements. Required reserves, in turn, are remunerated at the IOR rate, which acts as a stabilization policy instrument in this model chosen optimally by the central bank. The lending bank uses the deposits provided by the deposit bank as well as a cash injection from the central bank in order to supply working-capital loans to IG firms, and sets the loan rate as an endogenous risk premium over the interbank policy rate. For the given loan rate, monopolistic IG firms decide on the level of employment, prices and the demand for loans. Using a standard Dixit-Stiglitz (1977) technology, the FG firm combines all intermediate goods to produce a homogeneous final good used only for consumption purposes. We now turn to a more detailed exposition of the economic environment and equilibrium properties.

2.1 The Real Economy

Households have identical preferences over consumption (C_t) and labour (H_t). The objective of the representative household is to maximize,

$$U_t = \mathbb{E}_t \sum_{t=0}^{\infty} \beta^t \left\{ \frac{\vartheta_t C_t^{1-\varsigma}}{1-\varsigma} - \frac{H_t^{1+\gamma}}{1+\gamma} \right\}, \tag{1}$$

where $\mathbb{E}_t$ is the expectations operator, $\beta \in (0,1)$ is the discount factor, ς is the inverse of the intertemporal elasticity of substitution in consumption, and γ is the inverse of the Frisch elasticity of labour supply. A preference shock (ϑ_t) is added to capture exogenous changes in household's demand for consumption. This demand disturbance follows an $AR(1)$ process,

$$\log(\vartheta_t) = (1-\rho_\vartheta)\log(\vartheta) + \rho_\vartheta \log(\vartheta_{t-1}) + s.d(\alpha^\vartheta) \cdot \alpha_t^\vartheta, \tag{2}$$

where ϑ is the steady state value of the taste shock, ρ_ϑ is the degree of persistence, and α_t^ϑ is a random shock distributed as standard normal with a constant standard deviation given by $s.d(\alpha^\vartheta)$.[8]

Households enter period t with real cash holdings of M_t. They receive their wage bill $W_t H_t$

[8] Steady state values are denoted by dropping the time subscript.

paid as cash at the start of the period, with W_t denoting real wages. This cash is then used to make deposits D_t at the deposit bank. The households remaining cash balances of $M_t + W_t H_t - D_t$ become available to purchase consumption goods (C_t), subject to a cash-in-advance constraint, $C_t \leq M_t + W_t H_t - D_t$. At the end of the period, households receive all real profit income from financial intermediation (J_t^{FI}), and the IG firms ($\int_0^1 J_{j,t}^{IG} dj$).[9] Furthermore, households earn the gross interest payments on their deposits ($R_t^D D_t$). The real value of cash carried over to period $t+1$ is,

$$M_{t+1} \frac{P_{t+1}}{P_t} = M_t + W_t H_t - D_t - C_t + R_t^D D_t + J_t^{FI} + \int_0^1 J_{j,t}^{IG} dj. \tag{3}$$

With a positive deposit rate, $R_t^D > 1$, and taking real wages (W_t) and prices (P_t) as given, the first order conditions of the household's problem with respect to C_t, D_t and H_t can be summarized as,

$$\vartheta_t C_t^{-\varsigma} = \beta \mathbb{E}_t \left(R_t^D \frac{P_t}{P_{t+1}} \vartheta_{t+1} C_{t+1}^{-\varsigma} \right), \tag{4}$$

$$\frac{H_t^{\gamma}}{\vartheta_t C_t^{-\varsigma}} = W_t. \tag{5}$$

Equation (4) represents the Euler equation with respect to deposits, while (5) defines the optimal labour supply.

Each IG firm $j \in (0,1)$ faces the following linear production function,

$$Y_{j,t} = Z_{j,t} H_{j,t}, \qquad Z_{j,t} \equiv \varepsilon_{j,t} A_t, \tag{6}$$

where $H_{j,t}$ is employment by firm j in period t, and A_t is a mean one aggregate productivity factor following a standard $AR(1)$ process. The term $\varepsilon_{j,t}$ represents an idiosyncratic shock with a constant variance distributed uniformly over the interval $(\underline{\varepsilon}, \bar{\varepsilon})$.[10] The IG firm must borrow from a representative lending bank in order to pay households wages in advance. Let $L_{j,t}$ be the amount borrowed by firm j, then the (real) financing constraint is equal to,

$$L_{j,t} = W_t H_t. \tag{7}$$

[9] Households also receive profits from the final good firm, but these profits are equal to zero in equilibrium.

[10] We use the uniform distribution in order to generate plausible data-consistent steady state credit spreads as explained in the parameterization section. This simple distribution also enables a closed-form expression for credit risk. See also Faia and Monacelli (2007) who adopt a similar approach.

Financing labour costs bears risk and in case of default the lender expects to seize a fraction χ_t of the firm's output $(Y_{j,t})$. The term χ_t follows the $AR(1)$ shock process,

$$\log(\chi_t) = \left(1-\rho_\chi\right)\log(\chi) + \rho_\chi \log\left(\chi_{t-1}\right) + s.d\left(\alpha^\chi\right)\cdot\alpha_t^\chi, \tag{8}$$

where $\chi \in (0,1)$ is the steady state value of this fraction, ρ_χ is the degree of persistence, and α_t^χ is a random shock with a normal distribution and a constant standard deviation denoted by $s.d\left(\alpha^\chi\right)$. A shock to effective collateral (χ_t) represents a financial (credit) shock in this model, as it directly impacts credit risk at the firm level as well as bank credit spreads, as shown below.[11] In the good states of nature, each firm pays back the lending bank principal plus interest on loans. Consequently, and in line with the willingness to pay approach to debt contracts, default occurs when the expected value of seizable output $(\chi_t Y_{j,t})$, net of state verification and enforcement costs, is less then the amount that needs to be repaid to the lender at the end of the period, i.e., $\chi_t Y_{j,t} < R_t^L L_{j,t}$, where R_t^L denotes the gross lending rate. Using (6) and (7), the threshold value $(\varepsilon_{j,t}^M)$ below which the IG firm defaults is,

$$\varepsilon_{j,t}^M = \frac{R_t^L W_t}{\chi_t A_t}. \tag{9}$$

Therefore, the cut-off point is related to aggregate credit and supply shocks, the funding costs and real wages, and is *identical* across all firms (as in Agénor and Aizenman (1998)).[12] Given the uniform properties of ε_t, the closed-form expression for the probability of default is,

$$\Phi_t = \int_{\underline{\varepsilon}}^{\varepsilon_t^M} f(\varepsilon_t)d\varepsilon_t = \frac{\varepsilon_t^M - \underline{\varepsilon}}{\bar{\varepsilon} - \underline{\varepsilon}}. \tag{10}$$

Finally, the pricing decision during period t takes place in two stages. In the first stage, each IG producer minimizes the cost of employing labour, taking its effective costs $(R_t^L W_t)$ as given. This

[11] Tayler and Zilberman (2016a, 2016b) also introduce a similar type of financial/collateral/risk shock that directly hits borrowing costs.

[12] As we solve explicitly for the risk of default using a threshold condition, the collateral constraint in this model, from which we derive the cut-off point, is always binding.

minimization problem yields the real marginal cost,[13]

$$mc_t = \frac{R_t^L W_t}{Z_{j,t}}. \tag{11}$$

In the second stage, each IG producer chooses the optimal price for its good. Here Calvo (1983)-type contracts are assumed, where a portion of ω firms keep their prices fixed while a portion of $1-\omega$ firms adjust prices optimally given the going marginal cost and the loan rate. Solving the standard IG firm's problem yields the familiar form of the log-linear New Keynesian Phillips Curve (NKPC): $\widehat{\pi}_t = \beta \mathbb{E}_t \widehat{\pi}_{t+1} + k_p \widehat{mc}_t$, with $k_p \equiv (1-\omega)(1-\omega\beta)/\omega$.[14]

Importantly, note that the elements of the marginal cost directly impact $\varepsilon_{j,t}^M$ and consequently also the probability of default, the risk premium and the loan rate, as detailed below. Therefore, the output gap (a proxy for the marginal cost) will largely determine credit spreads, and provide an additional channel through which the central bank can influence borrowing costs and the economic activity. To fix ideas, we will refer to this mechanism as the *risk premium channel* that operates through the wider *credit cost channel* linking the lending rate (or credit spreads) to the output gap, output and inflation.[15]

2.2 Financial Intermediation

The banking sector consists of a representative commercial bank with two branch banks: a deposit bank and a lending bank.[16]

2.2.1 The Deposit Bank

The representative deposit bank receives deposits from all households, which are remunerated at R_t^D. It then keeps a fraction μ_t of its total deposits at the central bank in the form of required

[13] Below we show that the bank sets the loan rate based on the IG firm's default decision and threshold default value. Therefore, the risk of default has also a direct effect on the IG firms marginal cost through its endogenous impact on the cost of borrowing. In other words, firms internalize the possibility of default in their optimal pricing behaviour once they borrow at the going lending rate.

[14] Log-linear variables are denoted by '^'.

[15] While Agénor, Bratsiotis and Pfajfar (2014) also derive an endogenous risk premium in a credit cost channel model (albeit with sticky wages), these authors do not show how this premium may relate to the inflationary output gap. This direct channel linking the output gap to credit spreads is unique to our model, and is important in order to illustrate the impact of IOR on the real economy.

[16] The distinction between the deposit bank and the lending bank is similar to Glocker and Towbin (2012). However, our model differs significantly from theirs in terms of the setup, focus (interest on reserves versus required reserves), optimal banking behaviour and welfare implications (away from and at the ZLB).

reserves, for which it receives a gross rate of R_t^{μ}, and makes the rest of its deposits, $(1-\mu_t)D_t$, available to the lending bank at the gross interbank (policy) rate denoted by R_t^{CB}. The interbank rate and the interest rate facility on required reserves (IOR) are set by the central bank and are considered as stabilization policy instruments in this model. In each period, the deposit bank breaks-even such that,[17]

$$\mu_t R_t^{\mu} D_t + (1-\mu_t) R_t^{CB} D_t = R_t^D D_t,$$

with $\mu_t R_t^{\mu} D_t + (1-\mu_t) R_t^{CB} D_t$ and $R_t^D D_t$ denoting the total income and total costs experienced by the deposit bank, respectively. The above zero profit condition results in the following equilibrium deposit rate,

$$R_t^D = R_t^{CB} - \mu_t \left(R_t^{CB} - R_t^{\mu} \right), \tag{12}$$

where the policy-reserves rate spread is $R_t^{CB} - R_t^{\mu} \geq 0$.

Without required reserves ($\mu_t = 0$), the deposit rate equals to the refinance rate, $R_t^D = R_t^{CB}$ (see 12). However, in a fractional-reserve banking system ($\mu_t > 0$), the deposit rate is affected by the opportunity cost of holding reserves, represented by the spread $R_t^{CB} - R_t^{\mu} \geq 0$. Put differently, the deposit rate is set as a negative mark-up of the refinance rate due to the implicit costs of holding reserves, weighted by the spread between the refinance rate and the interest on reserves. Paying IOR therefore acts as a banking sector subsidy (enabling the deposit bank to pay a higher rate on deposits), whereas required reserves impose a tax on the banking system so long as $R_t^{CB} - R_t^{\mu} > 0$.[18]

2.2.2 The Lending Bank

The representative lending bank raises $(1-\mu_t)D_t$ funds via the deposit bank at the interbank gross rate (R_t^{CB}) and also receives liquidity (X_t) from the central bank, which is also remunerated at the

[17] Unlike Glocker and Towbin (2012) and Primus (2017), we ignore any ad-hoc convex costs / benefits in holding required and excess reserves. Put differently, excess reserves is *not* a choice variable for the deposit bank in this model whereas required reserves must be satisfied in accordance with regulation. We find that explicitly modeling excess reserves and such adjustment costs play only a negligible role in explaining business cycle dynamics in the context of our setup. However, the reserves ratio (μ_t) may alternatively be treated as the *total* fraction of reserves held at the central bank: required plus *voluntary* excess (without an obvious normative justification for the latter). Either way, a positive reserves to deposits ratio ($\mu_t > 0$), whether required or voluntary, provides an additional policy lever through which the central bank can stabilize the economy using IOR. Studying the distinction between interest paid on required and excess reserves is beyond the scope of this paper and is left for future work.

[18] Note that the equilibrium deposit rate can also be written as a weighted average of the policy rate and the interest on reserves. Specifically,

$$R_t^D = (1-\mu_t) R_t^{CB} + \mu_t R_t^{\mu}.$$

policy rate.[19] All funds are used to finance the working-capital needs of IG firms and thus act as liabilities to the deposit bank and to the central bank. The lending bank's balance sheet in real terms reads as,

$$L_t = (1 - \mu_t)D_t + X_t. \tag{13}$$

The loan rate is set at the beginning of the period, before firms engage in their production activity and prior to their labour demand and pricing decisions. Similar to Agénor, Bratsiotis and Pfajfar (2014), the lending bank breaks-even from its intermediation activity, such that the expected income from lending to a continuum of IG firms is equal to the total costs of borrowing these funds. The lending bank's expected intra-period zero profit condition from lending to firm j is,

$$\int_{\varepsilon_{j,t}^M}^{\bar{\varepsilon}} R_t^L L_{j,t} f(\varepsilon_{j,t}) d\varepsilon_{j,t} + \int_{\underline{\varepsilon}}^{\varepsilon_{j,t}^M} \chi_t Y_{j,t} f(\varepsilon_{j,t}) d\varepsilon_{j,t} = \left[(1 - \mu_t) D_t + X_t\right] R_t^{CB}, \tag{14}$$

where $f(\varepsilon_{j,t})$ is the probability density function of $\varepsilon_{j,t}$. The first element on the left hand side is the expected repayment to the lending bank in the non-default states, while the second element is the expected return to the lending bank in the default states, measured in terms of collateralized output $(\chi_t Y_{j,t})$. The terms $(1 - \mu_t)D_t R_t^{CB}$ and $X_t R_t^{CB}$ are the total costs of deposits and central bank liquidity, respectively. To derive the lending rate, we use the balance sheet equation (13), constraint (9) for $\chi_t \left(A_t \varepsilon_{j,t}^M\right) H_{j,t} = R_t^L L_{j,t}$, divide by $L_{j,t}$ and substitute the production function (6), such that (14) boils down to,

$$R_t^L - \int_{\underline{\varepsilon}}^{\varepsilon_{j,t}^M} (\varepsilon_{j,t}^M - \varepsilon_{j,t}) \chi_t A_t \frac{H_{j,t}}{L_{j,t}} f(\varepsilon_{j,t}) d\varepsilon_{j,t} = R_t^{CB}. \tag{15}$$

To find an explicit expression for the risk premium and the loan rate, we use the uniform distribution properties of the idiosyncratic shock. Specifically, the probability density of $\varepsilon_{j,t}$ is $1/(\bar{\varepsilon} - \underline{\varepsilon})$ and its mean is $\mu_\varepsilon = (\bar{\varepsilon} + \underline{\varepsilon})/2$. Using this information and re-substituting (9) in (15) yields the loan rate equation,[20]

$$R_t^L = \nu_t R_t^{CB}, \tag{16}$$

[19] Introducing a liquidity injection (X_t) is simply to allow the markets to clear (as in Ravenna and Walsh (2006)). In the model, the lending bank is indifferent between borrowing deposits from the deposit bank and receiving a central bank loan such that the loan rate pricing decision is unaffected.

[20] The cut-off value $\varepsilon_{j,t}^M$ depends on the state of the economy and hence it is identical across all IG firms. Similarly, real wages and labour employed by each IG firm are identical such that the volume of loans supplied by the lending bank is also the same. Thus, the subscript j is dropped in what follows.

with $\nu_t \equiv \left[1 - \left(\frac{\bar{\varepsilon}-\underline{\varepsilon}}{2\varepsilon_t^M}\right)\Phi_t^2\right]^{-1} > 1$ defined as the risk premium, and $\Phi_t = \int_{\underline{\varepsilon}}^{\varepsilon_t^M} f(\varepsilon_t)d\varepsilon_t = \frac{\varepsilon_t^M - \underline{\varepsilon}}{\bar{\varepsilon}-\underline{\varepsilon}}$ representing the probability of default. The loan rate is therefore set as an endogenous premium over the policy rate due to the possibility of firm default.

2.3 Monetary Policy and Interest on Reserves

The central bank is responsible for the conduct of monetary policy through the standard policy rate (which is also the interbank rate here), set according to the following Taylor (1993) rule,

$$R_t^{CB} = \max(R_t^{CB,NOT}, 1), \tag{17}$$

with $R_t^{CB,NOT}$ denoting the desired (or notional) gross interest rate,

$$R_t^{CB,NOT} = \left(R^{CB,NOT}\right)^{(1-\phi)} \left(R_{t-1}^{CB,NOT}\right)^{\phi} \left(\frac{\pi_t}{\pi}\right)^{(1-\phi)\phi_\pi}, \tag{18}$$

where the term $\phi \in (0,1)$ is the degree of interest rate smoothing, $\phi_\pi > 0$ is the policy coefficient measuring the relative weight on inflation from its steady state, and $R^{CB,NOT}$ is the steady state value of the nominal gross rate.[21] The central bank sets $R_t^{CB} = R_t^{CB,NOT}$ if and only if the policy rate reaction implies a non-zero nominal net interest rate.

Delegating financial stability considerations to central banks may require more than just conventional monetary policy. IOR is one of the policy instruments that has attracted attention for managing liquidity and financial stability during the financial crisis and in the aftermath of the Great Recession that followed (Cúrdia and Woodford (2011), Goodfriend (2011), Kashyap and the Stein (2012), Cochrane (2014) and Canzoneri, Cumby and Diba (2016)). In practice, this less-conventional policy tool has also been implemented by a number of central banks including the U.S. Fed, the ECB and the BoJ, as mentioned in the introduction. In this model, and in line with the perception of credit representing a credible measure of financial stability, the central bank

[21] We ignore a response to output (or the output gap) in the Taylor rule as we find that reacting to these variables adds only negligible welfare gains in normal times. This allows us also to clearly establish the relationship between inflation targeting monetary policy rules and IOR policies.

employs the following dynamic rule for IOR,[22]

$$R_t^{\mu} = \left(R_{t-1}^{\mu}\right)^{\rho_{R^{\mu}}} \left(R^{\mu}\right)^{(1-\rho_{R^{\mu}})} \left(\frac{L_t}{L}\right)^{(1-\rho_{R^{\mu}})r_s^{\mu}}, \tag{19}$$

where $\rho_{R^{\mu}} \in (0,1)$ is a persistence parameter, and r_s^{μ} measures the response of IOR to deviations in bank loans. We explore the stabilization roles and welfare implications of this policy instrument within our framework, which also allows for various financial frictions such as the credit cost channel, endogenous credit spreads and the ZLB for the policy rate. Finally, for the purpose of this paper, it is assumed that the required reserves ratio is *constant* at the level set by the central bank, $\mu_t = \mu$.[23,24]

2.4 Equilibrium

To clear the goods market, we assume the size of the liquidity injection from the central bank is $X_t = M_{t+1}\frac{P_{t+1}}{P_t} - M_t$. Following the financial intermediation process, the central bank receives $R_t^{CB}X_t + \mu_t D_t = J_t^{FI}$, which is paid back to the household in a lump-sum fashion.[25] In a symmetric equilibrium, we substitute the IG firms profits, total profits from the financial intermediation process, the equilibrium condition in the market for loans ($W_t H_t = (1-\mu_t)D_t + X_t$) and the size of the liquidity injection in identity (3) to obtain the goods market clearing condition, $Y_t = C_t$.

To solve the model, we log-linearize the behavioral equations and the resource constraint around

[22] See also Angelini, Neri and Panetta (2014) who use loans and loans to GDP as proxies for systemic risk in the context of a model examining the effects of countercyclical regulation. In the absence of a well-defined variable capturing systemic bank risk, the most observable financial variable central banks can respond to when adjusting IOR is credit. Having instead the credit to output ratio as a target variable would not materially affect our results as both these financial variables are strongly and positively correlated.

[23] We therefore do not attempt to explain why required reserves exist in the first place but rather treat this tool as an artifact of liquidity regulation or liquidity management (as practiced by the Fed and the ECB, among other central banks). Our goal is to study the macroeconomic and welfare properties of IOR *given* the imposition of the implicit tax on the banking system, set in the form of reserve requirements. For a more normative analysis on reserve requirements and excess reserves, and the market failure(s) that such type of liquidity regulation may solve, see Kashyap and Stein (2012) and Güntner (2015).

[24] Bratsiotis (2016) compares the effectiveness of dynamic reserve requirements (which respond to a measure of financial stability) with IOR as well as with credit-augmented monetary policy rules in a model with bank capital requirements, and only following shocks that do *not* push the policy rate to the ZLB. The aim of our paper, in contrast, is to formally and firmly establish the transmission effects of *solely* IOR on the real economy, and to study the implications of this tool also when the economy is mired in a deep recession and faces deflationary pressures (more in line with recent experience in advanced economies). Moreover, the policy rules we examine below are *less* restricted (yet still implementable), which helps to better understand the intrinsic interactions between inflation targeting monetary policy rules and IOR also in normal times and following financial shocks.

[25] The deposit and lending banks are perfectly competitive and therefore earn zero profits.

the non-stochastic, zero inflation ($\pi = 1$) steady state and take the percentage deviation from their counterparts under flexible prices. Before writing the equilibrium conditions in 'gap' form, it is worth noting that the flexible price (natural) level of output is $Y_t^n = \left[\frac{\vartheta_t Z_t^{1+\gamma}}{(pm) R_t^L}\right]^{\frac{1}{\gamma+\varsigma}}$, where $pm \equiv \lambda / (\lambda - 1)$ denotes the price mark-up resulting from monopolistic competition in the goods market, and λ is defined as the constant elasticity of substitution between intermediate goods. The efficient level of output, absent of the credit cost channel and nominal rigidities, is $Y_t^e = \left[\frac{\vartheta_t Z_t^{1+\gamma}}{(pm)}\right]^{\frac{1}{\gamma+\varsigma}} > Y_t^n$ such that in log-linear terms: $\hat{Y}_t^e - \hat{Y}_t^n = (\gamma + \varsigma)^{-1} \hat{R}_t^L$.

The log-linearized versions of (4), (5), (6), (9), (11), (12), (16), (17), (18) and (19) can then be used to express the model in terms of the following log-linear equations involving the welfare-relevant (efficient) output gap ($\widehat{x}_t \equiv \widehat{Y}_t - \widehat{Y}_t^e$), inflation ($\widehat{\pi}_t$), risk of default ($\hat{\Phi}_t$), the policy rate ($\hat{R}_t^{CB}$), the deposit rate ($\hat{R}_t^D$), the loan rate ($\hat{R}_t^L$), the IOR rate ($\hat{R}_t^\mu$) and the various shocks.[26]

$$\widehat{x}_t = \mathbb{E}_t \widehat{x}_{t+1} - \varsigma^{-1} \left(\hat{R}_t^D - \mathbb{E}_t \widehat{\pi}_{t+1} \right) + \widehat{u}_t, \tag{20}$$

$$\widehat{\pi}_t = \beta \mathbb{E}_t \widehat{\pi}_{t+1} + k_p (\varsigma + \gamma) \widehat{x}_t + k_p \hat{R}_t^L, \tag{21}$$

$$\hat{R}_t^D = (1 - \mu) \frac{R^{CB}}{R^D} \hat{R}_t^{CB} + \mu \frac{R^\mu}{R^D} \hat{R}_t^\mu, \tag{22}$$

$$\hat{R}_t^L = \hat{R}_t^{CB} + \Upsilon \hat{\Phi}_t, \tag{23}$$

$$\hat{\Phi}_t = \left(\frac{\varepsilon^M}{\varepsilon^M - \underline{\varepsilon}} \right) \left(\hat{R}_t^L + (\varsigma + \gamma) \widehat{x}_t + \hat{\varepsilon}_t - \hat{\chi}_t \right), \tag{24}$$

$$\hat{R}_t^\mu = \rho_{R^\mu} \hat{R}_{t-1}^\mu + (1 - \rho_{R^\mu}) r_s^\mu \hat{L}_t, \tag{25}$$

$$\hat{R}_t^{CB} = \max(\phi \hat{R}_{t-1}^{CB} + (1 - \phi) \phi_\pi \widehat{\pi}_t, 0), \tag{26}$$

where $k_p \equiv \frac{(1-\omega_p)(1-\omega_p \beta)}{\omega_p}$, $\Upsilon \equiv \frac{(\varepsilon^M + \underline{\varepsilon})(\bar{\varepsilon} - \underline{\varepsilon})}{2(\varepsilon^M)^2} \Phi^2 v$, $\nu \equiv \left[1 - \left(\frac{\bar{\varepsilon} - \underline{\varepsilon}}{2\varepsilon^M}\right) \Phi^2\right]^{-1}$ and $\varepsilon^M = (pm)^{-1} (\chi)^{-1} \mu_\varepsilon$ is the steady state *reduced-form* threshold value below which the IG firm defaults. The steady state risk of default is therefore $\Phi = \frac{\left[(pm)^{-1} \mu_\varepsilon / \chi\right] - \underline{\varepsilon}}{\bar{\varepsilon} - \underline{\varepsilon}}$ while the long run loan rate is $R^L = \nu R^{CB}$, with $R^{CB} = \frac{R^D - \mu R^\mu}{(1-\mu)}$ and $R^D = (\beta)^{-1}$. The steady state values for R^μ and μ are parameterized

[26] To write the model in 'gap' form we use the following relationship between the marginal cost and the output gap: $\widehat{mc}_t = \hat{R}_t^L + (\gamma + \varsigma) \hat{x}_t$, which is obtained by combining the log-linear versions of (5), (6), (11) and the definition of the output gap.

according to the U.S. data, as explained later in the text. The term

$$\widehat{u}_t \equiv (\gamma + \varsigma)^{-1} \left[(1+\gamma) \left(\mathbb{E}_t \hat{Z}_{t+1} - \hat{Z}_t \right) - \left(\frac{\gamma}{\varsigma} \right) \left(\mathbb{E}_t \hat{\vartheta}_{t+1} - \hat{\vartheta}_t \right) \right], \tag{27}$$

is a composite, exogenous "demand" disturbance term that depends on productivity and preference shocks, with $\hat{Z}_t \equiv \hat{\varepsilon}_t + \hat{A}_t$, and $\hat{\vartheta}_t$ given by the log-linear representation of (2). The financial shock ($\hat{\chi}_t$) is driven by the $AR(1)$ process in (8). Finally, credit can also be expressed as a function of the output gap and output,

$$\hat{L}_t = (\gamma + \varsigma) \hat{x}_t + \hat{Y}_t, \tag{28}$$

with the level of output given by,

$$\hat{Y}_t = \widehat{x}_t + \hat{Y}_t^e = \widehat{x}_t + (\gamma + \varsigma)^{-1} \left[\hat{\vartheta}_t + (1+\gamma) \hat{Z}_t \right]. \tag{29}$$

3 The Transmission Channels of Interest on Reserves

3.1 Interest on Reserves and the Refinance Rate

On October 6, 2008, the Fed announced that it would start paying interest on required (and excess) reserves in order to "give the Federal Reserve a greater scope to use its lending programs to address conditions in credit markets while also maintaining the federal funds rate close to the target established by the Federal Open Market Committee" (see Board of Governors, Federal Reserve System; October 6, 2008). By paying IOR, the Fed aims to eliminate effectively the implicit tax that reserve requirements impose on the banking system. More recently in 2015-2016, and following the sustained deflationary spirals experienced in the Eurozone and Japan, the ECB and BoJ have decided to lower the interest rate on required reserves to zero. To analyze the business cycle implications of IOR policy changes observed in the last few years, and how this tool may alter the behaviour of standard monetary policy, we now turn to illustrate the intuition behind the equilibrium conditions derived in the previous section.

Equation (20) is the Euler equation describing the determinants of the output gap. The gap is affected positively by its expected future value and negatively by the deposit rate, which itself increases with the policy rate and the IOR rate. Therefore, all else equal, a *rise* in IOR may *depress* the economic activity, $\partial \widehat{x}_t / \partial \hat{R}_t^{\mu} = -\varsigma^{-1} \mu \left(R^{\mu} / R^D \right) \leq 0$, leading also to direct dis-inflationary pressures through the NKPC, $\partial\widehat{\pi}_t/\partial\widehat{x}_t = k_p(\varsigma+\gamma) > 0$ (see (21)). The dis-inflationary impact that IOR produces via this *intertemporal substitution effect* alters the transmission mechanism of monetary policy *outside* of the ZLB. On the one hand, stronger dis-inflation may prompt the central bank to cut the policy rate and in this way raise output gap and inflation expectations (see (20), (22) and (26)). On the other hand, reducing the refinance rate can result in an amplified fall in prices via the direct *monetary policy cost channel*, which is transmitted through the broader *credit cost channel* that relates the loan rate to price inflation (equations (21), (23) and (26)). Hence, away from the ZLB and in the presence of a credit cost channel, IOR may conflict with standard monetary policy. However, If the economy faces a liquidity trap, and/or when the loan rate is an *endogenous* mark-up over the risk-free policy rate, varying IOR may provide the central bank an extra degree of freedom to stabilize the economy following various shocks.

3.2 Interest on Reserves and the Lending Rate

To examine how IOR impacts borrowing costs and consequently the real economy, we first use equations (23) and (24) to re-write the loan rate equation as a function of only the policy rate, the inflationary output gap and the exogenous shocks,

$$\hat{R}_t^L = \Psi_1 \hat{R}_t^{CB} + \Psi_2\left[(\varsigma+\gamma)\,\widehat{x}_t + \hat{\varepsilon}_t - \hat{\chi}_t\right], \tag{30}$$

where $\Psi_1 \equiv \frac{\left[2\varepsilon^M(\bar{\varepsilon}-\underline{\varepsilon})-\left(\varepsilon^M-\underline{\varepsilon}\right)^2\right]}{2\varepsilon^M(\bar{\varepsilon}-\varepsilon^M)} > 0$ and $\Psi_2 \equiv \frac{\left(\varepsilon^M+\underline{\varepsilon}\right)\left(\varepsilon^M-\underline{\varepsilon}\right)}{2\varepsilon^M(\bar{\varepsilon}-\varepsilon^M)} > 0$.

We then turn to study the effect of R_t^μ on R_t^L by calculating $\frac{\partial\hat{R}_t^L}{\partial\hat{R}_t^\mu} = \frac{\partial\hat{R}_t^L}{\partial\widehat{x}_t}\frac{\partial\widehat{x}_t}{\partial\hat{R}_t^D}\frac{\partial\hat{R}_t^D}{\partial\hat{R}_t^\mu}$, which yields,

$$\frac{\partial\hat{R}_t^L}{\partial\hat{R}_t^\mu} = -\Psi_2(\varsigma+\gamma)\,\varsigma^{-1}\mu\frac{R^\mu}{R^D} \leq 0. \tag{31}$$

Ceteris paribus, a rise in IOR contributes to a fall in the loan rate, which, in turn, promotes additional lending in the credit markets, as well as mitigates inflationary pressures through the credit cost channel. Specifically,

$$\frac{\partial\widehat{\pi}_t}{\partial\hat{R}_t^\mu} = \frac{\partial\widehat{\pi}_t}{\partial\hat{R}_t^L}\frac{\partial\hat{R}_t^L}{\partial\hat{R}_t^\mu} = -k_p\Psi_2(\varsigma+\gamma)\,\varsigma^{-1}\mu\frac{R^\mu}{R^D} \leq 0. \tag{32}$$

Hence, an increase in IOR unambiguously translates into falling prices through both the standard demand channel (explained above), and the credit cost channel. The latter operates through the positive relationship between the risk premium and the inflationary marginal production costs, proxied by the output gap.

The effect of IOR on the output gap is ambiguous and depends on the nature of the shock hitting the economy. As explained earlier, an increase in IOR raises the deposit rate, thereby lowering the output gap through an intertemporal substitution effect,

$$\frac{\partial \widehat{x}_t}{\partial \hat{R}_t^{\mu}} = \frac{\partial \widehat{x}_t}{\partial \hat{R}_t^{D}} \frac{\partial \hat{R}_t^{D}}{\partial \hat{R}_t^{\mu}} = -\varsigma^{-1} \mu \frac{R^{\mu}}{R^{D}} \leq 0. \tag{33}$$

However, from equation (30), the dis-inflationary effect caused by the fall in the output gap acts to *reduce* the risk premium and therefore the loan rate by,

$$\frac{\partial \hat{R}_t^{L}}{\partial \widehat{x}_t} = \Psi_2 (\varsigma + \gamma) \geq 0. \tag{34}$$

Intuitively, in the presence of adverse disturbances moving output and inflation in the *same* negative direction (such as preference shocks), the standard output gap-demand channel reinforces the credit cost channel following a *rise* in the IOR. In other words, the contraction in the output gap propagates the price dis-inflation instigated by the lower cost of borrowing. As a consequence, the policy rate is pushed further towards the ZLB, with upward pressure placed on the real deposit rate $(\hat{R}_t^{D} - \mathbb{E}_t \widehat{\pi}_{t+1})$. The latter, in turn, may contribute to a prolonged decline in the economic activity. Under these conditions, *cutting* the IOR rate can be a more effective tool to stimulate the economy and to bring inflation back to its target level. In contrast, following adverse shocks moving output and inflation in the *opposite* direction (such as supply or financial shocks in this model), then all else equal, *raising* IOR can potentially attenuate the trade-off between these two variables by *initially* lowering the output gap, reducing the cost of borrowing, thereby curbing inflationary pressures and *ultimately* promoting economic stability. Nevertheless, and as highlighted in the previous section, IOR policy alters the transmission mechanism of standard monetary policy, making it imperative to study how these widely-used policy tools interact with one another, both in normal times and during deep recessions. This analysis requires simulation methods that are performed in the next sections.

4 Parameterization and Model Evaluation

The baseline parameterization used to simulate the model is summarized in Table 1. Parameters that characterize tastes, preferences, price mark-ups, price stickiness and technology are all standard in the literature and are chosen to match observed ratios and interest rate spreads in the U.S.

Table 1: Benchmark Parameterization

Parameter	Value	Description
β	0.996	Discount Factor
ς	1.00	Inverse of Elasticity of Intertemporal Substitution
γ	1.00	Inverse of the Frisch Elasticity of Labour Supply
ϑ	1.00	Average Taste Preference
λ	6.00	Elasticity of Demand for Intermediate Goods
ω_p	0.70	Degree of Price Stickiness
A	1.00	Average Productivity Parameter
$\bar{\varepsilon}$	1.50	Idiosyncratic Productivity Shock Upper Range
$\underline{\varepsilon}$	1.00	Idiosyncratic Productivity Shock Lower Range
χ	0.97	Average Fraction of Collateral Seized in Default States
μ	0.10	Required Reserves Ratio
$\rho_{R^{\mu}}$	0.00	Degree of Persistence - IOR rule
r_s^{μ}	0.00	Response of IOR to Loans Deviations
ϕ	0.70	Degree of Persistence - Taylor rule
ϕ_{π}	2.00	Response of Policy Rate to Inflation Deviations
ρ_{ϑ}	0.90	Degree of Persistence - Demand Shock
ρ_{χ}	0.90	Degree of Persistence - Financial Shock
$s.d(\alpha^{\vartheta})$	0.014	Standard Deviation - Demand Shock
$s.d(\alpha^{\chi})$	0.10	Standard Deviation - Financial Shock

Elaborating on some of the unique parameters to this model. The subjective discount factor is set to $\beta = 0.996$, implying a yearly deposit rate of 1.6 percent. Furthermore, the required reserves ratio (μ) is equal to 0.1 (or 10 percent), while the IOR rate in annual terms is 1 percent. These values yield an annualized policy rate of 1.68 percent. The idiosyncratic productivity range is set between $(1.0, 1.5)$, which together with the fraction of output received in case of default pinned to $\chi = 0.97$, and a price mark-up of 20 percent, yields an annual credit spread of 2.04 percent and a loan to GDP ratio of 83 percent. All these estimates roughly correspond with the U.S. data.

The Taylor (1993) rule parameters in our benchmark case are set to $\phi = 0.7$ and $\phi_\pi = 2.0$, which are close to the coefficients estimates reported for the U.S. Fed using the International Monetary Fund Global Projection Model (Carabenciov et al. (2013)), and the values applied in Benes and Kumhof (2015). The *benchmark* calibration of the historical U.S. IOR reaction function implies $\rho_{R^\mu} = 0$ and $r_s^\mu = 0$, given that IOR is a relatively new tool applied as an unconventional monetary policy by some central banks. Indeed, we attempt to determine the *optimal* behaviour of IOR policy using a counterfactual experiment following various shocks, and examine its interaction with simple monetary policy rules.[27]

Finally, as for the main shocks examined in our paper, we fix the persistence parameters governing the evolution of financial and demand shocks, ρ_χ and ρ_ϑ, both to 0.90. The standard deviations associated with these shocks are given by $s.d(\alpha^\chi) = 0.10$ and $s.d(\alpha^\vartheta) = 0.014$, respectively. These values are within the range of Christiano, Motto and Rostagno (2014) and Benes and Kumhof (2015).[28] Based on these shock moments, Table 1A compares the theoretical moments of some of the model's key variables to their data counterparts, with all standard deviations measured in annualized percentage terms,[29]

Table 1A: Standard Deviations; Model versus Data

Observed Variable	Standard Deviations - Model	Standard Deviations - Data
Real Output Growth	2.30	2.55
Inflation	0.96	0.96
Credit Spreads	13.33	1.81
Policy Rate	1.51	1.95

Overall, the standard deviations corresponding with our small scale New Keynesian model are not inconsistent with the data. Where it falls short is in the large standard deviation inherent

[27] The degree of persistence in the IOR rule (ρ_{R^μ}) is always set to 0, as we find that including this parameter increases welfare losses when the IOR rule (r_s^μ) is set optimally.

[28] To save space, we do not present the policy implications of a technology shock as we find that these are qualitatively similar to the ones obtained following a financial disturbance.

[29] We use the U.S. data over the 2000:Q1-2015Q1 period, obtained from the FRED database.

in credit spreads. We attribute this finding to the nature of the credit cost channel and the type of financial innovation, both of which are unique to this model. Specifically, the lending rate is subject to financial amplification mechanisms, initiating from a direct shock to credit spreads that, by design, leads to a relatively higher variance in borrowing costs. Unlike the majority of the literature, where a financial shock is defined as a disturbance to net worth, in this setup, the credit disturbance is effectively a first-hand shock to risk or credit spreads. Our deliberately simplified framework excludes physical capital, investment, net worth, consumption habits, indexation and a greater array of shocks, all of which are important to produce a better match between the moments of the model and those of the data. These more realistic features are sacrificed in favour of model tractability and a more transparent illustration of the results. Indeed, with this relatively simple model, our aim is to deliver a clear intuition regarding the transmission mechanisms of IOR in a setup featuring financial frictions, and to provide consistent and meaningful policy prescriptions on how to apply this tool, both outside of and at the ZLB.

5 Optimal Simple Policy Rules and Welfare

In this section, we calculate optimal policy rules in response to financial and demand shocks, and study the interactions between standard monetary policy and IOR policy rules during *normal* times, or when the policy rate is *away from* the ZLB and is able to optimally adjust. The central bank's objective function is given by a second order approximation of the household's ex-ante expected utility written in 'gap' form,[30]

$$\sum_{t=0}^{\infty} \beta^t U_t \approx U - \frac{1}{2} U_C Y \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\left(\frac{\lambda}{\kappa_p} \right) (\widehat{\pi}_t)^2 + (\varsigma + \gamma) (\widehat{x}_t)^2 \right], \tag{35}$$

The policy rules examined are: Policy I (benchmark case) - a standard Taylor rule policy where the central bank sets exogenously $\phi_\pi = 2.0$, and no dynamic IOR policy ($r_s^\mu = 0$). Policy II - central bank responding optimally to inflation in the Taylor rule (solving for ϕ_π and setting $r_s^\mu = 0$). Policy III - central bank reacting optimally to inflation in the Taylor rule, and optimally to credit in the IOR rule (solving for ϕ_π and r_s^μ). The optimal parameters that maximize welfare are grid-searched

[30] The richer borrowing cost channel, featuring default risk and IOR, therefore does not change the *structure* of the loss function compared to standard New Keynesian models with just a monetary policy cost channel (see also Ravenna and Walsh (2006)). The detailed derivation of the welfare loss function is available upon request.

within the following implementable ranges: $\phi_\pi = [1:10]$ and $r_s^\mu = [-3:3]$ with step of 0.01.[31]

In considering Policies $j = II, III$, we measure the welfare gain of a particular policy j as a fraction of the consumption path under the benchmark case (Policy I) that must be given up in order to obtain the benefits of welfare associated with the various optimal policy rules; $\mathbb{E}_t \sum_{t=0}^{\infty} \beta^t U_t \left(C_t^j, H_t^j\right) = \mathbb{E}_t \sum_{t=0}^{\infty} \beta^t U_t \left((1-\Lambda) C_t^I, H_t^I\right)$, where Λ is a measure of welfare gain in units of steady state consumption. Given the utility function adopted and with $\varsigma = 1$, the expression for the consumption equivalent (Λ) in percentage terms is,

$$\Lambda = \left\{1 - \exp\left[(1-\beta)\left(\mathbb{W}_t^j - \mathbb{W}_t^I\right)\right]\right\} \times 100,$$

with $\mathbb{W}_t^j = \mathbb{E}_t \sum_{t=0}^{\infty} \beta^t U_t \left(C_t^j, H_t^j\right)$ representing the unconditional expectation of lifetime utility under policy $j = II, III$, and $\mathbb{W}_t^I = \mathbb{E}_t \sum_{t=0}^{\infty} \beta^t U_t \left(C_t^I, H_t^I\right)$ the welfare associated with the benchmark Policy I. A higher positive Λ implies a larger welfare gain and hence indicates that the policy is more desirable from a welfare perspective. The steady state of our model is independent of the monetary policy and IOR rules (ϕ_π, r_s^μ) so our computation of social welfare is comparable across all policy rules.

5.1 Financial Shock

Table 2 reports the optimal simple policy rules, the asymptotic standard deviations (measured in annual percentage terms) of key variables, and the welfare gain (Λ) of each policy relative to the benchmark, following a 1 standard deviation shock to χ_t.

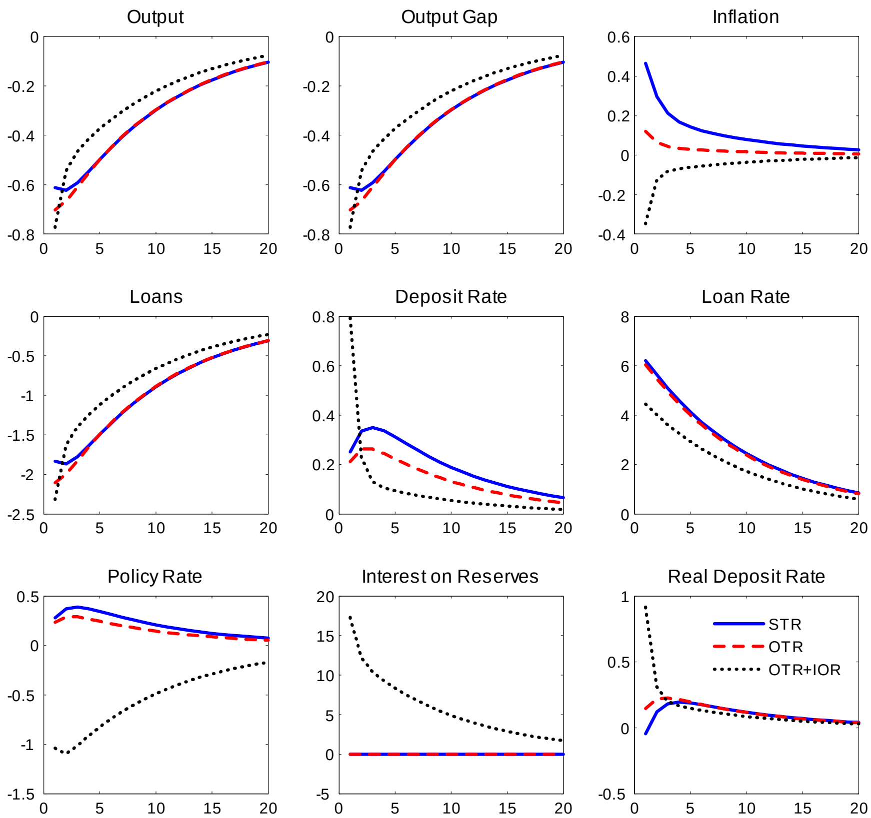
[31] In all policy rules we keep the persistence parameter in the Taylor rule at $\phi = 0.7$. As explained above, we set the persistence parameter in the IOR rule to zero as we find that a positive value for ρ_{R^μ} always increases welfare losses once r_s^μ is set optimally.

Table 2: Optimal Simple Policy Rules - Financial Shock

Policy I	Policy II	Policy III
$\phi_\pi = 2.00$	$\phi_\pi = 6.60$	$\phi_\pi = 10.0$
$r_s^\mu = 0.00$	$r_s^\mu = 0.00$	$r_s^\mu = -1.87$
$\Lambda = -$	$\Lambda = 4.61 \times 10^{-3}$	$\Lambda = 0.0116$
$s.d\,(\widehat{\pi}_t) = 0.68$	$s.d\,(\widehat{\pi}_t) = 0.16$	$s.d\,(\widehat{\pi}_t) = 0.40$
$s.d(\widehat{x}_t) = 1.65$	$s.d(\widehat{x}_t) = 1.71$	$s.d(\widehat{x}_t) = 1.42$
$s.d(\widehat{L}_t) = 4.96$	$s.d(\widehat{L}_t) = 5.13$	$s.d(\widehat{L}_t) = 4.25$

Figure 1 depicts the impulse response functions associated with the optimal policy parameters as calculated in Table 2 following a 1 percent negative financial shock.

Figure 1 - Adverse Financial Shock with Optimal Policy Rules



i) Figure 1 compares between Policy I (Standard Taylor Rule - 'STR') to Policy II (Optimal Taylor Rule - 'OTR'), and Policy III (Optimal Taylor Rule plus Interest on Reserves - 'OTR+IOR'). ii) Interest rates and inflation are measured in annualized percentage point deviations from steady state. The rest of the variables are measured in annualized percentage deviations.

In benchmark Policy I, an adverse financial shock directly increases the risk premium and the loan rate, both of which bring about a rise in the marginal cost and inflation, and produce a contraction in the output gap and lending due to the credit cost channel effect.[32] With standard Taylor rule parameters ($\phi_\pi = 2$), the policy rate increases following the inflationary impact of the

[32]Notice that output is equal to the output gap following credit shocks: $\hat{Y}_t = \widehat{x}_t$ for $\hat{\vartheta}_t = \hat{Z}_t = 0$ (see equation (29)).

shock, thereby fueling a hike in the lending and deposit rates. The rise in borrowing costs yields an accelerated incline in risk and a more substantial fall in output. At the same time, the decline in the output gap dampens the rise in the cost of borrowing and inflation via both the standard demand channel of monetary policy as well as the credit cost channel, as explained above. However, given the nature of the adverse financial shock hitting directly credit risk, the spike in the loan rate raises inflation, and discourages both output and credit.[33]

Policy II prescribes a relatively strong response to inflation in the Taylor rule ($\phi_\pi = 6.60$). In this way, the refinance rate and thus the deposit rate *initially* increase, both of which lower the output gap even further, but contain the inflationary pressures inherent in the adverse financial shock. The relative fall in prices acts to raise the real deposit rate, thereby prompting an additional decline in the GDP. This result highlights the trade-off faced by central banks between stabilizing inflation and output following an inflationary negative financial shock, as also alluded to in Gilchrist, Schoenle, Sim and Zakrajsek (2016). With a micro-founded loss function, the welfare contribution from the more profound decline in inflation volatility dominates the welfare losses arising from the slightly larger fall in output, such that a strengthened reaction to inflation fluctuations in the monetary policy rule is optimal. Moreover, the easing of inflationary pressures *ultimately* moderates the increase in the policy rate, which, as a result, contributes further to price stability and welfare through the monetary policy cost channel.

Examining Policy III, the combination of a significantly higher IOR and a stronger feedback from inflation to the monetary policy rule ($\phi_\pi = 10.0$, $r_s^\mu = -1.87$) attains the highest welfare gain. Optimal policy calls for substantially raising IOR by around 17 percentage points (annually) in response to adverse financial shocks, intrinsic in higher borrowing costs and deteriorating lending conditions. Upon impact, inflating the rate paid on reserves increases the deposit rate, generating therefore a one period exaggerated decline in the output gap. At the same time, with the central bank paying a higher rate on reserves, the lending bank can afford to charge a lower loan rate due to the negative impact that IOR inflicts on the output gap and the risk premium. This outcome propagates the dis-inflationary effects emanating from the initial fall in the output gap, but also leads to an *improvement* in future output expectations. Due to the demand-pull dis-inflation, linked with the higher deposit rate, the central bank reacts *more* aggressively to prices in the monetary

[33] GDP and *aggregate* price inflation moving in *opposite* directions in response to *financial shocks* is also supported by the empirical findings of Gilchrist, Schoenle, Sim and Zakrajsek (2016).

policy rule, resulting in a lower refinance rate and in an easing of borrowing cost pressures. In turn, this cost-push dis-inflation subdues the descend in aggregate demand, thereby prompting a *shorter and less persistent* recession. Hence, despite the higher volatility and welfare costs associated with dis-inflation (compared to Policy II), the far less pronounced declining levels in lending and GDP translate into an overall welfare enhancement of 0.0116 percent. It is worth noting that If IOR is not coordinated with a more hawkish Taylor rule, then the risks of greater dis-inflation outweigh the gains from moderating the fall in output. Put differently, as unconventional monetary policy in the form of IOR is introduced, the degree of the response to prices in the Taylor rule becomes a more pertinent issue, especially when the policy rate is away from the ZLB. However, if the policy rate is constrained by the ZLB, a stronger reaction to loans (in absolute value) in the IOR rule may have destabilizing effects on the real economy by dragging the refinance rate down towards the ZLB.

To summarize, the policy implications of our model following an adverse financial shock are *qualitatively* in line with the monetary policy operations pursued by the Fed during the peak of the financial crisis in 2008, when it started paying IOR and notably lowered the federal funds rate. The federal funds rate pushed closer towards the ZLB is *quantitatively* also supported by this model (see the behaviour of the policy rate falling by just over 1 percentage point annually), while the 17 percentage point annual increase in IOR is remarkably higher than the rise observed in the U.S. since the onset of the financial crisis. Nevertheless, the aim of this counterfactual exercise is to understand how IOR should *optimally* respond to a negative credit risk shock. In practice, it is not clear whether the Fed actually followed an optimal policy during the height of the credit crunch in 2008, when it only introduced the payment on reserves facility.

5.2 Preference (Demand) Shock

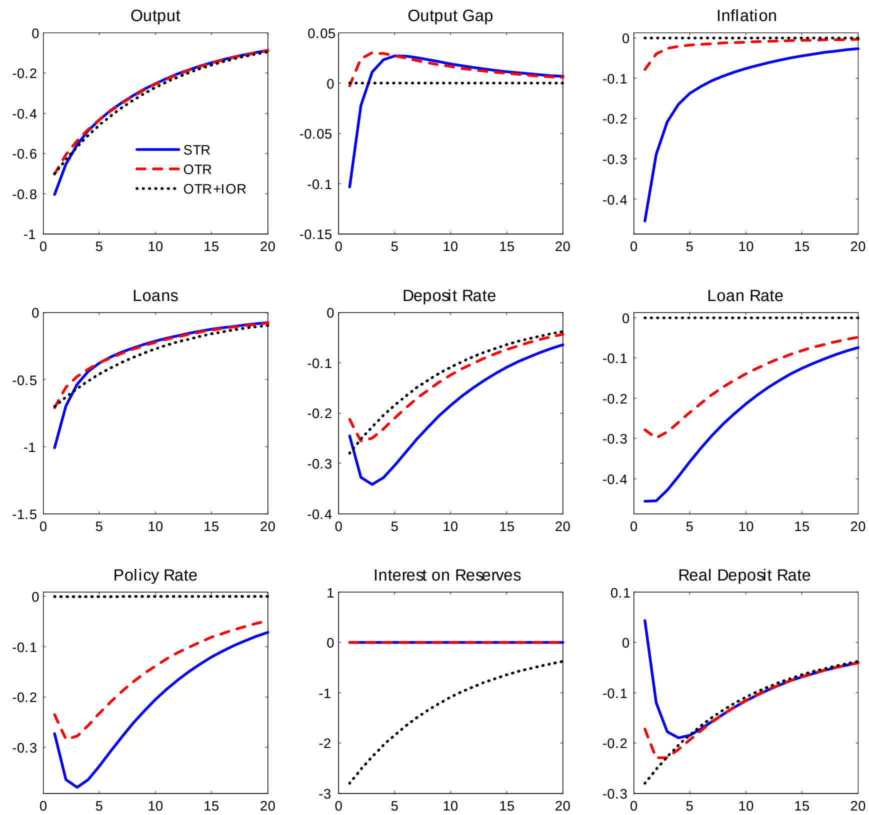
Table 3 shows the optimal simple policy rules, the asymptotic standard deviations of key variables, and the welfare gain (Λ) of each policy relative to the benchmark, following a 1 standard deviation shock to ϑ_t.

Table 3: Optimal Simple Policy Rules - Preference Shock

Policy I	Policy II	Policy III
$\phi_\pi = 2.00$	$\phi_\pi = 10.0$	$\phi_\pi \in (2, 100)$
$r_s^\mu = 0.00$	$r_s^\mu = 0.00$	$r_s^\mu = 1.00$
$\Lambda = -$	$\Lambda = 6.46 \times 10^{-4}$	$\Lambda = 6.67 \times 10^{-4}$
$s.d\,(\widehat{\pi}_t) = 0.67$	$s.d\,(\widehat{\pi}_t) = 0.10$	$s.d\,(\widehat{\pi}_t) = 0.00$
$s.d(\widehat{x}_t) = 0.13$	$s.d(\widehat{x}_t) = 0.08$	$s.d(\widehat{x}_t) = 0.00$
$s.d(\widehat{L}_t) = 1.64$	$s.d(\widehat{L}_t) = 1.40$	$s.d(\widehat{L}_t) = 1.60$

Figure 2 displays the impulse response functions associated with the optimal policy parameters as calculated in Table 3 following a 1 percent adverse preference shock.

Figure 2 - Adverse Preference Shock with Optimal Policy Rules



i) Figure 2 compares between Policy I (Standard Taylor Rule - 'STR') to Policy II (Optimal Taylor Rule - 'OTR'), and Policy III (Optimal Taylor Rule plus Interest on Reserves - 'OTR+IOR'). ii) Interest rates and inflation are measured in annualized percentage point deviations from steady state. The rest of the variables are measured in annualized percentage deviations.

Starting from benchmark Policy I, an adverse preference (demand) shock delivers a direct dip in the GDP and the output gap, which lead to a reduction in prices through a standard demand channel affecting the NKPC, and also to a decline in the risk premium. The fall in the risk premium acts to lower the lending rate and therefore exacerbate price dis-inflation via the credit cost channel. In response to the falling price level, the central bank lowers the policy rate, which, on the one hand, may cushion the plunge in inflation, but, on the other, amplify price dis-inflation due to the direct monetary policy cost channel mechanism. Given our standard parameterization, the direct demand effect of the output gap on inflation dominates such that upon impact, output and the output gap decline, prices decrease while the main interest rates are lowered. Therefore, following a preference shock, the lending rate is procyclical with respect to the economic activity, as opposed to the consequences arising from a financial shock.[34]

In Policy II, a stronger reaction to inflation in the Taylor rule ($\phi_\pi = 10.0$) provides a non-negligible welfare benefit. By responding more stringently to inflation, the central bank *initially* cuts the policy rate, which then mitigates the fall in prices, output, output gap and credit. As inflation converges back to its equilibrium level, the drop in the refinance rate becomes *essentially less* pronounced such that loan rate fluctuations are attenuated. Through the credit cost channel, the relative rise in the lending rate facilitates an incline in inflation, which, in turn, lowers the real deposit rate and encourages an improvement in the output gap.

Focusing now on Policy III, we find that lowering IOR by roughly 3 percentage points (annually) in response to the plummet in credit demand ($r_s^\mu = 1.0$) yields the highest welfare gain, and in fact minimizes welfare losses comprised of inflation and output gap volatilities. Cutting IOR to a negative 2 percent annual rate following an adverse preference shock increases the loan rate, which, as a result, raises inflation and helps to restore the target level of this variable. Moreover, a lower rate on reserves associated with this relative rise in inflation, allows for a curtailment in the real deposit rate; an effect that reinforces the rise in prices, and boosts the output gap. With a micro-founded loss function, an IOR reduction is therefore optimal against the backdrop of a negative demand disturbance, *regardless* of the reaction to inflation in the monetary policy rule. Specifically, we vary $\phi_\pi \in (2, 100)$ and find that once the IOR policy is set optimally, there are zero welfare differences from adjusting ϕ_π. The major welfare improvement of 6.67×10^{-4} percent therefore stems from the optimal setting of IOR.

However, notice that the relative increase in the loan rate, originating from the implementation of the state-contingent IOR policy, amplifies the contraction and standard deviations in credit and GDP compared to Policy II. Hence, while a negative IOR policy is optimal in maximizing welfare, it also creates a conflict for the central bank between pursuing price stability and financial stability (measured in terms of credit volatility). Given the considerable weight the ECB places on price

[34] De Fiore and Tristani (2013) also find that following some shocks, the risk premium and the cost of borrowing are procyclical with respect to GDP.

stability, and its objective to boost consumer prices in light of the persistent low inflation currently experienced in the Eurozone, the IOR policy cuts undertaken in 2015 and 2016 are not inconsistent with the predictions of this model.

6 Interest on Reserves and the Zero Lower Bound

We now turn to examine the implications of the ZLB on the dynamics and standard deviations of key variables, as well as the stabilization properties of an IOR rule in a liquidity trap environment. To solve the model with an occasionally binding ZLB constraint, we implement the methodology developed in Guerrieri and Iacoviello (2015), who propose a piecewise-linear approach that: i) combines multiple regimes of the same model; and ii) solves for the model-implied expected future prices. Specifically, in our setup we define two regimes: the first when the ZLB binds and the second when it does not. The combination of the two different regimes generates strong non-linearities in the model variables, and constructs a piecewise-linear approximation to the original non-linear model. This approximation is then applied to determine the duration and probability of procuring the ZLB, both of which endogenously impact the dynamics and moments of key variables[35]

We study the effects of a sizeable adverse preference demand shock that creates a negative co-movement between inflation and output, such that the central bank lowers the policy rate until the ZLB constraint becomes binding.[36] For this purpose, we increase the standard deviation of the disturbance from 0.014 to 0.0175 percent, and examine a shock with a magnitude of $4 \times s.d(\alpha^{\vartheta})$, with $s.d(\alpha^{\vartheta}) = 0.0175$. The combination of the higher standard deviation and the multiplicative scale of the shock are set to cause the economy to reach a liquidity trap upon impact, and stay there for 4 periods (under a benchmark monetary policy rule: $\phi_{\pi} = 2$ and $\phi = 0.7$). Admittedly, the duration of the ZLB in our model is significantly shorter than the one observed for the United States and the Eurozone for nearly a decade (see also Carrillo and Poilly (2013)).[37] Nevertheless,

[35] In the context of a perfect foresight setup, as in this model, using either the Guerrieri and Iacoviello (2015) solution method or Holden's (2016) algorithm, produces the exact same results. In general, Holden's (2016) algorithm can be applied to higher order pruned perturbations (thereby providing higher accuracy results) and account for future uncertainty, all of which are absent from the Guerrieri and Iacoviello (2015) method.

[36] As implied from the above analysis *away* from the ZLB, an adverse financial shock to credit spreads (or risk) in this setup is *inflationary* and does *not* drive the nominal policy rate to the ZLB (more in line with Gilchrist, Schoenle, Sim and Zakrajsek (2016)). For a discussion on risk premium shocks that produce a co-movement between output and inflation, thereby pushing the nominal refinance rate towards the ZLB, see Amano and Shukayev (2012), and Carrillo and Poilly (2013). These models do *not* feature a credit cost channel as in our model, but do include investment and physical capital.

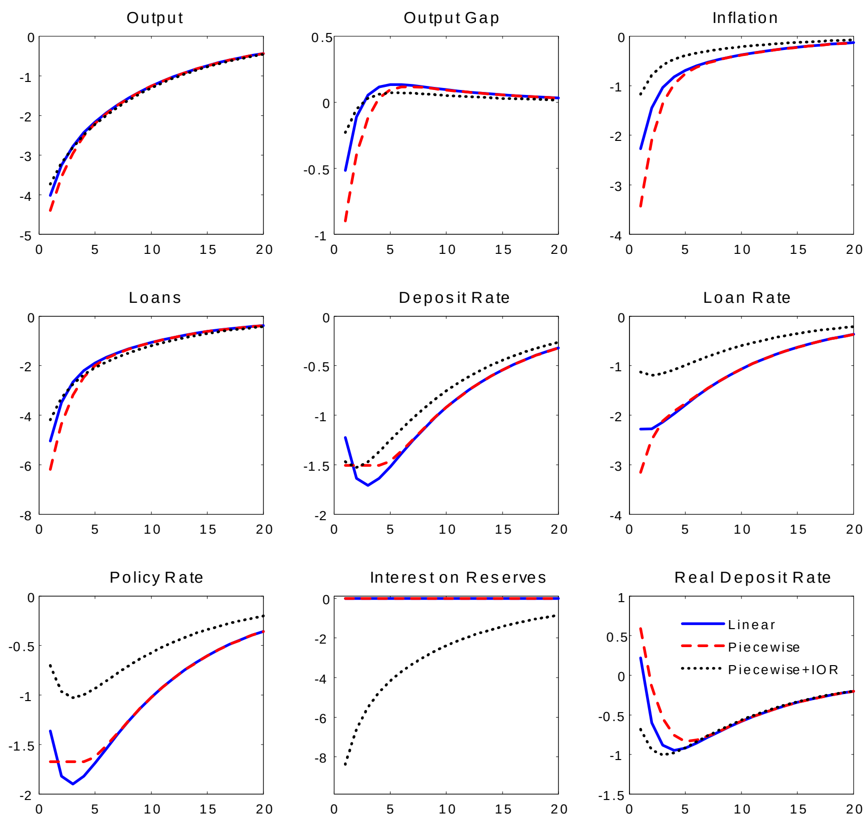
[37] We could potentially raise the size of the shock which would significantly increase the duration at the ZLB.

given our parameterization choices, our model attains the ZLB with a frequency of 7.40 percent, consistent with empirical evidence.

Figure 3 shows the response of key variables to a negative unexpected large preference shock that drags the economy into a liquidity trap. The figure compares between three different scenarios: i) Scenario I ('Linear') - a standard Taylor rule ($\phi_\pi = 2$ and $\phi = 0.7$) that disregards the ZLB; ii) Scenario II ('Piecewise') - a piecewise-linear solution where the policy rate (with $\phi_\pi = 2$ and $\phi = 0.7$) is struck by the ZLB; iii) Scenario III ('Piecewise+IOR') - a piecewise-linear solution where the ZLB is occasionally binding, the refinance rate follows a standard rule ($\phi_\pi = 2$ and $\phi = 0.7$), and the IOR rule is set to $r_s^\mu = 0.5$. This degree of response to credit deviations in the IOR rule is sufficient to illustrate our main policy implications highlighted below.

However, we choose the standard deviation and scale of the shock in order to prevent the loan rate from falling into negative territories. As explained earlier, the loan rate is procyclical with respect to the economic activity in the case of demand shocks. Therefore, a large(r) adverse preference shock drives the cost of borrowing to below zero (in net terms), which would make this *benchmark* exercise empirically irrelevant.

Figure 3 - Adverse Preference Shock - Liquidity Trap: High Taylor Rule Persistence



i) Figure 3 compares between Scenario I (linear model - 'Linear') to Scenario II (piecewise-linear model - 'Piecewise'), and Scenario III (piecewise-linear model with interest on reserves - 'Piecewise+IOR'). ii) Interest rates and inflation are measured in annualized percentage point deviations from steady state. The rest of the variables are measured in annualized percentage deviations.

As is evident from Figure 3, there is a striking difference in the behaviour of macro and financial variables implied by the piecewise-linear Scenario II compared to the linear Scenario I. The contraction in inflation, output gap, output, borrowing costs and loans is far more severe when the policy rate is constrained by the ZLB and is thus unable to adjust further in order to bring down the deposit rate. Because the demand channel of monetary policy dominates its cost channel mechanism, the central bank would find it welfare-enhancing to further lower the refinance rate despite the dis-inflationary effects linked with the monetary policy cost channel. However, as the central bank is unable to accommodate for the decline in the output gap and inflation using the policy rate alone, the real deposit rate increases, thereby generating a prolonged and exacerbated economic recession.

Under the piecewise-linear Scenario III, we find that the duration of the liquidity trap is minimized and can in fact be prevented with the implementation of an IOR policy instrument ($r_s^{\mu} = 0.5$). Intuitively, the rate on reserves renders the central bank an extra degree of freedom in seeking its primary objectives via the risk premium component of the credit cost channel (see also Section 3.2). Commitment to a lower IOR over the course of the shock encourages an expansion in the output gap and an incline in the loan rate, two mechanisms that contribute to the relative rise in prices. The moderated fall in inflation also averts the policy rate from tumbling into the ZLB, thereby inducing downward pressure on the real deposit rate and reinforcing the improvement in the economic activity. As the decline in inflation becomes less pronounced, and as the expected future output gap and inflation advance, the monetary policy rate needs not to follow a strict inflation targeting rule. In this way, IOR releases the policy rate (and the deposit rate) from the ZLB territory, and insulates the economy from the repercussions of a liquidity trap in the short run.

Table 4: Key standard deviations for different specifications, and welfare gains from IOR policy at the ZLB

	Linear	Piecewise-Linear	Piecewise-Linear with IOR
(ϕ_π= 2, $\phi = 0.7$)	$s.d\,(\widehat{\pi}_t) = 0.84$ $s.d(\widehat{x}_t) = 0.16$ $s.d(\widehat{L}_t) = 2.05$	$s.d\,(\widehat{\pi}_t) = 2.33$ $s.d(\widehat{x}_t) = 0.74$ $s.d(\widehat{L}_t) = 3.49$	$s.d\,(\widehat{\pi}_t) = 0.46$ $s.d(\widehat{x}_t) = 0.07$ $s.d(\widehat{L}_t) = 1.98$
Probability of hitting ZLB (percent)	–	7.40	2.30
Duration at the ZLB (periods)	–	4	0
Welfare Cost/Gain	–	-0.074	$+7.45 \times 10^{-3}$
(ϕ_π= 2, $\phi = 0.0$)	$s.d\,(\widehat{\pi}_t) = 0.95$ $s.d(\widehat{x}_t) = 0.16$ $s.d(\widehat{L}_t) = 1.52$	$s.d\,(\widehat{\pi}_t) = 5.46$ $s.d(\widehat{x}_t) = 1.82$ $s.d(\widehat{L}_t) = 6.40$	$s.d\,(\widehat{\pi}_t) = 0.58$ $s.d(\widehat{x}_t) = 0.09$ $s.d(\widehat{L}_t) = 1.80$
Probability of hitting ZLB (percent)	–	15.0	5.70
Duration at the ZLB (periods)	–	7	2
Welfare Cost/Gain	–	-0.452	$+8.38 \times 10^{-3}$
(ϕ_π= 10, $\phi = 0.7$)	$s.d\,(\widehat{\pi}_t) = 0.12$ $s.d(\widehat{x}_t) = 0.10$ $s.d(\widehat{L}_t) = 1.73$	$s.d\,(\widehat{\pi}_t) = 0.19$ $s.d(\widehat{x}_t) = 0.10$ $s.d(\widehat{L}_t) = 1.80$	$s.d\,(\widehat{\pi}_t) = 0.06$ $s.d(\widehat{x}_t) = 0.05$ $s.d(\widehat{L}_t) = 1.94$
Probability of hitting ZLB (percent)	–	4.20	0
Duration at the ZLB (periods)	–	0	0
Welfare Cost/Gain	–	-2.87×10^{-4}	$+2.35 \times 10^{-4}$
(ϕ_π= 10, $\phi = 0.0$)	$s.d\,(\widehat{\pi}_t) = 0.10$ $s.d(\widehat{x}_t) = 0.12$ $s.d(\widehat{L}_t) = 1.62$	$s.d\,(\widehat{\pi}_t) = 0.18$ $s.d(\widehat{x}_t) = 0.12$ $s.d(\widehat{L}_t) = 1.89$	$s.d\,(\widehat{\pi}_t) = 0.05$ $s.d(\widehat{x}_t) = 0.07$ $s.d(\widehat{L}_t) = 1.92$
Probability of hitting ZLB (percent)	–	5.30	0.60
Duration at the ZLB (periods)	–	1	0
Welfare Cost/Gain	–	-3.01×10^{-4}	$+2.38 \times 10^{-4}$

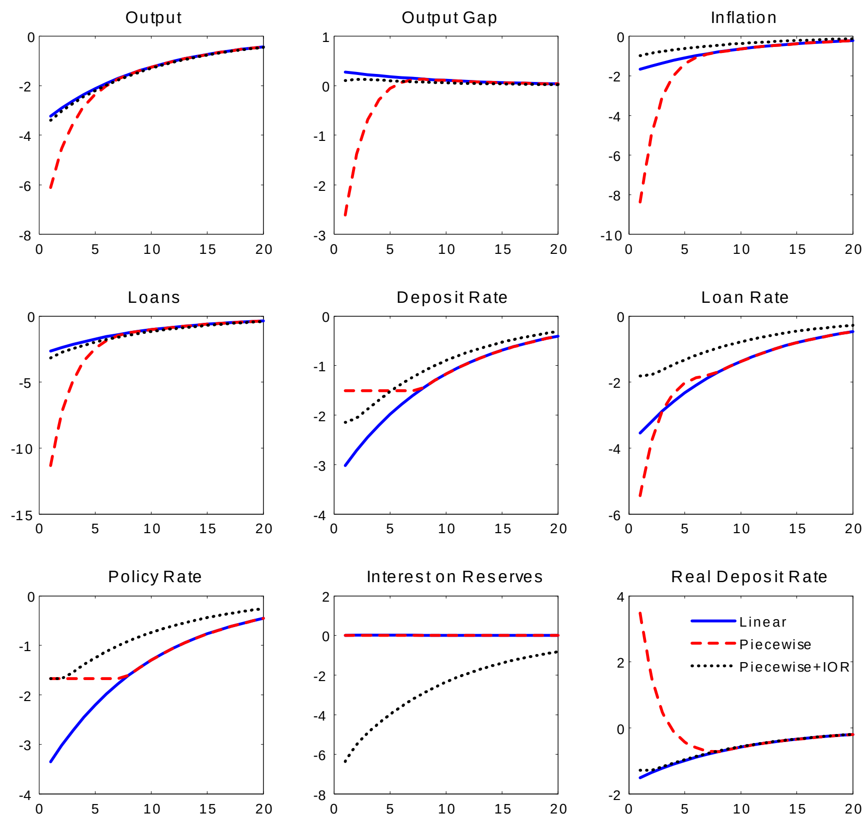
Notes: i) The standard deviations of key variables are represented in annualized rates.

ii) The welfare cost / gain is the percentage consumption equivalent, measured relative to the 'Linear' scenario.

The differences between the three various scenarios are further reflected in Table 4. This table shows the simulated standard deviations in key variables, the frequency at which the ZLB is hit (or the probability of attaining the ZLB), the duration of the ZLB upon the impact of the shock, and the relative welfare cost/gain of the piecewise-linear model without and with IOR policy compared to the linear case. Interestingly, increasing the weight on the IOR rule minimizes the spell in a liquidity trap, considerably reduces the standard deviations in key macro variables, and achieves a meaningful welfare benefit following a large adverse preference shock.

We also perform a sensitivity analysis in Table 4 and show that when the degree of the refinance rate intertia is lower than the benchmark ($\phi = 0.0$), then the liquidity trap lasts for longer (7 against 4 periods), while the ZLB hits more frequently (15 against 7.4 percent). With the imposition of the ZLB, less smoothing in the policy rate implies a more substantial drop in inflation, giving rise to an amplified increase in the real deposit rate and a more acute economic downturn. These outcomes extend the length of a liquidity trap, make the policy rate hit the ZLB more frequently, and amplify the standard deviations in key variables. The impact of an IOR policy rule, nonetheless, is similar to the benchmark case (with $\phi = 0.7$), and limits the time span of a liquidity trap upon the impact of the shock, yet does not completely eliminate it due to the severity of the recession. In this regime, and for the same reasons explained above, we find that increasing the weight of $r_s^{\mu} > 0.5$ lifts the policy rate out of the ZLB at an earlier period, mitigates the probability of a descend towards a liquidity trap, and promotes even higher welfare gains. Figure 4 depicts the three different scenarios, as defined above, but with the persistence parameter in the policy rule set to zero.

Figure 4 - Adverse Preference Shock - Liquidity Trap: Low Taylor Rule Persistence



i) Figure 4 compares between Scenario I (linear model - 'Linear') to Scenario II (piecewise-linear model - 'Piecewise'), and Scenario III (piecewise-linear model with interest on reserves - 'Piecewise+IOR'). ii) Interest rates and inflation are measured in annualized percentage point deviations from steady state. The rest of the variables are measured in annualized percentage deviations.

Finally, we also examine the effect of an IOR policy when the central bank follows an aggressive inflation targeting rule ($\phi_\pi = 10$). In this case, we find that a hawkish monetary policy rule can reduce the probability of striking the ZLB, confirming the results of Adam and Billi (2007). However, even here we find that varying the rate on reserves adds further welfare gains to merely applying a standard monetary policy rule.[38] This result also prevails when the degree of persistence

[38] We also confirm that adding a response to output and/or loans in the standard Taylor rule following large adverse

in the Taylor rule is zero. Our model therefore supports the implementation of a negative IOR in a liquidity trap (as currently practiced by the ECB), and also the use of IOR in more normal times depending on the nature of the shock.[39]

7 Concluding Remarks

By employing a standard New Keynesian model modified for a credit cost channel, endogenous financial risk, a fractional-reserve banking sector and the ZLB, we shed new insights on the welfare implications and stabilization properties of IOR. We show that varying IOR according to the state of the business and financial cycles has meaningful effects on the behaviour of macroeconomic and financial variables in normal times as well as in liquidity traps. In normal times, altering IOR also modifies the optimal conduct of inflation-targeting monetary policy rules in response to both financial and demand shocks. Following sizeable negative demand shocks, IOR can largely insulate the economy from the adverse repercussions of the ZLB. Indeed, the distinctive risk premium channel highlighted in our model presents an additional motivation for applying an IOR facility by affording the central bank an extra degree of freedom to pursue its primary mandates.

This paper also advances an alternative answer to the highly topical question: how can a liquidity trap be avoided, and which policies can help to achieve this goal? Blanchard, Dell'Ariccia and Mauro (2010) propose increasing the inflation target. Nakov (2008) suggests to change the monetary policy strategy such that in times of low (high) inflation the central bank promises to raise (lower) inflation to its target level. Finally, Adam and Billi (2007) put forward the idea to increase the aggressiveness of monetary policy in order to reduce the probability of hitting the ZLB. Contributing to this literature, we advocate for routinely adjusting interest on reserves based on a simple rule that reacts to financial market conditions, just like a standard Taylor rule normally responds to variations in inflation and output. The policy implications derived from our simple model are fairly consistent with the policy actions undertaken by central banks in advanced economies since the onset of the financial crisis and the Great Recession.

Clearly, given the gradual implementation of the Basel III regulatory accords, it is imperative

demand shocks can prevent the policy rate from hitting the ZLB. However, *once* the policy rate is struck by the ZLB and is *unable* to further adjust, the IOR becomes an important tool that can effectively release the economy from a liquidity trap.

[39] This is in contrast to Ireland (2014), who finds only a limited role for adjusting IOR during normal times.

to understand the coordination between unconventional monetary policy and macroprudential regulation, and to identify from a *normative* perspective the market failures that each type of policy may solve. We leave this interesting open topic for future research.

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