

CAMP Working Paper Series  
No 9/2019

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Andrew Binning, Hilde C. Bjørnland and Junior Maih



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# Is Monetary Policy Always Effective? Incomplete Interest Rate Pass-through in a DSGE Model\*

Andrew Binning<sup>†</sup>     Hilde C. Bjørnland<sup>‡</sup>     Junior Maih<sup>§</sup>

November 22, 2019

## Abstract

We estimate a regime-switching DSGE model with a banking sector to explain incomplete and asymmetric interest rate pass-through, especially in the presence of a binding zero lower bound (ZLB) constraint. The model is estimated using Bayesian techniques on US data between 1985 and 2016. The framework allows us to explain the time-varying interest rate spreads and pass-through observed in the data. We find that pass-through tends to be delayed in the short run, and incomplete in the long run. All this impacts the dynamics of the other macroeconomic variables in the model. In particular, we find monetary policy to be less effective under incomplete pass-through. Furthermore, the behavior of pass-through in the loan rate is different from that of the deposit rate shocks. This creates asymmetric dynamics at the zero lower bound, and incomplete pass-through exacerbates that asymmetry.

**JEL-codes:** C68, E52, F41

**Keywords:** Banking sector, incomplete or asymmetric interest rate pass-through, DSGE

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\*This Working Paper should not be reported as representing the views of Norges Bank or the New Zealand Treasury. The views expressed are those of the authors and do not necessarily reflect those of Norges Bank or the New Zealand Treasury. We thank participants at seminars in Norges Bank and BI Norwegian Business School, and participants at the EABCN Conference on "Time-varying Models for Monetary Policy and Financial Stability" at EUI, Florence, and the 27th SNDE Symposium in the Federal Reserve Bank of Dallas for constructive comments and fruitful discussions. This work is part of the research activities at the Centre for Applied Macroeconomics and Commodity Prices (CAMP) at the BI Norwegian Business School.

<sup>†</sup>The New Zealand Treasury. Email: [andrew.binning@treasury.govt.nz](mailto:andrew.binning@treasury.govt.nz)

<sup>‡</sup>BI Norwegian Business School and Norges Bank. Email: [hilde.c.bjornland@bi.no](mailto:hilde.c.bjornland@bi.no)

<sup>§</sup>Norges Bank and BI Norwegian Business School. Email: [Junior.Maih@norges-bank.no](mailto:Junior.Maih@norges-bank.no)

# 1 Introduction

Understanding the transmission mechanism is vitally important for gaining insight into how monetary policy affects the macroeconomy. A key link in this chain is the translation of central bank policy rates into the market interest rates faced by borrowers and savers. Delayed and incomplete interest rate pass-through is a “bottleneck” that reduces the impact/effectiveness of monetary policy on the rest of the economy. The problem is of particular interest when the economy is operating in the vicinity of the zero lower bound (ZLB) and there are questions of how much and how fast interest rate cuts will be passed on. In this paper we investigate interest rate pass-through through the lens of a DSGE model with a banking sector and an occasionally binding ZLB constraint.

Interest rate pass-through has been studied in econometric time series models (see for instance [de Bondt \(2005\)](#), and [Kok and Werner \(2006\)](#) for single equation ECM/ARDL models, [Frisancho-Mariscal and Howells \(2010\)](#), and [Akosah \(2015\)](#) for VECM models, [Sander and Kleimeier \(2004\)](#) for VAR model, and [Fry-McKibbin and Zheng \(2016\)](#), [de Haan and Poghosyan \(2007\)](#), and [Apergis and Cooray \(2015\)](#) for various non-linear econometric time series models). While these contributions are important, they abstract from critical issues that would affect the measure of pass through itself. Those issues pertain, for instance, to the endogeneity of the policy rate, which is usually assumed exogenous in the measure of interest rate pass through. That endogeneity naturally calls for the measurement of pass-through in a structural framework. This is why more than acknowledging the endogeneity of the policy rate, this paper proceeds to estimating pass-through in a Dynamic Stochastic General Equilibrium (DSGE) model.

Little work has been done to seriously address the issue of interest rate pass-through in DSGE models. The typical route taken by DSGE modelers, like [Beneš and Lees \(2010\)](#) and [Gerali et al. \(2010\)](#), has been merely to match market interest rates by including various frictions in the interest rate setting process, but without investigating the implications of incomplete interest rate pass-through for policy and for the dynamics of macroeconomic variables. The present study aims to fill that gap.

Our goal is to quantify incomplete pass-through, try to better understand some of the factors that affect interest rate pass-through and investigate its implications for the effectiveness of monetary policy in normal times but also at the zero lower bound. To this end we embed the banking structure introduced by [Gerali et al. \(2010\)](#) into a simple

regime-switching DSGE model, which we estimate using Bayesian techniques on US data between 1985 and 2016. Our focus on structural DSGE models allows us to highlight the economic channels through which shocks affect the economy, which is important in assessing the transmission from interest rates to the economy. In particular, with such a strategy we will be able to analyze the consequences of incomplete interest rate pass-through for the economy and policy for a wide array of specific shocks.

The regime-switching strategy embedded in the approach adds further benefits. The model we study allows for multiple steady states. In particular, we account for the zero lower bound on interest rates through a separate zero lower bound-monetary policy regime. Hence, in contrast to standard DSGE/multivariate models, in which asymmetry, time variation and non-linearities are killed by linearization, our modeling approach allows us to investigate (i) how policy rates affect market rates, especially in the vicinity of the lower bound; (ii) the impact of delayed and incomplete pass-through on the macroeconomy and for policy, and finally, (iii) the cost of incomplete interest rate pass-through.

Having moved away from the problematic measure of rate pass-through used in simple econometric models, we need to redefine a measure of pass-through. A further contribution of this paper is to propose two new measures of pass-through in a multivariate system. Our measures reflect the endogenous determination of both the policy and market interest rates and the variety of shocks that can affect the policy interest rate.<sup>1</sup> Our first method measures pass-through using the impulse responses to all the structural shocks from a multivariate model. As a consequence the degree of pass-through will depend on the shock hitting the economy. Similar methods have been suggested by [Shambaugh \(2008\)](#) and [Rincón-Castro and Rodríguez-Niño \(2016\)](#) to investigate exchange rate pass-through in multivariate models. Our second method involves simulating artificial data from the multivariate model, then estimating univariate measures of pass-through on the simulated data. Using this approach we treat the model as a laboratory and test how different assumptions affect the degree of pass-through. Moreover, we can calculate an aggregate measure of pass-through using this method, something we cannot easily obtain using our first measure.

Putting all those elements together, we are able to explain the time-varying interest

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<sup>1</sup>Note that while our measures of pass-through are implemented in the context of a DSGE model, they can easily be applied to other multivariate models like VAR models for example, and used to measure exchange rate pass-through as well.

rate spreads and pass-through observed in the data. In particular, we find evidence that pass-through tends to be delayed in the short run and incomplete in the long run. The magnitude of pass-through also depends on the shocks that hit the economy: for some shocks pass-through is fast but for some others pass-through is slow. For both the deposit and loan rates, the lowest pass-through is observed for the cost-push shocks. Furthermore, we find that retail banks tend to adjust their markups to absorb some of the shocks. Finally, the behavior of pass-through in the loan rate is different from that of the deposit rate shocks. This creates asymmetric dynamics at the zero lower bound, and incomplete pass-through exacerbates that asymmetry.

The remainder of the paper is structured as follows. Section 2 describes a DSGE model with a banking sector, while Section 3 defines two ways to measure interest rate pass-through. Section 4 discusses estimation and parameterization, while we present the main results in Section 5. We conclude in Section 6.

## 2 A model with banking

We develop a simple DSGE model with a banking sector. The need for a banking sector arises through a loan-in-advance constraint on intermediate goods producers. More specifically intermediate goods producers are required to finance a portion of their investment goods purchases through a one-period loan. Our representation of the banking sector is simple, avoiding the introduction of multiple types of agents as required by the [Bernanke et al. \(1999\)](#), and [Iacoviello \(2005\)](#) frameworks. As a consequence we can focus on the complex mechanisms involved in interest rate setting in the banking sector and interest rate pass-through. However, it also means the model does not have a financial accelerator, which will likely affect interest rate pass-through. The setup of the rest of the model - i.e. households, firms and the government sector - is standard. For this reason we only focus on the banking sector and monetary policy in this section, and their relationship to regime switching. A full derivation of the model can be found in [Appendix A](#).

### 2.1 An Overview of the States

We assume the model economy's dynamics are conditional on four discrete states of nature. At any given time the model economy can be in one of two monetary policy states and

one of two markup Markov processes. This is reflected by introducing separate Markov chains for the monetary policy and markup states. The monetary policy state determines whether policy is set according to a Taylor-type rule which occurs in the normal state ( $N$ ), or the economy is at the zero lower bound state ( $Z$ ) where policy follows an exogenous process, so that  $s_{1,t} = N, Z$ . The monetary policy state also affects the markups and markdowns charged by retail banks and the degree of rigidity they face when adjusting market interest rates. The markup Markov process determines whether markups and markdowns on market interest rates are high ( $H$ ) or low ( $L$ ) and the degree of rigidity in adjusting market interest rates, when the economy is away from the lower bound, so that  $s_{2,t} = H, L$ . We introduce two regime-switching parameters,  $\mathbf{z}(s_{1,t})$  which identifies the monetary policy regime and  $\mathbf{m}(s_{2,t})$  which identifies the markup regime. We assume

$$\mathbf{z}(Z) = 1 \text{ and } \mathbf{z}(N) = 0, \quad (1)$$

with the states  $Z$  and  $N$  are governed by the following Markov transition matrix

$$\mathbb{Q}_Z = \begin{bmatrix} 1 - p_{N,Z} & p_{N,Z} \\ p_{Z,N} & 1 - p_{Z,N} \end{bmatrix}, \quad (2)$$

where  $p_{N,Z}$  is the probability of moving from state  $N$  to state  $Z$ ,  $1 - p_{N,Z}$  is the probability of remaining in state  $N$ , equally,  $p_{Z,N}$  is the probability of moving from state  $Z$  to state  $N$ , and  $1 - p_{Z,N}$  is the probability of remaining in state  $Z$ . We assume the regime-specific markup parameter takes the values

$$\mathbf{m}(H) = 1 \text{ and } \mathbf{m}(L) = 0. \quad (3)$$

The states  $H$  and  $L$  are governed by the Markov transition matrix

$$\mathbb{Q}_m = \begin{bmatrix} 1 - q_{H,L} & q_{H,L} \\ q_{L,H} & 1 - q_{L,H} \end{bmatrix}. \quad (4)$$

where  $q_{H,L}$  is the probability of moving from state  $H$  to state  $L$ ,  $1 - q_{H,L}$  is the probability of remaining in state  $H$ , equally,  $q_{L,H}$  is the probability of moving from state  $L$  to state  $H$ , and  $1 - q_{L,H}$  is the probability of remaining in state  $L$ .

## 2.2 The Banking Sector

Following [Gerali et al. \(2010\)](#), the banking sector is divided into two types of banks, wholesale banks and retail banks. Wholesale banks collect deposits from retail banks, and

produce loans using deposits and bank equity, which they in turn supply to retail banks. The exact setup for this sector can be found in Appendix A. The retail banking sector is comprised of loan-making and deposit-taking branches. As a means of representing retail loan and deposit rates as a markup and markdown, respectively, over policy rates, [Gerali et al. \(2010\)](#) treat intermediate loans and deposits issued by retail banks as differentiated. As a consequence of this assumption, there is a continuum of loan-making and deposit-taking banks, normalized to unit mass, each producing a differentiated loan or deposit. We let  $z$  index retail banks.

The  $z$ th loan-making bank sets the interest rate on loans to maximize the sum of the expected present value of its profits, subject to a quadratic cost of changing interest rates. This can be represented by

$$\Psi_{L,0}(z) = E_t \left\{ \sum_{t=0}^{\infty} \mathcal{M}_{0,t}^* \left( \frac{P_0}{P_t} \right) \left[ R_{L,t}(z)L_t(z) - \exp(\varepsilon_{L,t}) \mathbb{R}_{L,t}L_t(z) - \dots \right] \right. \\ \left. \dots - \frac{\phi_L(r_t)}{2} R_{L,t}L_t \left[ \frac{R_{L,t}(z)}{R_{L,t-1}(z)} - 1 \right]^2 \right\}, \quad (5)$$

where  $\mathcal{M}_{t,t+1}^*$  is the real stochastic discount factor,  $P_t$  is the price level,  $R_{L,t}(z)$  is the interest rate charged for loans issued by the  $z$ th bank,  $L_t(z)$  is loans issued by the  $z$ th bank,  $\varepsilon_{L,t}$  is a markup shock,  $R_{L,t}$  is the aggregate interest rate on loans,  $L_t$  is aggregate loans and  $\mathbb{R}_{L,t}$  the wholesale interest rate charged on loans. Note that the degree of rigidity  $\phi_L(r_t)$  is a function of the regime. The  $z$ th loan-making bank chooses the interest rate on loans to maximize profits. Assuming a symmetric equilibrium leads to the following behavioral rule for the aggregate loan interest rate

$$\left( \frac{v_L(r_t)}{v_L(r_t) - 1} \right) \exp(\varepsilon_{L,t}) \frac{\mathbb{R}_{L,t}}{R_{L,t}} - 1 - \tilde{\phi}_L(r_t) \frac{R_{L,t}}{R_{L,t-1}} \left[ \frac{R_{L,t}}{R_{L,t-1}} - 1 \right] + \dots \\ \dots + E_t \left\{ \tilde{\phi}_L(r_{t+1}) \mathcal{M}_{t,t+1}^* \left( \frac{1}{\pi_{t+1}} \right) \left( \frac{R_{L,t+1}}{R_{L,t}} \right)^2 \frac{L_{t+1}}{L_t} \left[ \frac{R_{L,t+1}}{R_{L,t}} - 1 \right] \right\} = 0. \quad (6)$$

This resembles a New Keynesian Phillips curve for the interest rate on loans where the marginal cost term is the interest rate charged on loans by the wholesale bank. The reduced form persistence parameter,  $\tilde{\phi}_L(r_t) \equiv \frac{\phi_L(r_t)}{v_L(r_t) - 1}$ , and elasticity of substitution between differentiated loans,  $v_L(r_t)$ , are functions of the regime. We make this relationship more explicit by assuming

$$\tilde{\phi}_L(r_t) = \mathbf{z}(s_{1,t}) \tilde{\phi}_{Z,L} + (1 - \mathbf{z}(s_{1,t})) (\mathbf{m}(s_{2,t}) \tilde{\phi}_{H,L} + (1 - \mathbf{m}(s_{2,t})) \tilde{\phi}_{L,L}). \quad (7)$$

The loan mark-up is determined according to

$$\mu_L(r_t) = \mathbf{z}(s_{1,t})\mu_{Z,L} + (1 - \mathbf{z}(s_{1,t}))(\mathbf{m}(s_{2,t})\mu_{H,L} + (1 - \mathbf{m}(s_{2,t}))\mu_{L,L}), \quad (8)$$

where the elasticity of substitution between differentiated loans is related to the markup through

$$v_L(r_t) = \frac{\mu_L(r_t)}{\mu_L(r_t) - 1}. \quad (9)$$

The  $z$ th deposit-taking bank sets interest rates to maximize its expected discounted future stream of profits, subject to a quadratic adjustment cost on changing interest rates so that

$$\Psi_{D,0}(z) = E_t \left\{ \sum_{t=0}^{\infty} \mathcal{M}_{t,t+1}^* \left( \frac{P_0}{P_t} \right) \left[ \begin{array}{l} \exp(\varepsilon_{D,t}) \mathbb{R}_{D,t} D_t(z) - R_{D,t}(z) D_t(z) - \dots \\ \dots - \frac{\phi_D(r_t)}{2} R_{D,t} D_t \left[ \frac{R_{D,t}(z)}{R_{D,t-1}(z)} - 1 \right]^2 \end{array} \right] \right\}, \quad (10)$$

where  $R_{D,t}(z)$  is the deposit interest rate for loans issued by the  $z$ th bank,  $D_t(z)$  is deposits issued by the  $z$ th bank,  $\varepsilon_{D,t}$  is a markup shock,  $R_{D,t}$  is the aggregate deposit interest rate,  $D_t$  is aggregate deposits and  $\mathbb{R}_{D,t}$  the wholesale interest rate charged on deposits. As was the case for loan-making banks,  $\phi_D(r_t)$  is a function of the regime. The  $z$ th deposit-taking bank chooses deposit interest rates to maximize their lifetime profits. Assuming a symmetric equilibrium leads to the following behavioral rule for aggregate deposit interest rates

$$1 - \left( \frac{v_D(r_t)}{v_D(r_t) - 1} \right) \exp(\varepsilon_{D,t}) \frac{\mathbb{R}_{D,t}}{R_{D,t}} - \tilde{\phi}_D(r_t) \frac{R_{D,t}}{R_{D,t-1}} \left[ \frac{R_{D,t}}{R_{D,t-1}} - 1 \right] + \dots \\ \dots + E_t \left\{ \tilde{\phi}_D(r_{t+1}) \mathcal{M}_{t,t+1}^* \left( \frac{1}{\pi_{t+1}} \right) \left( \frac{R_{D,t+1}}{R_{D,t}} \right)^2 \frac{D_{t+1}}{D_t} \left[ \frac{R_{D,t+1}}{R_{D,t}} - 1 \right] \right\} = 0. \quad (11)$$

Just as was the case for loan-making banks, the reduced form rigidity parameter,  $\tilde{\phi}_D(r_t) \equiv \frac{\phi_D(r_t)}{v_D(r_t) - 1}$ , and the elasticity of substitution between differentiated deposits,  $v_D(r_t)$ , are functions of the regime. Furthermore we assume that

$$\tilde{\phi}_D(r_t) = \mathbf{z}(s_{1,t})\tilde{\phi}_{Z,D} + (1 - \mathbf{z}(s_{1,t}))(\mathbf{m}(s_{2,t})\tilde{\phi}_{H,D} + (1 - \mathbf{m}(s_{2,t}))\tilde{\phi}_{L,D}), \quad (12)$$

and the markdown on deposits is determined by

$$\mu_D(r_t) = \mathbf{z}(s_{1,t})\mu_{Z,D} + (1 - \mathbf{z}(s_{1,t}))(\mathbf{m}(s_{2,t})\mu_{H,D} + (1 - \mathbf{m}(s_{2,t}))\mu_{L,D}), \quad (13)$$

where the markdown is related to the elasticity of substitution through

$$v_D(r_t) = \frac{\mu_D(r_t)}{\mu_D(r_t) - 1}. \quad (14)$$



## 2.3 Monetary Policy

The monetary authority sets interest rates  $R_t$  according to

$$R_t = \max(R_{ZLB,t}, R_t^*), \quad (15)$$

where  $R_t^*$  is the interest rate set during normal times, which is determined according to a Taylor-type rule

$$R_t^* = R_{t-1}^{*\rho_R} \left( R^* \left( \frac{\pi_t}{\pi} \right)^{\kappa_\pi} \left( \hat{Y}_t \right)^{\kappa_Y} \right)^{1-\rho_R} \exp(\varepsilon_{R,t}), \quad (16)$$

where  $\hat{Y}_t$  is the output gap.  $R_{ZLB,t}$  is the interest rate set when the economy is at the zero lower bound, which we assume evolves according to the exogenous process

$$R_{ZLB,t} = \mathbf{K} + \varepsilon_{ZLB,t}. \quad (17)$$

$\mathbf{K}$  is a parameter set equal to the effective lower bound and  $\varepsilon_{ZLB,t}$  is a small shock added to avoid a stochastic singularity. In order to model the lower bound constraint on interest rates using regime-switching, we follow [Binning and Maih \(2016\)](#) and replace equation (15) with

$$R_t = \mathbf{z}(s_{1,t})R_{ZLB,t} + (1 - \mathbf{z}(s_{1,t}))R_t^*. \quad (18)$$

## 3 Measuring Pass Through

Measuring interest rate pass-through in single linear equation models is a trivial exercise. In such models the policy interest rate is assumed to be exogenous and long-run interest rate pass-through can be determined by inspecting the estimated coefficients of the model. In multivariate models, however, the task is more complicated, as both the policy interest rate and the market interest rate are usually assumed to be endogenous. A simple approach to measuring pass-through could involve shocking the system with a monetary policy shock and then calculating interest rate pass-through from the resulting impulse response function. While this is a useful exercise in itself, it does not reflect the data generating process as there are a multitude of shocks that can affect the variables in the system.<sup>2</sup>

In this paper we propose two general methods of measuring interest rate pass-through in multivariate models. Our measures reflect the endogenous determination of both the

<sup>2</sup>This is a point that has been made by [Shambaugh \(2008\)](#) and [Rincón-Castro and Rodríguez-Niño \(2016\)](#) in the context of measuring exchange rate pass-through.

policy and market interest rates and the variety of shocks that can affect the policy interest rate. The nature of multivariate models means that we do not assign a causal interpretation to our measures of pass-through, but instead treat pass-through as a correlation. We investigate our measures of pass-through using a DSGE model, but we note they can easily be applied to other multivariate models like VAR models for example, and used to measure exchange rate pass-through as well.

Our first method measures pass-through using the impulse responses to all the structural shocks from a multivariate model. As a consequence the degree of pass-through will depend on the shock hitting the economy.<sup>3</sup> Similar methods have been suggested by [Shambaugh \(2008\)](#) and [Rincón-Castro and Rodríguez-Niño \(2016\)](#) to investigate exchange rate pass-through in multivariate models.

Our second method involves simulating artificial data from the multivariate model, and then estimating univariate measures of pass-through on the simulated data. Using this approach we treat the model as a laboratory and test how different assumptions affect the degree of pass-through. Moreover, we can calculate an aggregate measure of pass-through using this method, something we cannot easily obtain using our first measure. We describe these measures in more detail below.

### 3.1 An IRF Based Measure

Our first method measures pass-through using the impulse responses to all the structural shocks from a multivariate model. As a consequence, the degree of pass-through will depend on the shock hitting the economy. As discussed above, exchange rate pass-through has been investigated by [Shambaugh \(2008\)](#) and [Rincón-Castro and Rodríguez-Niño \(2016\)](#) in multivariate models. They recognize that the correlation between the exchange rate and the price of imported goods is a function of not only the parameters of the model, but also the types of shocks hitting the economy. Moreover it is not useful to treat all movements in the exchange rate as exogenous, especially in a multivariate setting where the exchange rate can respond to a number of different shocks and variables. Instead they look at exchange rate pass-through using the impulse responses for a number of different structural shocks.

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<sup>3</sup>In non-linear models, the size and sign of the shock could have an impact on the degree of interest rate pass-through.

We adopt a similar approach to [Shambaugh \(2008\)](#) and [Rincón-Castro and Rodríguez-Niño \(2016\)](#) when measuring interest rate pass-through, and evaluate it for a set of structural shocks using the impulse responses from the model. Our measure of pass-through  $\tau$  periods after the shock is given by

$$PT_{M,\tau}(\pm\varepsilon_{j,t}) = \frac{\sum_{t=0}^{\tau} |\hat{R}_{M,t}(\pm\varepsilon_{j,0})|}{\sum_{t=0}^{\tau} |\hat{R}_t(\pm\varepsilon_{j,0})|} \quad (19)$$

where  $M = D, L$

and where  $\hat{R}_{M,t}(\pm\varepsilon_{j,t})$  is the impulse response for the market interest rate  $t$  periods after the  $j$ th shock has hit the economy.  $\hat{R}_t(\pm\varepsilon_{j,t})$  is the impulse response for the policy interest rate  $t$  periods after the  $j$ th shock has hit the economy. Our IRF-based measure of interest pass-through uses the absolute value of the impulse response functions as secondary cycles in the impulse response function could switch sign. We also allow for differences in pass-through depending on the sign of the shock. This is important if the model exhibits asymmetric impulse response functions.

### 3.2 Reduced Form Measures

Our second approach involves simulating artificial data from the DSGE model, treating the policy interest rate as exogenous, and then estimating an autoregressive distributed lag (ARDL) model on the simulated data. The ARDL model is chosen because the data are stationary and it is a reasonably common model for estimating interest rate pass-through in the literature. Our ARDL models of the market rate are estimated on 10 lags of the market rate, the contemporaneous policy rate, and 10 lags of the policy rate.<sup>4</sup> The ARDL model we estimate takes the general form

$$\Delta R_{M,t}(\mathbf{M}, \theta) = \sum_{i=1}^p \alpha_{M,i} \Delta R_{M,t-i}(\mathbf{M}, \theta) + \sum_{j=0}^p \alpha_{R,j} \Delta R_{t-i}(\mathbf{M}, \theta) + u_t \quad (20)$$

where  $\mathbf{M}$  refers to the the data being generated by a structural model, and  $\theta$  represents the parameter vector used to generate the data in the structural model.

<sup>4</sup>Note: because the model is non-linear and potentially asymmetric we could estimate nonlinear (threshold) ARDL models, but we do not do so here, in the interest of simplicity.

Our reduced form single equation measure of pass-through is useful because we can calculate an overall measure of interest rate pass-through. We can also produce a counterfactual measure of interest pass-through by changing the parameterization of the DSGE model, to better understand the factors that affect interest rate pass-through.

## 4 Model Solution and Parametrization

We solve our models using a perturbation method for regime switching rational expectations models. The model will then be estimated on US data using Bayesian methods, as described in the sections below.

### 4.1 Model solution

The equilibrium conditions of the model form a nonlinear system of regime-switching rational expectation equations that can be summarized as

$$E_t \sum_{r_{t+1}=1}^h p_{r_t, r_{t+1}} f(x_{t+1}(r_{t+1}), x_t(r_t), x_{t-1}, \varepsilon_t, \theta_{r_t}) = 0$$

where  $E_t$  is the expectations operator,  $f(\cdot)$  is a system of nonlinear functions representing the equilibrium conditions,  $x_t$  is the vector of endogenous variables,  $r_t = 1, 2, \dots, h$  and  $r_{t+1} = 1, 2, \dots, h$  denote the regimes in periods  $t$  and  $t + 1$  with  $h$  being the maximum number of regimes,  $\varepsilon_t \sim N(0, I)$  is the vector of stochastic shocks,  $\theta_{r_t}$  is the vector collecting all the parameters of the model in regime  $r_t$ ,  $p_{r_t, r_{t+1}}$ , an entry of the transition matrix  $Q_t$ , is the probability of going from regime  $r_t$  in the current period to regime  $r_{t+1}$  in the next period.

In our model,  $h$  such systems have to be simultaneously solved for generic minimum-state-variable (MSV) policy functions of the form

$$x_t(r_t) = T_{r_t}(x_{t-1}, \varepsilon_t)$$

These policy functions are regime specific but take into account the behavior of the economic system in all other regimes.

Unfortunately, in general, there is no analytical solution to the problem at hand, which would enable us to find the exact functions  $T_{r_t}(\cdot)$  that solve the problem. The best we can do, therefore, is to find a suitable approximation. Several authors in the

literature have attacked this type of problems using projection methods, a technique that proceeds by discretizing the space of the endogenous and exogenous state variables: [Davig \(2004\)](#), [Davig and Leeper \(2007, 2008\)](#), [Bi and Traum \(2012, 2014\)](#), [Davig et al. \(2010, 2011\)](#), [Richter et al. \(2014\)](#). Projection methods, unfortunately, suffer from the curse of dimensionality and would be essentially infeasible in the current context where the number of state variables is significant.

Another strand of the literature addresses this type of problems by adding regime switching to a linear or linearized constant-parameter system. Examples include [Svensson and Williams \(2007\)](#), [Farmer et al. \(2011\)](#), [Bianchi \(2013\)](#), [Cho \(2016\)](#), [Bianchi and Ilut \(2017\)](#), [Bianchi and Melosi \(2017\)](#). Relative to projection methods, a key advantage of this approach is that the resulting conditionally linear rational expectations system can be easily solved (exactly) and can handle large systems. One disadvantage is that economic agents are not aware of the switching process prior to linearization. In other words, the resulting policy functions, in general, are inconsistent with an original problem in which economic agents make decisions taking into account the additional uncertainty brought about by the fact that the regime prevailing next period is unknown in the current one. Another drawback of this approach is that it forces a unique steady state to the system, which is not appropriate for a model like ours in which the zero lower bound is treated as a separate steady state.

A solution approach that addresses the drawbacks listed above and in particular neatly embeds the switching mechanism is called perturbation. Several perturbation algorithms designed to solve regime-switching rational expectations can be found in the literature. The algorithm by [Foerster et al. \(2016\)](#) imposes a unique steady state, which is not suitable for our purpose, while the one by [Barthelemy and Marx \(2017\)](#) is not implemented in RISE, the toolbox we use for our computations. The perturbation algorithm we use is [Maih \(2015\)](#), which allows the possibility of multiple steady states and endogenous transition probabilities. See [Maih \(2015\)](#) and [Maih and Waggoner \(2018\)](#)<sup>5</sup>. The approximated policy function takes the form

$$x_t(r_t) \approx x(r_t) + T_{r_t,z}(z_t - z(r_t)) + \frac{1}{2!}T_{r_t,zz}(z_t - z(r_t))^{\otimes 2} + \dots + \frac{1}{p!}T_{r_t,z^{(p)}}(z_t - z(r_t))^{\otimes p}$$

---

<sup>5</sup>The perturbation algorithms of [Maih \(2015\)](#), [Foerster et al. \(2016\)](#) and [Maih and Waggoner \(2018\)](#) are all implemented in the RISE toolbox. See also [Bjørnland et al. \(2018\)](#) for the use of the RISE toolbox in a different application.

where  $z_t \equiv [x'_{t-1}, \sigma, \varepsilon'_t]'$  is the vector of state variables and  $\sigma$  the perturbation parameter.

## 4.2 Model parameterization: Taking the model to the data

Taking the model to the data requires combining the policy function with a measurement equation relating observable variables  $y_t$  to unobservable variables  $x_t$ . Such a measurement equation can be expressed as

$$y_t = m_{r_t}(x_t, \eta_t)$$

where  $\eta_t$  is a vector of measurement errors.

We let vector  $y_t$  comprise US data on per capita GDP growth ( $\Delta \log Y_t$ ), per capita consumption growth ( $\Delta \log C_t$ ), per capita investment growth ( $\Delta \log I_t$ ), price inflation ( $\pi_t$ ), wage inflation ( $\pi_{W,t}$ ), the fed funds rate ( $R_t$ ), the loan interest rate ( $R_{L,t}$ ) and the deposit interest rate ( $R_{D,t}$ ). The model is stochastically detrended and so there is no pre-filtering of the data. Hence, variables are included in levels and growth rates.

The combination of the policy functions and the measurement equations form the regime-switching state-space model, which is used to compute the likelihood function. We apply a modification of the [Kim and Nelson \(1999\)](#) filter to this state-space form to compute the (approximate) likelihood of the data given a parameter vector  $\theta$ , which includes both the structural model parameters and the parameters pertaining to the transition matrix<sup>6</sup>.

The likelihood is then combined with a prior distribution on the parameters to form the posterior kernel, which we maximize to find the mode of the posterior distribution. Then we take a sample of 200,000 draws from the posterior distribution using a standard Markov Chain Monte Carlo (MCMC) technique, namely the Metropolis-Hastings algorithm. All the computations carried out using the RISE toolbox.

The estimation sample runs from 1985Q1 to 2016Q3 and includes the Great Moderation, the financial crisis and the ZLB period. We choose this period because the loan rate does not go back much further although the regime-switching framework can handle longer samples with the possible addition of extra regimes.

Table 2 in Appendix B provides a description of all the parameters in the model.

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<sup>6</sup>The difference between the Kim and Nelson filter and the filtering algorithm used in this paper resides in the collapsing rule. The latter algorithm is computationally more efficient but yields the same results as the Kim and Nelson algorithm.

We calibrate a set of the parameters where we are unlikely to get good estimates from the data. In particular, the elasticity of substitution between differentiated intermediate goods ( $\epsilon$ ) and elasticity of substitution between differentiated labor ( $\nu$ ) are chosen to ensure steady state mark-ups of 20% in the goods and labour markets.  $\mu_{Z,D}$ , the gross mark-down on deposit rates at the ZLB is fixed at 1, because at the ZLB deposit rates are the same as the policy rate, i.e. we can't mark them down lower than the ZLB. We set  $\omega$  to 0.5 so that banks distribute 50% of their profits as dividends and 50% is reinvested in the business. We set the depreciation rate of bank capital ( $\delta_b$ ) to 0.1 which is in line with [Gerali et al. \(2010\)](#). We set  $\psi = 1$  which implies that all investment goods must be bought using one period loans from the bank. Capital's share of income is set to 0.35, well within the standard range used in the literature. We refer to Table 3 in Appendix B for the calibrated parameters.

We estimate the remaining parameters of the model using Bayesian methods (see Table 4 in Appendix B for details). For some of the parameters we use tight priors because we had difficulty getting them to remain within reasonable ranges. In particular, we set the prior for habit formation ( $\chi$ ) to be 0.7. The estimated value is quite close due to the tight prior. The prior on the inverse of the Frisch elasticity of labor supply ( $\eta$ ) is centered on 2, which is well within the range estimated in previous studies. However the distribution was truncated at 1 and the estimated distribution has conglomerated around 1. The prior on the inverse of the intertemporal elasticity of substitution ( $\sigma$ ) is centered on 2, a commonly used number in the literature. Estimation has moved the parameter lower to a posterior mean of 1.8605. The prior for the time preference parameter  $\beta$  is centered on 0.9988, which is consistent with the average interest rate over the estimation period. Estimation pushes the parameter up a bit, although this is constrained by the tight prior. Priors for  $\phi_P$  and  $\phi_W$ , the weights on the Rotemberg adjustment costs for prices and wages, respectively are centered on 10, which is within the plausible range for these parameters. Estimates of these parameters remain within plausible regions.

The prior for the weight on investment adjustment costs ( $\phi_I$ ) is centered on 3, this is close to the number estimated by [Christiano et al. \(2005\)](#). The priors for  $\xi_P$  and  $\xi_W$ , the weights on indexation are centered on 0.5, estimation moves these parameters almost all the way to zero, indicating that there is not a lot of persistence in wage and price inflation, or that the model can generate enough endogenous persistence. The priors

for the markups/markdowns for the retail interest rates have been chosen to match the average markups/markdowns observed in normal times and ZLB times in the US. The priors are tight, so that we remain within reasonable ranges for these parameters.

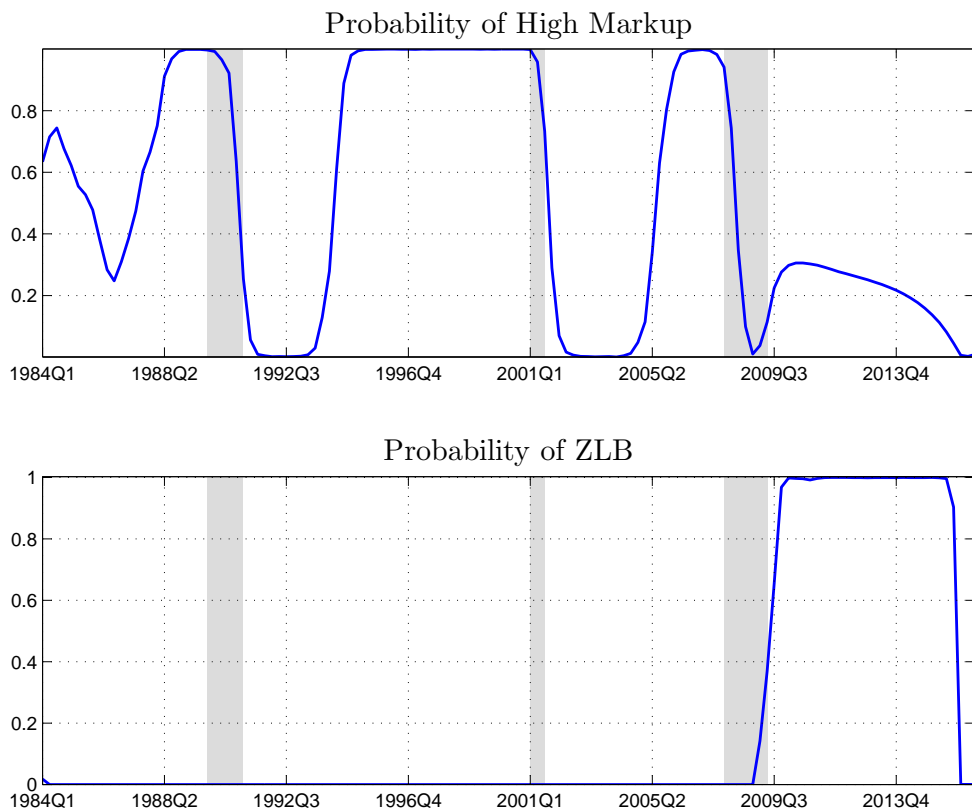
We used triangular priors on the persistence parameters for the adjustment costs on retail interest rates to ensure that the parameters are bounded from above. We center the priors for both sets of transition probabilities on 0.125. This implies that the expected duration in the normal and ZLB states is eight quarters and the expected duration in the high and low interest rate mark-up states is also eight quarters. The posterior mean estimate for the transition probability  $q_{H,L}$  is 0.1064, which implies an expected duration of nearly 10 quarters in the high interest mark-up state. The posterior mean estimate for  $q_{L,H}$  is 0.0653, which implies an expected duration of more than 15 quarters. The posterior mean estimate of  $p_{N,Z}$  is 0.0317, which implies the expected duration of the normal state to be 31 quarters. The posterior mean of  $p_{Z,N}$  is 0.3168, which implies the expected duration of the ZLB state is three quarters.

The estimates for the transition probabilities to the ZLB state are similar to those in [Binning and Maih \(2016\)](#). Finally, the priors for the Taylor rule coefficients,  $\kappa_\pi$  and  $\kappa_y$  are centered on 1.5 and 0.12. Estimation raises  $\kappa_\pi$  to about 2 and  $\kappa_y$  to about 0.27. The smoothing parameter has a tight prior centered on 0.7, as a consequence we do not move far from the prior.

## 5 Results/Policy analysis

We now present in Section [5.1](#) results using our two methods of measuring interest rate pass-through in multivariate models. Examining impulse responses to all the structural shocks from a multivariate model, and estimating ARDL models on simulated data. We examine overall pass-through and also the corresponding shocks specific measures of interest rate pass-through. Finally, we examine to what extent interest rate pass-through also depends on the key monetary policy parameters. Section [5.2](#) then performs some simulations, where we examine interest rate pass through at the zero lower bound on the policy rate. Finally, in Section [5.3](#) we examine the loss of incomplete pass-through.





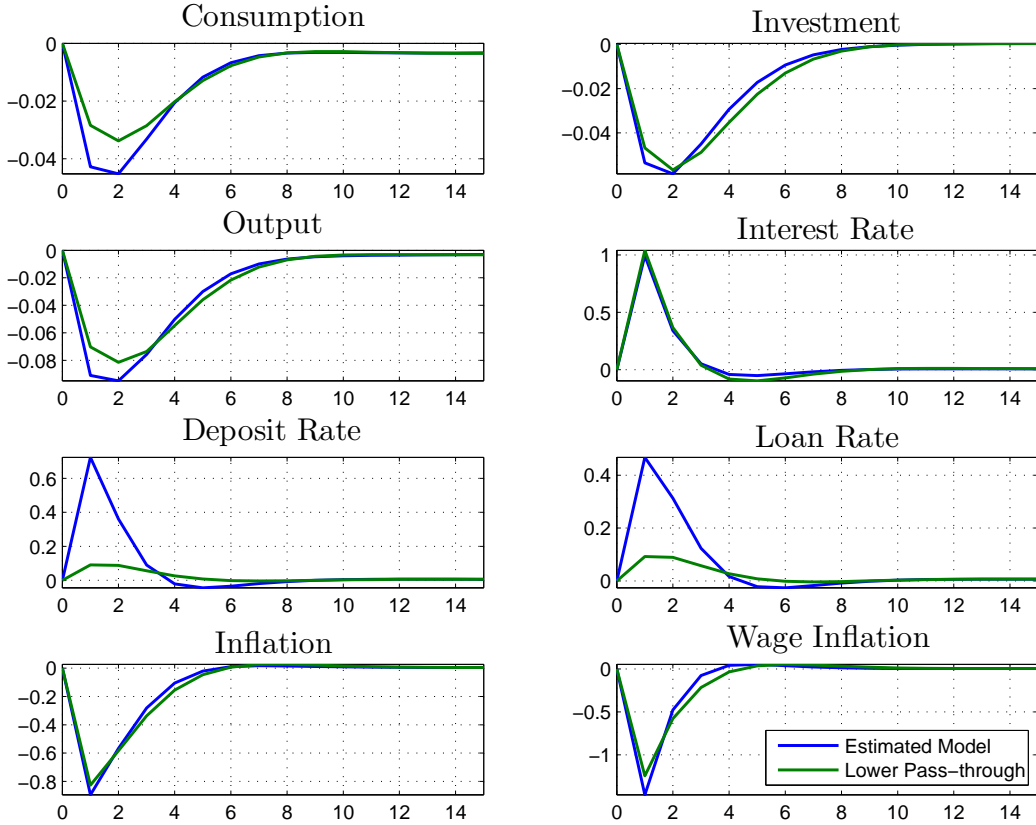
**Figure 1.** State probabilities. The top panel is the probability of being in a high mark up state, while the lower panel is the probability of being at the zero lower bound (ZLB). Grey vertical bars represent periods of NBER dated recessions.

## 5.1 Incomplete and nonlinear pass through

We start by graphing the state probabilities in Figure 1. The upper panel shows when the U.S. economy is in a high markup state, while the lower panel shows when the policy is at the ZLB. From the upper panel we see that the U.S. economy seems to be in high markup states until each recession comes along. Then when a recession occurs the economy switches to a low markup state.

From the lower panel we see that the change in the probability of being in the ZLB state occurs when very sharp interest cuts were made in the second part of 2008, sending the nominal interest rate to its effective lower bound. This timing for the ZLB resembles that of [Binning and Maih \(2016\)](#). By the end of the sample (fall 2016) the probability of being in the ZLB falls sharply as interest rate are finally increased in this period.

Figure 2 shows the impulse responses to a contractionary monetary policy shock. The figure compares the responses of the estimated model to the responses from a parame-

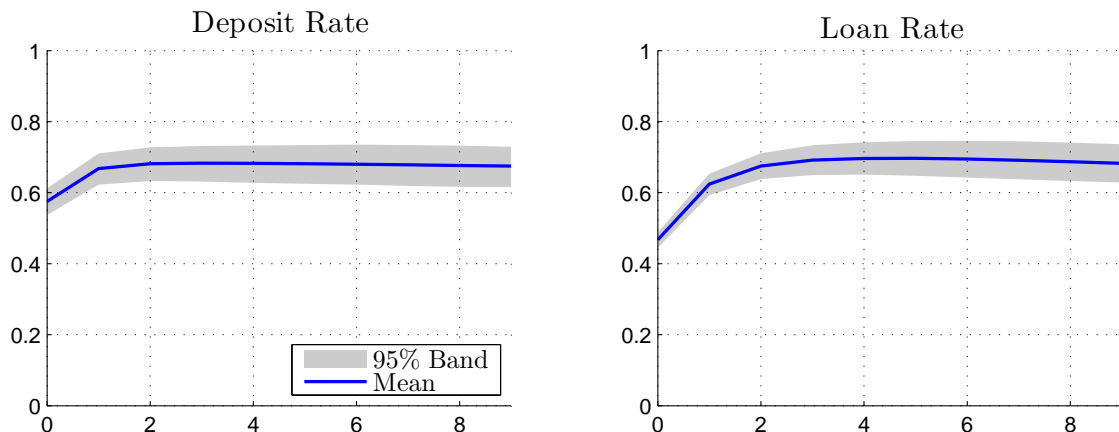


**Figure 2.** Impulse responses to a monetary policy shock. The figure compares the responses of the estimated model to the responses from a parameterization of the model with lower pass-through, i.e.,  $\tilde{\phi}_L(r_t) = 10$  and  $\tilde{\phi}_D(r_t) = 10$  (see the main text for additional details).

terization of the model with lower pass-through. More specifically, we set the reduced form persistence parameters for loans and deposits to, respectively,  $\tilde{\phi}_L(r_t) = 10$  and  $\tilde{\phi}_D(r_t) = 10$ , where we recall that  $\tilde{\phi}_L(r_t) \equiv \frac{\phi_L(r_t)}{v_L(r_t)-1}$  and  $\tilde{\phi}_D(r_t) \equiv \frac{\phi_D(r_t)}{v_D(r_t)-1}$  (see equations (7) and (12) above).

It can be seen that for the same size of the monetary policy shock, the response of the variables is smaller in the lower-pass-through model than in the estimated model (c.f. Figure 2). This is in particular evident for consumption and output. This also implies that in the lower-pass-through scenario, policy would have to do more in order to achieve the type of adjustment implied by the estimated model. Hence, policy is less effective under incomplete or low interest rate pass-through.

Figure 3 plots the overall pass-through for the deposit rate (left frame) and the loan rate (right frame) using the ARDL measure, discussed in Section 3, alongside their 95% probability bands. In this exercise, the simulations used to estimate ARDL models are



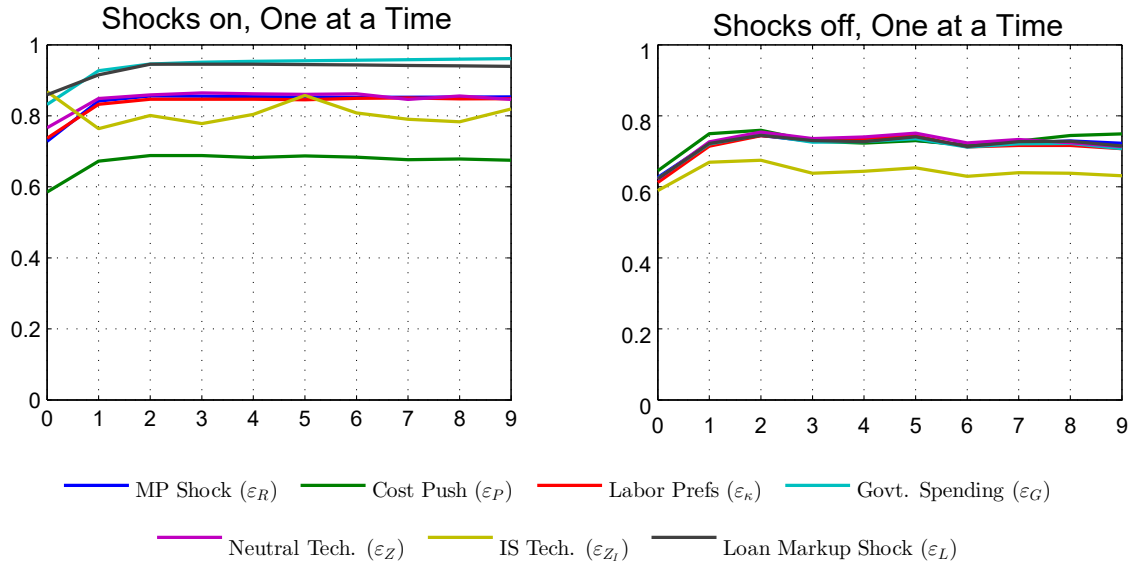
**Figure 3.** Overall interest pass-through for the deposit rate (left frame) and the loan rate (right frame) using the autoregressive distributed lag (ARDL) measure, discussed in section 3, alongside their 95% probability bands.

done using all the shocks in the DSGE model. We note that for both rates, pass-through is incomplete both in the short term and the long term. Furthermore, in the short term, pass through for the loan rate is smaller than for the deposit rate, while in the long run, the opposite holds, i.e. in the long run pass-through is smaller for deposit rate than for loan rate.

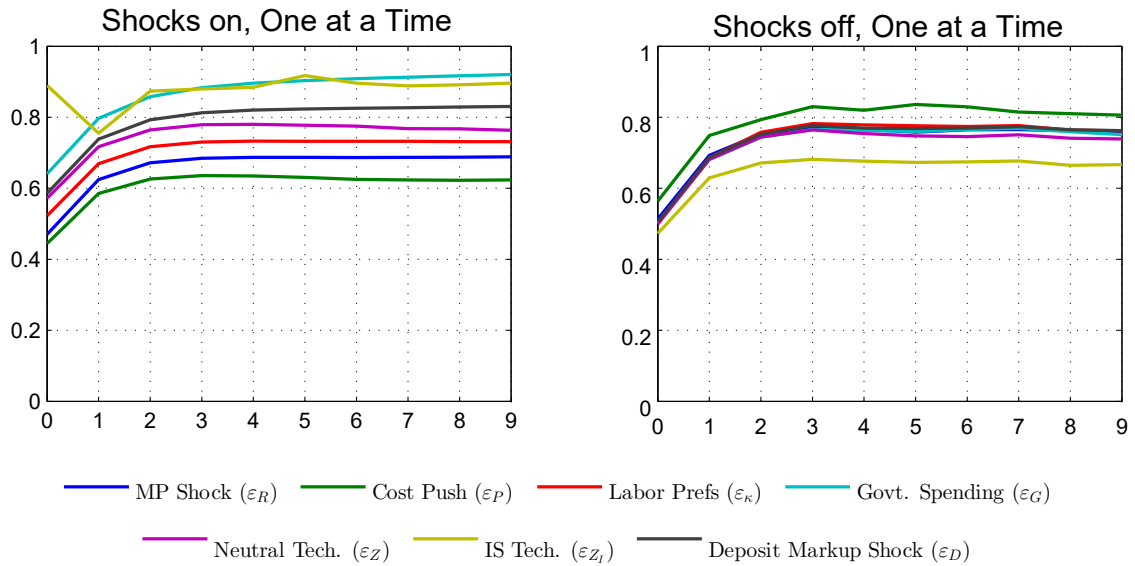
In Figures 4 and 5 we graph the corresponding shocks specific measures of interest rate pass-through for the deposit rate and the loan rate respectively. In both figures, we plot in the left frame the pass-through from each shock in turn assuming all the other shocks are zero. In the right frame, we do the opposite exercise. That is, we turn off each shock in turn, letting all the others be active.

Starting with the left frame in Figure 4, we see that for all shocks displayed, pass-through is incomplete. Of these, government spending and loan rate markup shocks show the highest degree of pass-through, followed by labor preference, monetary policy and neutral technology, which have roughly the same pass-through, and then investment-specific technology shocks. Finally, the lowest pass-through is observed for the cost-push shocks.<sup>7</sup>

<sup>7</sup>Note that we were unable to estimate an ARDL model with the consumption shock, because the correlation between the policy rate and market rate was too high (approx 0.99), implying complete or near complete pass-through on impact for that shock.

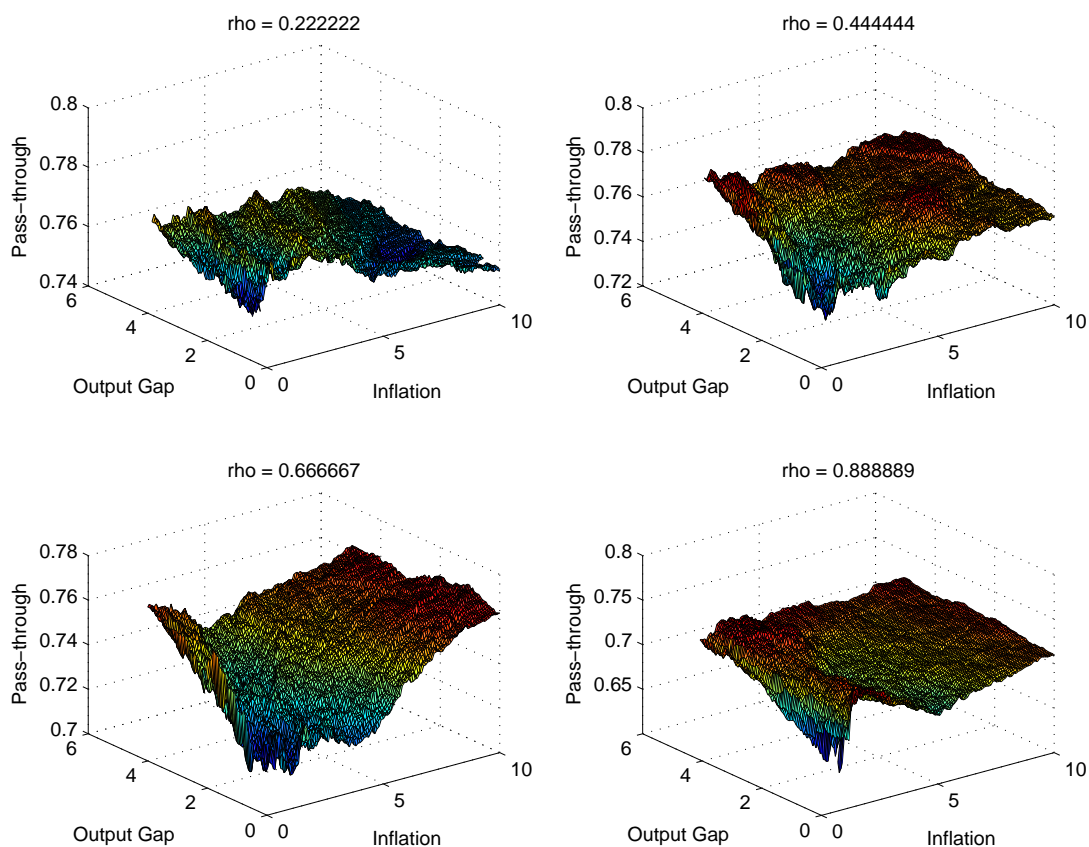


**Figure 4.** Deposit rate pass-through, given different shocks. Left frame displays the pass-through from each shock in turn assuming all the other shocks are zero. Right frame displays the opposite exercise. That is we turn off each shock in turn letting all the others be active.



**Figure 5.** Loan rate pass-through, given different shocks. Left frame displays the pass-through from each shock in turn assuming all the other shocks are zero. Right frame displays the opposite exercise. That is, we turn off each shock in turn, letting all the others be active.

The right frame, which analyzes the effect of turning off one shock at the time, confirms the picture from above. All shocks contribute to reducing pass-through. Still, interest pass-through is lower in the absence of investment specific shocks, and marginally higher in the absence of cost-push shocks.

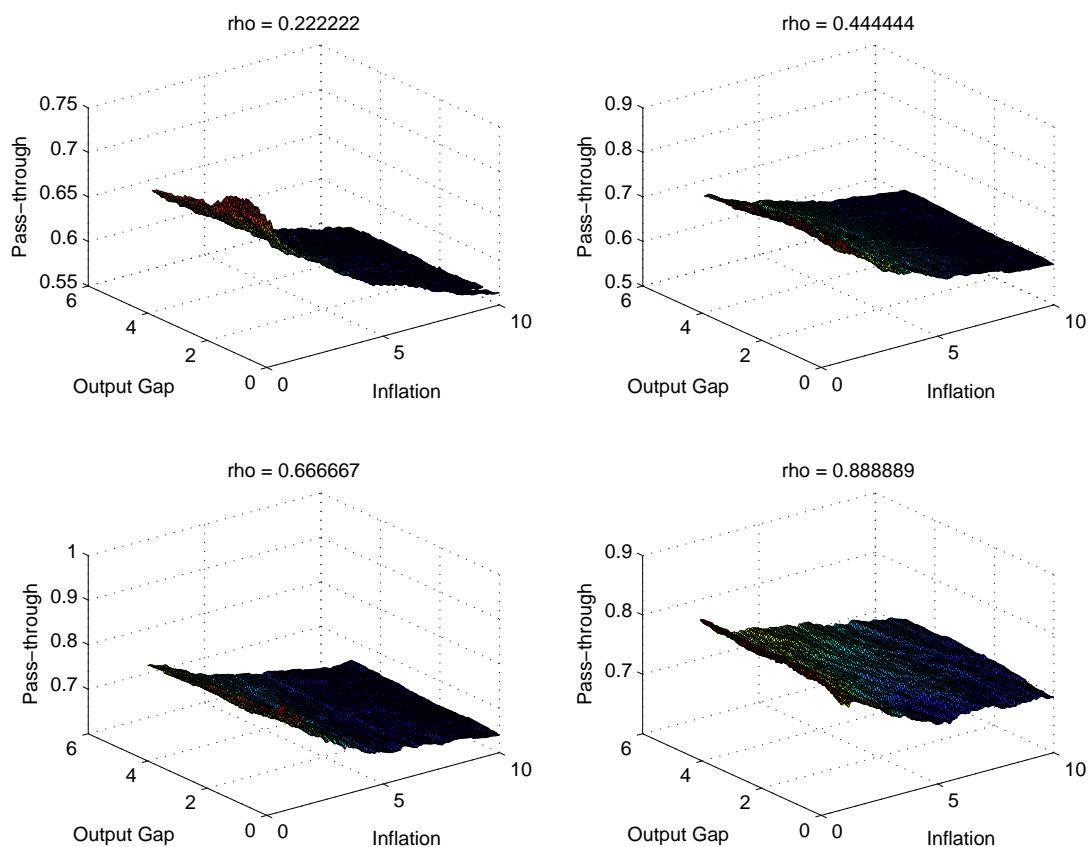


**Figure 6.** Loan Rate Pass-Through: Varying Monetary Policy Parameters

Turning to the loan rate, the left frame in Figure 5 suggests that government spending and technology shocks show the highest pass-through, followed by deposit rate, neutral technology, labor preferences and monetary policy shocks. The lowest pass-through is observed for the cost push shocks, as was also the case for the deposit rate. Finally, the right frame shows that interest pass-through is lower in the absence of investment specific shocks, and higher in the absence of cost-specific shocks.

Taken together, Figures 4 and 5 suggest that the degree of interest rate pass-through crucially depends on the shock. The figures also suggest that the pass-through behavior of the loan rate is different from that of the deposit rate.

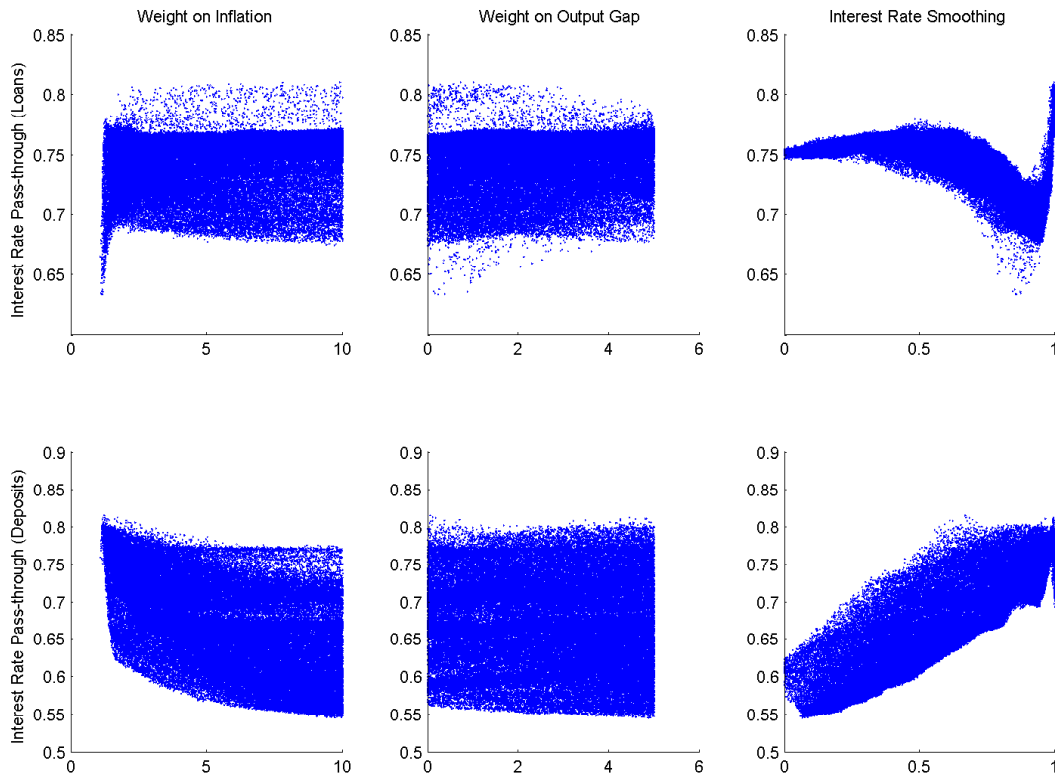
The pass through measures computed using the ARDL technique where one shock is active at a time turn out to be remarkably similar to those generated using our other pass-through measure based on a more direct computation of the impulse responses. This can be seen in Figure 11 and Figure 12 in Appendix C for the deposit rate pass-through and the loan rate pass-through, respectively.



**Figure 7.** Deposit Rate Pass-Through: Varying Monetary Policy Parameters

We now turn to analyzing how pass-through is affected by key monetary policy parameters. To that end, we measure the long run interest rate pass-through on a grid over the reaction of the policy rate to the output gap ( $\kappa_y$ ), the reaction to inflation ( $\kappa_\pi$ ) and the interest rate smoothing ( $\rho_R$ ). We plot the results for the loan rate in Figure 6 and for the deposit rate in Figure 7. The message that can be read from the two figures is that everything else equal, the degree of interest rate pass-through is a highly nonlinear function of the policy parameters: changing the value of the interest rate smoothing dramatically changes the profile of the interest rate pass-through with respect to the other policy parameters. Here too, it is seen that the pass-through behavior for the deposit rate is different from that of the loan rate.

Another way to look at the relationship between policy parameters and the degree of pass through is to look at each parameter separately. This is what Figure 8 does. We can now more clearly see the important role of the smoothing parameter. For the deposit rate (lower panels), pass through tends to increase with the degree of interest rate



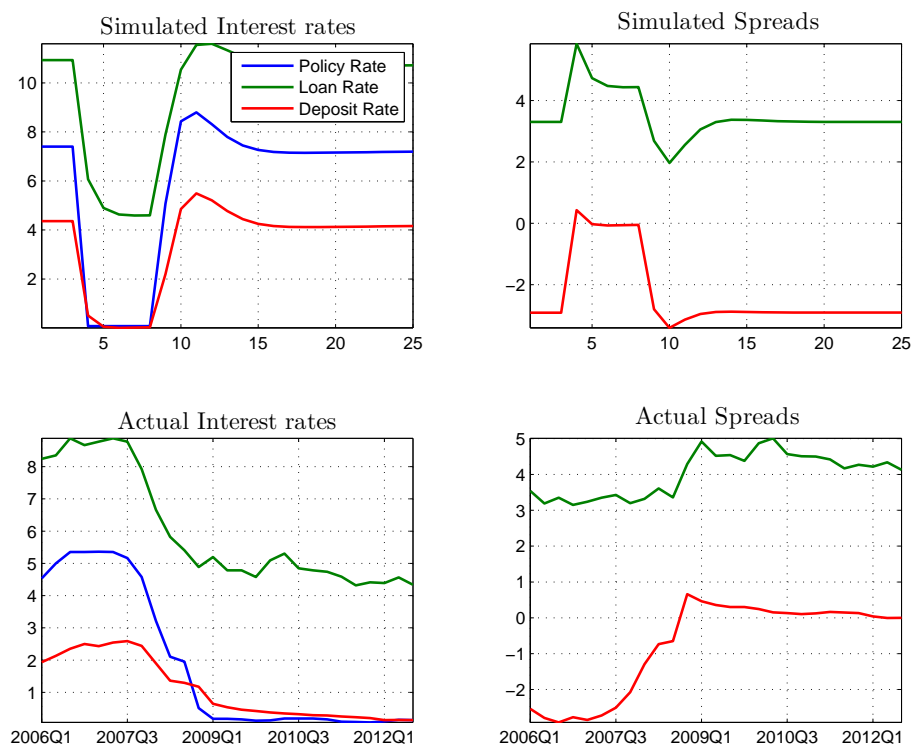
**Figure 8.** Loan rate Rate Pass-Through: Varying Monetary Policy Parameters

smoothing. The behavior is quite different for the pass through to the loan rate (upper panel). Originally the degree of pass through increases with the smoothing parameter. But at some point, interest rate pass through starts decreasing just to change course again as the smoothing parameter approaches unity.

Summing up, we have seen that the degree of interest rate pass-through crucially depends on the shocks hitting the economy. Furthermore, the analysis suggest that the pass-through behavior of the loan rate is different from that of the deposit rate, and finally, that the pass-through is affected by key monetary policy parameters. In particular, the degree of interest rate pass-through is a highly nonlinear function of the policy parameters. Also here, the pass-through behavior for the deposit rate is different from that of the loan rate.

## 5.2 Dynamics at the zero-lower bound

So far we have looked at interest rate pass through without any reference to the lower bound on the policy rate. With the zero-lower bound (ZLB) one should expect the dynamics of the system to change. But before looking into a counterfactual analysis, it is

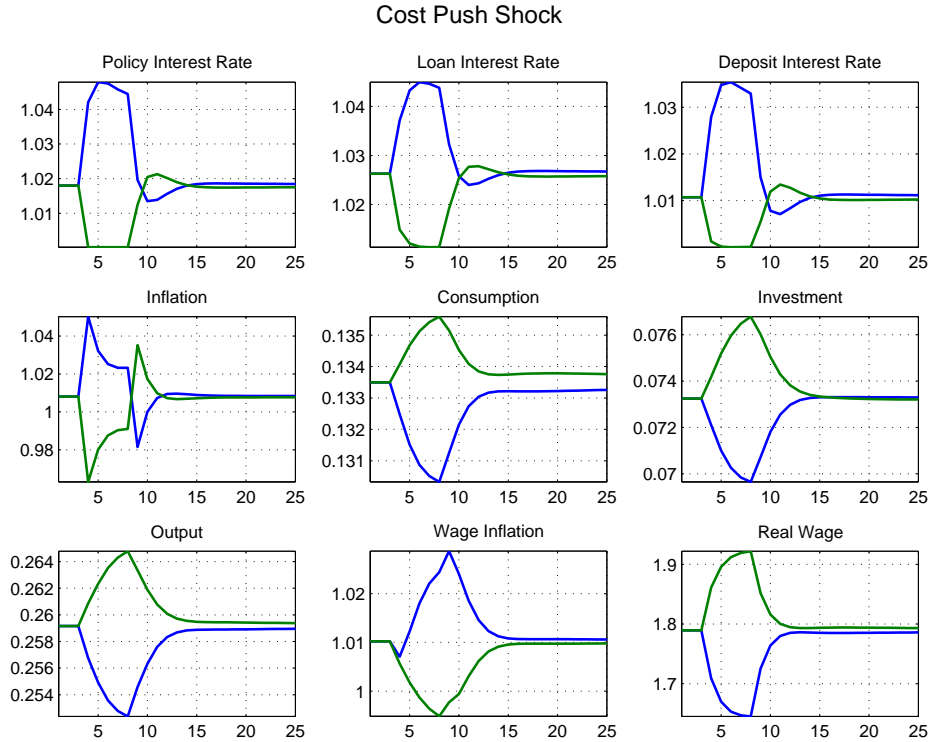


**Figure 9.** Dynamics at the ZLB: Actual vs Simulated Data

important to see how well our model represents the data over the ZLB period. Figure 9 presents in its top panels the simulated series on interest rates (left panel) and on spreads (right panel). The figure also plots in its lower panels the actual counterparts of those variables zooming in on the period in which the ZLB was active. As can be seen from the figure, the simulated data compare well with the actual series both in terms of patterns and in terms of magnitudes.

To gain more insight into the workings of the model, we compare the dynamics induced by one sequence of adverse cost-push shocks and the exact same sequence of shocks but with opposite signs in Figure 10. The figure shows that with the ZLB, the dynamics of the system becomes asymmetric. In particular, the adjustment in consumption, investment, output and inflation is smaller in the ZLB scenario than in the opposite scenario, that is, where the interest rate increases. Hence, policy would be less effective under the ZLB. The combination of this result with the insights from Figure 2 suggest that with lower pass-through the responses of the different variables would be even smaller. Conversely, complete pass through would assuage the effects induced by the ZLB. Hence, we have shown





**Figure 10.** Asymmetric effects of cost-push shocks at the ZLB. The model compares the dynamics induced by one sequence of adverse cost-push shocks and the exact same sequence of shocks but with opposite signs

### 5.3 The cost of incomplete pass-through

To better understand and quantify the costs of incomplete interest rate pass-through and the effectiveness of monetary policy, we compare the loss calculated from an ad hoc loss function from a series of simulations, both factual and counterfactual. More specifically, we simulate the model for 1000 periods under both the estimated parameterization of the model (with incomplete pass-through), and a counterfactual parameterizations of complete pass-through. In the latter we are switching off the Rotemberg rigidities in the deposit and lending interest rate setting equations and removing the markup/markdown on deposit and lending interest rates so that retail interest rates are set equal to the policy rate in the steady state. We use the same sequence of shocks for both the simulations. Figure 13 in the Appendix C compares the responses to simulation of cost push shocks, using the estimated model and a model with full pass-through.

To calculate the loss, we adopt the following ad hoc loss function

$$L_0 = E_0 \left\{ \sum_{t=0}^{\infty} \beta^t \left[ \hat{\pi}_t^2 + \gamma_Y \hat{Y}_t^2 + \gamma_R (\Delta \hat{R}_t)^2 \right] \right\}$$

where  $\gamma_Y = 0.5$  and  $\gamma_R = 0.5$ . We report the losses from each simulation in Table 1.

**Table 1.** The cost of incomplete pass-through

Simulation	Loss
Estimated/incomplete pass-through	1.0234
Complete Pass-through	1.0000

Comparing the relative losses, we find the loss to be higher in the models with incomplete pass-through compared to the model without rigidities and without markups/markdowns. This is consistent with the results we have reported so far.

## 6 Conclusion

We use a medium scale regime-switching DSGE model with a banking sector to analyze the effects of incomplete and asymmetric interest rate pass-through. The model is estimated using Bayesian techniques on US data between 1985 and 2016. We find interest rate pass-through to be mostly incomplete, but with the magnitude of the pass through depending on the shocks that hit the economy. Shocks also create asymmetric dynamics at the ZLB and incomplete pass-through exacerbates that asymmetry. We further note that pass-through is nonlinear with respect to policy parameters. In particular, the value of the interest rate smoothing dramatically changes the profile of the interest rate pass-through with respect to the other policy parameters. In all cases, we find the behavior of pass-through in the loan rate to be different from that of the deposit rate. Putting all this together, we show that policy is less effective under incomplete pass-through.

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# Appendices

## Appendix A Model

In this section we describe the model economy we use to investigate interest rate pass-through. Our setup is reasonably standard. The model is comprised of households, firms, banks, a fiscal authority and a monetary authority. Households consume the final good, supply their own variety of labor in return for labor income and receives dividends from firms and banks, which they own. Households hold deposits with a retail bank. Labor is differentiated which gives each household a degree of market power and the ability to choose wages, subject to quadratic adjustment costs, to minimize their disutility of working. Firms produce a differentiated intermediate good using a common neutral technology, labor and capital which they own. They choose quantities of labor, capital, investment and prices to maximize the expected present value of their profits, subject to quadratic adjustment costs on changing investment and prices and a loan-in-advance constraint. Final goods are produced by a perfectly competitive “packing” firm that aggregates intermediate goods according to a CES production technology.

In the absence of any frictions or imperfections, conventional DSGE models do not require a banking sector. Following [Edwards and Vegh \(1997\)](#) and [Christiano et al. \(2005\)](#) we introduce a banking sector via a loan-in-advance (LIA) constraint. More specifically firms have to take out a loan at the beginning of the period to pay for a fixed fraction of their investment good purchases each period. Firms repay the loan at the end of the period. Following [Gerali et al. \(2010\)](#), the banking sector is divided into retail and wholesale banks, where retail banks are further divided into deposit-taking and loan-making banks. [Gerali et al. \(2010\)](#) introduces differentiated deposits and loans as a means of introducing markups (and markdowns) of the loan and deposit interest rates over the policy rate.

In the baseline model, loan and deposit taking banks choose loan and deposit interest rates to maximize the present value of their profits, subject to a quadratic adjustment cost on changing interest rates. This results in interest rate setting rules that resemble the Rotemberg Philips curves for price and wage setting.

Final loans and deposits are produced by a perfectly competitive aggregator firm

that aggregates loans and deposits from the retail banks according to a CES production technology.

## A.1 Households

The economy is populated by a continuum of households, normalized to unit mass. Each household derives positive utility from consumption, relative to the previous periods level of aggregate consumption, and disutility from working. Utility for the  $i$ th household takes the form

$$U_t = E_t \left\{ \sum_{t=0}^{\infty} \beta^t \left( \prod_{j=0}^t d_{t+j} \right) \left[ A_t \frac{(\mathcal{C}_t / \mathbb{Z}_{Y,t})^{1-\sigma}}{1-\sigma} - \kappa \frac{N_t(i)^{1+\eta}}{1+\eta} \right] \right\},$$

where

$$\log A_t = \rho_A \log A_{t-1} + \varepsilon_{A,t},$$

is a consumption preference-shifter,  $\mathcal{C}_t = C_t - \chi \bar{C}_{t-1}$  is a consumption index,  $C_t$  is consumption,  $\mathbb{Z}_{Y,t}$  is a composite technology process that grows at the same rate as consumption on the balanced growth path, and  $N_t(i)$  is the labor variety supplied by the  $i$ th household.  $d_{t+j}$  is a preference shifter term where we assume  $d_0 = 1$ . The  $i$ th household faces the following budget constraint

$$C_t + D_t = \frac{D_{t-1} R_{D,t-1}}{\pi_t} + \frac{W_t(i)}{P_t} N_t(i) - \frac{\phi_W}{2} \frac{W_t}{P_t} N_t \left[ \frac{W_t(i)}{W_{t-1}(i)} - \tilde{\pi}_{W,t} \right]^2 + (1-\omega) \frac{J_{t-1}}{\pi_t} + T_t + \Psi_t + \Phi_t, \quad (\text{A.1})$$

where  $D_t$  is deposits,  $R_{D,t}$  is the interest rate paid on deposits,  $W_t$  is the nominal wage,  $P_t$  is the price level for final goods,  $\pi_{W,t}$  is wage inflation,  $J_{t-1}$  is total profits from the banking sector,  $T_t$  is lump sum taxes,  $\Psi_t$  is profits from intermediate goods producers and  $\Phi_t$  is the price, wage and interest rate adjustment costs that are rebated to households. The term  $\tilde{\pi}_{W,t} \equiv \pi_{W_t}^{\xi_W} \pi_W^{1-\xi_W}$  captures wage indexation behavior from wage setters. Perfect competition and cost minimization by the labor packing or aggregating firm leads to the following demand schedule for the  $i$ th household's variety of labor

$$N_t(i) = \left( \frac{W_t(i)}{W_t} \right)^{-\varepsilon} N_t. \quad (\text{A.2})$$

Households choose allocations of date  $t$  consumption, deposits and wages to maximize the sum of their current and expected discounted stream of future period utilities, subject to



the budget constraint (equation A.1). Setting this up as the Lagrangean:

$$\mathcal{L}_t = E_t \left\{ \sum_{t=0}^{\infty} \beta^t \left( \prod_{j=0}^t d_{t+j} \right) \left[ -\lambda_t \left[ \begin{array}{c} A_t \frac{(\mathcal{E}_t / \mathbb{Z}_{Y,t})^{1-\sigma}}{1-\sigma} - \kappa \frac{N_t(i)^{1+\eta}}{1+\eta} - \\ C_t + D_t - \frac{D_{t-1} R_{D,t-1}}{\pi_t} - \frac{W_t(i)}{P_t} N_t(i) + \dots \\ \dots + \frac{\phi_W}{2} \frac{W_t}{P_t} N_t \left[ \frac{W_t(i)}{W_{t-1}(i)} - \tilde{\pi}_{W,t} \right]^2 - (1-\omega) \frac{J_{t-1}}{\pi_t} - \dots \\ \dots - T_t - \Psi_t - \Phi_t \end{array} \right] \right] \right\}. \quad (\text{A.3})$$

Substituting A.2 into A.3 gives

$$\mathcal{L}_t = E_t \left\{ \sum_{t=0}^{\infty} \beta^t \left( \prod_{j=0}^t d_{t+j} \right) \left[ -\lambda_t \left[ \begin{array}{c} A_t \frac{(\mathcal{E}_t / \mathbb{Z}_{Y,t})^{1-\sigma}}{1-\sigma} - \kappa \frac{\left( \left( \frac{W_t(i)}{W_t} \right)^{-\nu} N_t \right)^{1+\eta}}{1+\eta} - \\ C_t + D_t - \frac{D_{t-1} R_{D,t-1}}{\pi_t} - \frac{W_t(i)^{1-\nu} W_t^\nu}{P_t} N_t + \dots \\ \dots + \frac{\phi_W}{2} \frac{W_t}{P_t} N_t \left[ \frac{W_t(i)}{W_{t-1}(i)} - \tilde{\pi}_{W,t} \right]^2 - (1-\omega) \frac{J_{t-1}}{\pi_t} - \dots \\ \dots - T_t - \Psi_t - \Phi_t \end{array} \right] \right] \right\}.$$

Optimization results in the following first-order conditions. The first-order condition for consumption:

$$\frac{\partial \mathcal{L}_t}{\partial C_t} = A_t (C_t - \chi C_{t-1})^{-\sigma} \mathbb{Z}_{Y,t}^{\sigma-1} - \lambda_t = 0. \quad (\text{A.4})$$

The first-order condition for deposits:

$$\frac{\partial \mathcal{L}_t}{\partial D_t} = -\lambda_t + E_t \left\{ \beta d_{t+1} \frac{\lambda_{t+1} R_{D,t}}{\pi_{t+1}} \right\} = 0. \quad (\text{A.5})$$

The first-order condition for wages:

$$\begin{aligned} \frac{\partial \mathcal{L}_t}{\partial W_t(i)} &= \nu \kappa \frac{N_t(i)^{1+\eta}}{W_t(i)} + \lambda_t (1-\nu) \frac{N_t(i)}{P_t} - \lambda_t \phi_W \frac{W_t N_t}{P_t W_{t-1}(i)} \left[ \frac{W_t(i)}{W_{t-1}(i)} - \tilde{\pi}_{W,t} \right] + \dots \\ &\dots + E_t \left\{ \beta d_{t+1} \lambda_{t+1} \phi_W \frac{W_{t+1}(i) W_{t+1} N_{t+1}}{P_{t+1} W_t(i)^2} \left[ \frac{W_{t+1}(i)}{W_t(i)} - \tilde{\pi}_{W,t+1} \right] \right\} = 0. \end{aligned} \quad (\text{A.6})$$

From A.4 we get the marginal utility of consumption:

$$\lambda_t = A_t (C_t - \chi C_{t-1})^{-\sigma} \mathbb{Z}_{Y,t}^{\sigma-1}. \quad (\text{A.7})$$

From A.5 we get the consumption Euler equation:

$$\lambda_t = E_t \left\{ \beta d_{t+1} \frac{\lambda_{t+1} R_{D,t}}{\pi_{t+1}} \right\}, \quad (\text{A.8})$$

which we use to construct the real stochastic discount factor:

$$\mathcal{M}_{t,t+1} = E_t \left\{ \beta d_{t+1} \frac{\lambda_{t+1}}{\lambda_t} \right\}. \quad (\text{A.9})$$

Finally we obtain the wage Phillips curve from equation A.6:

$$\begin{aligned} & \left( \frac{v}{v-1} \right) \kappa \frac{N_t^\eta P_t}{\lambda_t W_t} - 1 - \left( \frac{\phi_W}{v-1} \right) \pi_{W,t} [\pi_{W,t} - \tilde{\pi}_{W,t}] + \dots \\ & \dots + E_t \left\{ \beta d_{t+1} \frac{\lambda_{t+1}}{\lambda_t} \left( \frac{\phi_W}{v-1} \right) \frac{\pi_{W,t+1}^2}{\pi_{t+1}} \left( \frac{N_{t+1}}{N_t} \right) [\pi_{W,t+1} - \tilde{\pi}_{W,t+1}] \right\} = 0, \end{aligned} \quad (\text{A.10})$$

where we have assumed a symmetric equilibrium with  $W_t(i) = W_t$  and  $N_t(i) = N_t$ .

## A.2 Investment Goods Producers

A continuum of perfectly competitive investment goods producers produce an identical final investment good. We drop the firms' subscripts and consider a representative final investment goods producer. Final investment goods ( $I_t$ ) are produced using a production process that combines investment specific (embodied) technology with raw investment goods ( $X_t$ , which comes from final goods producers) according to the production function

$$I_t = Z_{I,t} X_t,$$

where embodied (investment specific) technology evolves according to the following process

$$Z_{I,t} = Z_{I,0} \exp(g_{Z_I} \cdot t + \mathcal{A}_{Z_I,t}), \quad \mathcal{A}_{Z_I,t} = \rho_{\mathcal{A}_{Z_I}} \mathcal{A}_{Z_I,t-1} + \varepsilon_{Z_I,t}. \quad (\text{A.11})$$

Producers of final investment goods maximize their period profits by choosing the quantity of raw investment goods to use in production, where period profits are given by:

$$\begin{aligned} \Psi_{I,t} &= P_{I,t} I_t - P_t X_t, \\ &= P_{I,t} Z_{I,t} X_t - P_t X_t. \end{aligned}$$

We obtain the first-order condition for the investment goods producer

$$\frac{\partial \Psi_{I,t}}{\partial X_t} = P_{I,t} Z_{I,t} - P_t = 0,$$

which implies

$$\frac{P_{I,t}}{P_t} = \frac{1}{Z_{I,t}}, \text{ and } P_{I,t} I_t = P_t X_t.$$

### A.3 Intermediate Goods Producers

Differentiated intermediate goods are produced by a continuum of firms, normalized to unit mass. The  $h$ th firm produces intermediate goods by combining capital and labor inputs with a common (neutral) technology according to the Cobb-Douglas production technology

$$Y_t(h) = Z_t K_{t-1}(h)^\alpha N_t(h)^{1-\alpha}. \quad (\text{A.12})$$

The common neutral technology evolves according to the process

$$Z_t = Z_0 \exp(g_Z \cdot t + \mathcal{A}_{Z,t}), \quad \mathcal{A}_{Z,t} = \rho_{\mathcal{A}_Z} \mathcal{A}_{Z,t-1} + \varepsilon_{Z,t}. \quad (\text{A.13})$$

Dixit-Stiglitz aggregation and cost minimization by the perfectly competitive final goods producer implies producers of the  $h$ th intermediate good face the following demand schedule

$$Y_t(h) = \left( \frac{P_t(h)}{P_t} \right)^{-\varepsilon} Y_t. \quad (\text{A.14})$$

Intermediate goods producers own the capital they use in the production process. Firm  $h$ 's capital stock evolves according to the process

$$K_t(h) = I_t(h) \left( 1 - \frac{\phi_I}{2} \left( \frac{I_t(h)}{I_{t-1}(h)} - \mu_I \right)^2 \right) - (1 - \delta) K_{t-1}(h). \quad (\text{A.15})$$

Each intermediate goods producer is subject to a loan-in-advance (LIA) constraint when purchasing investment goods. As a consequence each firm must fund a portion of their investment goods through a one period loan. Firm  $h$ 's LIA constraint can be summarized as follows

$$L_t(h) \geq \psi \frac{P_{I,t}}{P_t} I_t(h). \quad (\text{A.16})$$

Firms maximize their expected discounted stream of period profits by choosing allocations of date  $t$  investment, capital, labor, loans and date  $t$  prices, subject to constraints [A.12](#), [A.15](#) and [A.16](#) and a quadratic cost on adjusting prices.<sup>8</sup> This can be represented by

<sup>8</sup>Note that we assume all constraints bind with equality in equilibrium.

the Lagrangean:

$$\Psi_0(h) = E_0 \left\{ \sum_{t=0}^{\infty} \mathcal{M}_{0,t}^* \left[ \begin{array}{l} \exp(\mathbb{P}_t) \frac{P_t(h)}{P_t} Y_t(h) - \frac{W_t}{P_t} N_t(h) - \frac{P_{I,t}}{P_t} I_t(h) + L_t(h) - d_t \frac{R_{L,t-1} L_{t-1}(h)}{\pi_t} - \dots \\ \dots - \frac{\phi_P}{2} Y_t \left[ \frac{P_t(h)}{P_{t-1}(h)} - \tilde{\pi}_t \right]^2 - \dots \\ \dots - Q_t(h) \left[ K_t(h) - I_t(h) \left( 1 - \frac{\phi_I}{2} \left( \frac{I_t(h)}{I_{t-1}(h)} - \mu_I \right)^2 \right) - \dots \right] - \dots \\ \dots - (1 - \delta) K_{t-1}(h) \\ \dots - \Phi_t(h) [Y_t(h) - Z_t K_{t-1}(h)^\alpha N_t(h)^{1-\alpha}] - \dots \\ \dots - \Upsilon_{L,t}(h) [L_t(h) - \psi \frac{P_{I,t}}{P_t} I_t(h)] \end{array} \right] \right\}. \quad (\text{A.17})$$

Where  $\tilde{\pi}_t = \pi_{t-1}^\xi \pi^{1-\xi}$  is the inflation index firms index prices to when adjusting prices and  $\mathcal{M}_{t,t+1}^* = E_t \left\{ \beta \frac{\lambda_{t+1}}{\lambda_t} \right\}$  is the modified real stochastic discount factor. We use this stochastic discount factor in place of the household's stochastic discount because the household's stochastic discount factor causes implausibly large swings in investment and capital when we switch between the normal and ZLB (steady-) states. To ensure a degree of symmetry between the household's consumption Euler equation and the firm's intertemporal borrowing decision, we augment the firm's repayment decision with the preference shifter term  $d_t$  so that the first-order condition resembles what we would observe if the firm were using the household's stochastic discount factor. This also prevents implausibly large swings in the price of new capital goods when switches between the normal and ZLB (steady-) states.

Substituting [A.14](#) into [A.17](#) gives:

$$\Psi_0(h) = E_0 \left\{ \sum_{t=0}^{\infty} \mathcal{M}_{0,t}^* \left[ \begin{array}{l} \exp(\mathbb{P}_t) \left( \frac{P_t(h)}{P_t} \right)^{1-\varepsilon} Y_t - \frac{W_t}{P_t} N_t(h) - \frac{P_{I,t}}{P_t} I_t(h) + L_t(h) - d_t \frac{R_{L,t-1} L_{t-1}(h)}{\pi_t} - \dots \\ \dots - \frac{\phi_P}{2} Y_t \left[ \frac{P_t(h)}{P_{t-1}(h)} - \tilde{\pi}_t \right]^2 - \dots \\ \dots - Q_t(h) \left[ K_t(h) - I_t(h) \left( 1 - \frac{\phi_I}{2} \left( \frac{I_t(h)}{I_{t-1}(h)} - \mu_I \right)^2 \right) - \dots \right] - \dots \\ \dots - (1 - \delta) K_{t-1}(h) \\ \dots - \Phi_t(h) \left[ \left( \frac{P_t(h)}{P_t} \right)^{-\varepsilon} Y_t - Z_t K_{t-1}(h)^\alpha N_t(h)^{1-\alpha} \right] - \dots \\ \dots - \Upsilon_{L,t}(h) [L_t(h) - \psi \frac{P_{I,t}}{P_t} I_t(h)] \end{array} \right] \right\}$$

Optimization by the firm results in the following set of first-order conditions. The first-

order conditions for investment:

$$\begin{aligned} \frac{\partial \Psi_t(h)}{\partial I_t(h)} &= -\frac{P_{I,t}}{P_t} + Q_t(h) \left[ 1 - \frac{\phi_I}{2} \left( \frac{I_t(h)}{I_{t-1}(h)} - \mu_I \right)^2 - \phi_I \left( \frac{I_t(h)}{I_{t-1}(h)} - \mu_I \right) \frac{I_t(h)}{I_{t-1}(h)} \right] + \dots \\ &\dots + \psi \Upsilon_{L,t}(h) \frac{P_{I,t}}{P_t} + E_t \left\{ \mathcal{M}_{t,t+1}^* \phi_I Q_{t+1}(h) \left( \frac{I_{t+1}(h)}{I_t(h)} - \mu_I \right) \left( \frac{I_{t+1}(h)}{I_t(h)} \right)^2 \right\} = 0. \end{aligned} \quad (\text{A.18})$$

capital

$$\frac{\partial \Psi_t(h)}{\partial K_t(h)} = -Q_t(h) + E_t \left\{ \mathcal{M}_{t,t+1}^* \left( \alpha \Phi_{t+1}(h) \frac{Y_{t+1}(h)}{K_t(h)} + (1 - \delta) Q_{t+1}(h) \right) \right\} = 0. \quad (\text{A.19})$$

hours worked

$$\frac{\partial \Psi_t(h)}{\partial N_t(h)} = -\frac{W_t}{P_t} + (1 - \alpha) \Phi_t(h) \frac{Y_t(h)}{N_t(h)} = 0. \quad (\text{A.20})$$

loans

$$\frac{\partial \Psi_t(h)}{\partial L_t(h)} = 1 - \Upsilon_{L,t}(h) - E_t \left\{ \mathcal{M}_{t,t+1}^* d_{t+1} \frac{R_{L,t}}{\pi_{t+1}} \right\} = 0. \quad (\text{A.21})$$

and prices

$$\begin{aligned} \frac{\partial \Psi_t(h)}{\partial P_t(h)} &= (1 - \varepsilon) \exp(\mathbb{P}_t) \frac{Y_t(h)}{P_t} + \varepsilon \Phi_t(h) \frac{Y_t(h)}{P_t(h)} - \phi_P \frac{Y_t}{P_{t-1}(h)} \left[ \frac{P_t(h)}{P_{t-1}(h)} - \tilde{\pi}_t \right] + \dots \\ &\dots + E_t \left\{ \phi_P \mathcal{M}_{t,t+1}^* Y_{t+1} \frac{P_{t+1}}{P_t(h)^2} \left[ \frac{P_{t+1}(h)}{P_t(h)} - \tilde{\pi}_{t+1} \right] \right\} = 0. \end{aligned} \quad (\text{A.22})$$

Rearranging [A.18](#) gives:

$$\begin{aligned} \frac{P_{I,t}}{P_t} &= Q_t \left[ 1 - \frac{\phi_I}{2} \left( \frac{I_t}{I_{t-1}} - \mu_I \right)^2 - \phi_I \left( \frac{I_t}{I_{t-1}} - \mu_I \right) \frac{I_t}{I_{t-1}} \right] + \psi \Upsilon_{L,t} \frac{P_{I,t}}{P_t} + \dots \\ &\dots + E_t \left\{ \mathcal{M}_{t,t+1}^* \phi_I Q_{t+1} \left( \frac{I_{t+1}}{I_t} - \mu_I \right) \left( \frac{I_{t+1}}{I_t} \right)^2 \right\} = 0. \end{aligned}$$

From equation [\(A.19\)](#) we get the standard Tobin's Q relationship:

$$Q_t = E_t \left\{ \mathcal{M}_{t,t+1}^* \left( \alpha \Phi_{t+1} \frac{Y_{t+1}}{K_t} + (1 - \delta) Q_{t+1} \right) \right\}.$$

From [A.20](#) we get the firm's demand for labor

$$\frac{W_t}{P_t} = (1 - \alpha) \Phi_t \frac{Y_t}{N_t}.$$

From [A.21](#) we get the firm's demand for loans

$$1 - \Upsilon_{L,t} = E_t \left\{ \mathcal{M}_{t,t+1}^* d_{t+1} \frac{R_{L,t}}{\pi_{t+1}} \right\}.$$

From [A.22](#) we get the Price Phillips curve

$$\begin{aligned} \left( \frac{\varepsilon}{\varepsilon - 1} \right) \Phi_t - \exp(\mathbb{P}_t) - \left( \frac{\phi_P}{\varepsilon - 1} \right) \pi_t [\pi_t - \tilde{\pi}_t] + \dots \\ \dots + E_t \left\{ \left( \frac{\phi_P}{\varepsilon - 1} \right) \mathcal{M}_{t,t+1}^* \frac{Y_{t+1}}{Y_t} \pi_{t+1} [\pi_{t+1} - \tilde{\pi}_{t+1}] \right\} = 0. \end{aligned}$$

where we assume a symmetric equilibrium so that  $P_t(i) = P_t$  and  $Y_t(i) = Y_t$ .

## A.4 Monetary Policy and Markup Regimes

We assume the model economy's dynamics are conditional on four discrete states of nature. At any given time the model economy can be in one of two monetary policy states and one of two markup states. This is reflected by introducing separate Markov chains for the monetary policy and markup states. The monetary policy state determines whether policy is set according to a Taylor-type rule which occurs in the normal state ( $N$ ), or the economy is at the zero lower bound state ( $Z$ ) where policy follows an exogenous process, so that  $s_{1,t} = N, Z$ . The monetary policy state also affects the markups and markdowns charged by retail banks and the degree of rigidity they face when adjusting market interest rates. The markup state affects whether markups and markdowns on market interest rates are high ( $H$ ) or low ( $L$ ) and the degree of rigidity in adjusting market interest rates, when the economy is away from the lower bound, so that  $s_{2,t} = H, L$ . We introduce two regime-switching parameters,  $\mathbf{z}(s_{1,t})$  which is conditional on the monetary policy regime and  $\mathbf{m}(s_{2,t})$  which is conditional on the markup regime. We assume

$$\mathbf{z}(Z) = 1 \text{ and } \mathbf{z}(N) = 0, \quad (\text{A.23})$$

with the states  $Z$  and  $N$  are governed by the following Markov transition matrix

$$\mathbb{Q}_Z = \begin{bmatrix} 1 - p_{N,Z} & p_{N,Z} \\ p_{Z,N} & 1 - p_{Z,N} \end{bmatrix}. \quad (\text{A.24})$$

We assume the regime-specific markup parameter takes the values

$$\mathbf{m}(H) = 1 \text{ and } \mathbf{m}(L) = 0. \quad (\text{A.25})$$

The states  $H$  and  $L$  are governed by the Markov transition matrix

$$\mathbb{Q}_m = \begin{bmatrix} 1 - q_{H,L} & q_{H,L} \\ q_{L,H} & 1 - q_{L,H} \end{bmatrix}. \quad (\text{A.26})$$

## A.5 The Banking Sector

Following [Gerali et al. \(2010\)](#), the banking sector is divided into three different types of banks: wholesale banks, deposit-taking banks and loan-making banks. Wholesale banks take deposits from deposit-taking banks and combine them with bank equity to supply loans to loan-making banks. Deposit-taking banks supply deposits to aggregators, who in turn supply them to households. Loan-making banks supply deposits to aggregators, who in turn bundle them and supply them to intermediate goods producers.

### A.5.1 Loan and Deposit Demand

#### Deposits

There is a continuum of deposit-taking banks normalized to unit mass. Each bank supplies a differentiated stock of deposits. Deposits supplied to the  $i$ th household are bundled by an aggregator according to the CES technology

$$D_t(i) = \left[ \int_0^1 D_t(i, z)^{1 - \frac{1}{v_D(r_t)}} dz \right]^{\frac{v_D(r_t)}{v_D(r_t) - 1}}.$$

Cost minimization by the perfectly competitive aggregator implies the following demand for deposits by the  $i$ th household for deposits from the  $z$ th bank

$$D_t(i, z) = \left( \frac{R_{D,t}(z)}{R_{D,t}} \right)^{-v_D(r_t)} D_t(i).$$

Aggregating over households

$$D_t = \int_0^1 D_t(i) di = \int_0^1 \left[ \int_0^1 D_t(i, z)^{1 - \frac{1}{v_D(r_t)}} dz \right]^{\frac{v_D(r_t)}{v_D(r_t) - 1}} di = \left[ \int_0^1 D_t(z)^{1 - \frac{1}{v_D(r_t)}} dz \right]^{\frac{v_D(r_t)}{v_D(r_t) - 1}},$$

which implies the aggregate demand function for deposits from the  $z$ th bank

$$D_t(z) = \left( \frac{R_{D,t}(z)}{R_{D,t}} \right)^{-v_D(r_t)} D_t.$$

#### Loans

There is also a continuum of banks, each supplying a differentiated loan product, normalized to unit mass. Loans supplied to the  $h$ th firm are produced according the CES aggregation technology

$$L_t(h) = \left[ \int_0^1 L_t(h, z)^{1 - \frac{1}{v_L(r_t)}} dz \right]^{\frac{v_L(r_t)}{v_L(r_t) - 1}}.$$

Cost minimization by the perfectly competitive loan aggregators implies the demand schedule for the  $h$ th intermediated goods producer for loans produced by the  $z$ th retail bank

$$L_t(h, z) = \left( \frac{R_{L,t}(z)}{R_{L,t}} \right)^{-v_L(r_t)} L_t(h).$$

Aggregating over firms

$$L_t = \int_0^1 L_t(h) dh = \int_0^1 \left[ \int_0^1 L_t(h, z)^{1 - \frac{1}{v_L(r_t)}} dz \right]^{\frac{v_L(r_t)}{v_L(r_t) - 1}} dh = \left[ \int_0^1 L_t(z)^{1 - \frac{1}{v_L(r_t)}} dz \right]^{\frac{v_L(r_t)}{v_L(r_t) - 1}},$$

which also leads to the aggregate demand function for loans from the  $z$ th retail bank

$$L_t(z) = \left( \frac{R_{L,t}(z)}{R_{L,t}} \right)^{-v_L(r_t)} L_t.$$

### A.5.2 Wholesale Banks

Wholesale banks are constrained to obey the following balance sheet identity

$$L_t(w) = D_t(w) + K_{B,t}(w),$$

so that the  $w$ th bank must fund its loans ( $L_t(w)$ ) through deposits ( $D_t(w)$ ) or bank equity ( $K_{B,t}(w)$ ). Bank equity expands and contracts according to the following process

$$K_{B,t}(w) = (1 - \delta_B) K_{B,t-1}(w) + \omega J_{t-1}(w).$$

The  $w$ th wholesale bank maximizes the expected present value of their future profit streams by choosing the quantity of deposits and loans, subject to the balance sheet identity<sup>9</sup>

$$\Psi_0(w) = E_0 \left\{ \sum_{t=0}^{\infty} \mathcal{M}_{0,t}^* \left( \frac{P_0}{P_t} \right) \left[ \begin{array}{l} \mathbb{R}_{L,t} L_t(w) - \mathbb{R}_{D,t} D_t(w) - K_{B,t}(w) - \dots \\ \dots - \Theta_t [L_t(w) - D_t(w) - K_{B,t}(w)] \end{array} \right] \right\},$$

from the wholesaler's first-order conditions we get the following relationships between loan rates, deposit rates and the policy rate

$$\mathbb{R}_{L,t} = R_t,$$

$$\mathbb{R}_{D,t} = R_t.$$

### A.5.3 Retail Banks

Retail banks produce differentiated loans and deposits. They are also subject to frictions that prevent them from adjusting retail interest rates one for one with wholesale interest rates. We consider two types of interest rate-setting frictions. Following [Gerali et al. \(2010\)](#), we assume that retail banks are subject to quadratic costs of adjustment.

### A.5.4 Interest Rate-Setting Frictions: Rotemberg Adjustment Costs

#### Loan Branch

<sup>9</sup>Note that we have dropped the quadratic adjustment cost on changing loans that is present in the [Gerali et al. \(2010\)](#) model because it only had a very minimal impact of the dynamics of loans and lending rates in our model.



The  $z$ th loan-making bank sets the interest rate on loans to maximize the sum of the expected present value of their profits, subject to a quadratic cost of changing interest rates.

$$\Psi_{L,0}(z) = E_t \left\{ \sum_{t=0}^{\infty} \mathcal{M}_{0,t}^* \left( \frac{P_0}{P_t} \right) \left[ \begin{array}{l} R_{L,t}(z) L_t(z) - \exp(\varepsilon_{L,t}) \mathbb{R}_{L,t} L_t(z) - \dots \\ \dots - \frac{\phi_L(r_t)}{2} R_{L,t} L_t \left[ \frac{R_{L,t}(z)}{R_{L,t-1}(z)} - 1 \right]^2 \end{array} \right] \right\}.$$

Substituting in the demand for loans

$$\Psi_{L,0}(z) = E_t \left\{ \sum_{t=0}^{\infty} \mathcal{M}_{0,t}^* \left( \frac{P_0}{P_t} \right) \left[ \begin{array}{l} R_{L,t}(z)^{1-v_L(r_t)} R_{L,t}^{v_L(r_t)} L_t - \dots \\ \dots - \exp(\varepsilon_{L,t}) \mathbb{R}_{L,t} R_{L,t}(z)^{-v_L(r_t)} R_{L,t}^{v_L(r_t)} L_t - \dots \\ \dots - \frac{\phi_L(r_t)}{2} R_{L,t} L_t \left[ \frac{R_{L,t}(z)}{R_{L,t-1}(z)} - 1 \right]^2 \end{array} \right] \right\}.$$

The first-order condition for the  $z$ th loan-making bank

$$\begin{aligned} \frac{\partial \Psi_{L,t}(z)}{\partial R_{L,t}(z)} &= (1 - v_L(r_t)) L_t(z) + v_L(r_t) \exp(\varepsilon_{L,t}) \frac{\mathbb{R}_{L,t}}{R_{L,t}(z)} L_t(z) - \dots \\ &\quad \dots - \phi_L(r_t) \frac{R_{L,t} L_t}{R_{L,t-1}(z)} \left[ \frac{R_{L,t}(z)}{R_{L,t-1}(z)} - 1 \right] + \dots \\ &\quad \dots + E_t \left\{ \phi_L(r_{t+1}) \mathcal{M}_{t,t+1}^* \frac{R_{L,t+1} R_{L,t+1}(z) L_{t+1}}{\pi_{t+1} R_{L,t}(z)^2} \left[ \frac{R_{L,t+1}(z)}{R_{L,t}(z)} - 1 \right] \right\} = 0. \end{aligned}$$

Which gives the following Phillips curve relationship for interest rate setting

$$\begin{aligned} &\left( \frac{v_L(r_t)}{v_L(r_t) - 1} \right) \exp(\varepsilon_{L,t}) \frac{\mathbb{R}_{L,t}}{R_{L,t}} - 1 - \left( \frac{\phi_L(r_t)}{v_L(r_t) - 1} \right) \frac{R_{L,t}}{R_{L,t-1}} \left[ \frac{R_{L,t}}{R_{L,t-1}} - 1 \right] + \dots \\ &\quad \dots + E_t \left\{ \left( \frac{\phi_L(r_{t+1})}{v_L(r_t) - 1} \right) \mathcal{M}_{t,t+1}^* \left( \frac{1}{\pi_{t+1}} \right) \left( \frac{R_{L,t+1}}{R_{L,t}} \right)^2 \frac{L_{t+1}}{L_t} \left[ \frac{R_{L,t+1}}{R_{L,t}} - 1 \right] \right\} = 0, \quad (\text{A.27}) \end{aligned}$$

where we assume a symmetric equilibrium so that  $R_{L,t}(z) = R_{L,t}$  and  $L_t(z) = L_t$ . We further simplify this as follows

$$\begin{aligned} &\left( \frac{v_L(r_t)}{v_L(r_t) - 1} \right) \exp(\varepsilon_{L,t}) \frac{\mathbb{R}_{L,t}}{R_{L,t}} - 1 - \tilde{\phi}_L(r_t) \frac{R_{L,t}}{R_{L,t-1}} \left[ \frac{R_{L,t}}{R_{L,t-1}} - 1 \right] + \dots \\ &\quad \dots + E_t \left\{ \tilde{\phi}_L(r_{t+1}) \mathcal{M}_{t,t+1}^* \left( \frac{1}{\pi_{t+1}} \right) \left( \frac{R_{L,t+1}}{R_{L,t}} \right)^2 \frac{L_{t+1}}{L_t} \left[ \frac{R_{L,t+1}}{R_{L,t}} - 1 \right] \right\} = 0. \quad (\text{A.28}) \end{aligned}$$

where  $\tilde{\phi}_L(r_t) = \frac{\phi_L(r_t)}{v_L(r_t) - 1}$  and

$$\tilde{\phi}_L(r_t) = \mathbf{z}(s_{1,t}) \tilde{\phi}_{ZLB,L} + (1 - \mathbf{z}(s_{1,t})) (\mathbf{m}(s_{2,t}) \tilde{\phi}_{H,L} + (1 - \mathbf{m}(s_{2,t})) \tilde{\phi}_{L,L}). \quad (\text{A.29})$$

Likewise, the markup on loans and the markdown on deposits are determined by

$$\mu_L(r_t) = \mathbf{z}(s_{1,t}) \mu_{ZLB,L} + (1 - \mathbf{z}(s_{1,t})) (\mathbf{m}(s_{2,t}) \mu_{H,L} + (1 - \mathbf{m}(s_{2,t})) \mu_{L,L}), \quad (\text{A.30})$$

where the markup is related to the elasticity of substitution through

$$v_L(r_t) = \frac{\mu_L(r_t)}{\mu_L(r_t) - 1}. \quad (\text{A.31})$$

### Deposit Branch

The  $z$ th deposit taking bank sets interest rates to maximize their expected discounted future stream of profits, subject to a quadratic adjustment cost on changing interest rates

$$\Psi_{D,0}(z) = E_t \left\{ \sum_{t=0}^{\infty} \mathcal{M}_{t,t+1}^* \left( \frac{P_0}{P_t} \right) \left[ \begin{array}{l} \exp(\varepsilon_{D,t}) \mathbb{R}_{D,t} D_t(z) - R_{D,t}(z) D_t(z) - \dots \\ \dots - \frac{\phi_D(r_t)}{2} R_{D,t} D_t \left[ \frac{R_{D,t}(z)}{R_{D,t-1}(z)} - 1 \right]^2 \end{array} \right] \right\}.$$

Substituting in the demand function for deposits

$$\Psi_{D,0}(z) = E_t \left\{ \sum_{t=0}^{\infty} \mathcal{M}_{t,t+1}^* \left( \frac{P_0}{P_t} \right) \left[ \begin{array}{l} \exp(\varepsilon_{D,t}) \mathbb{R}_{D,t} R_{D,t}(z)^{-v_D(r_t)} R_{D,t}^{v_D(r_t)} D_t - \dots \\ \dots - R_{D,t}(z)^{1-v_D(r_t)} R_{D,t}^{v_D(r_{t+1})} D_t - \dots \\ \dots - \frac{\phi_D(r_t)}{2} R_{D,t} D_t \left[ \frac{R_{D,t}(z)}{R_{D,t-1}(z)} - 1 \right]^2 \end{array} \right] \right\}.$$

The first-order condition for deposits

$$\begin{aligned} \frac{\partial \Psi_{D,t}(z)}{\partial R_{D,t}(z)} &= -v_D(r_t) \exp(\varepsilon_{D,t}) \frac{\mathbb{R}_{D,t}}{R_{D,t}(z)} D_t(z) - (1 - v_D(r_t)) D_t(z) - \dots \\ &\quad \dots - \phi_D(r_t) \frac{R_{D,t} D_t}{R_{D,t-1}(z)} \left[ \frac{R_{D,t}(z)}{R_{D,t-1}(z)} - 1 \right] + \dots \\ &\quad \dots + E_t \left\{ \phi_D(r_{t+1}) \mathcal{M}_{t,t+1}^* \frac{R_{D,t+1} R_{D,t+1}(z) D_{t+1}}{\pi_{t+1} R_{D,t}(z)^2} \left[ \frac{R_{D,t+1}(z)}{R_{D,t}(z)} - 1 \right] \right\} = 0, \end{aligned}$$

which gives the following Phillips curve-type relationship for interest rates set by deposit-taking banks

$$\begin{aligned} 1 - \left( \frac{v_D(r_t)}{v_D(r_t) - 1} \right) \exp(\varepsilon_{D,t}) \frac{\mathbb{R}_{D,t}}{R_{D,t}} - \left( \frac{\phi_D(r_t)}{v_D(r_t) - 1} \right) \frac{R_{D,t}}{R_{D,t-1}} \left[ \frac{R_{D,t}}{R_{D,t-1}} - 1 \right] + \dots \\ \dots + E_t \left\{ \left( \frac{\phi_D(r_{t+1})}{v_D(r_t) - 1} \right) \mathcal{M}_{t,t+1}^* \left( \frac{1}{\pi_{t+1}} \right) \left( \frac{R_{D,t+1}}{R_{D,t}} \right)^2 \frac{D_{t+1}}{D_t} \left[ \frac{R_{D,t+1}}{R_{D,t}} - 1 \right] \right\} = 0, \quad (\text{A.32}) \end{aligned}$$

where we assume a symmetric equilibrium so that  $R_{D,t}(z) = R_{D,t}$  and  $D_t(z) = D_t$ . We further simplify this as follows

$$\begin{aligned} 1 - \left( \frac{v_D(r_t)}{v_D(r_t) - 1} \right) \exp(\varepsilon_{D,t}) \frac{\mathbb{R}_{D,t}}{R_{D,t}} - \tilde{\phi}_D(r_t) \frac{R_{D,t}}{R_{D,t-1}} \left[ \frac{R_{D,t}}{R_{D,t-1}} - 1 \right] + \dots \\ \dots + E_t \left\{ \tilde{\phi}_D(r_{t+1}) \mathcal{M}_{t,t+1}^* \left( \frac{1}{\pi_{t+1}} \right) \left( \frac{R_{D,t+1}}{R_{D,t}} \right)^2 \frac{D_{t+1}}{D_t} \left[ \frac{R_{D,t+1}}{R_{D,t}} - 1 \right] \right\} = 0. \quad (\text{A.33}) \end{aligned}$$

where  $\tilde{\phi}_D(r_t) = \frac{\phi_L(r_t)}{v_L(r_t)-1}$  and

$$\tilde{\phi}_D(r_t) = \mathbf{z}(s_{1,t})\tilde{\phi}_{ZLB,D} + (1 - \mathbf{z}(s_{1,t}))(\mathbf{m}(s_{2,t})\tilde{\phi}_{H,D} + (1 - \mathbf{m}(s_{2,t}))\tilde{\phi}_{L,D}). \quad (\text{A.34})$$

Likewise, the markup on loans and the markdown on deposits are determined by

$$\mu_D(r_t) = \mathbf{z}(s_{1,t})\mu_{ZLB,D} + (1 - \mathbf{z}(s_{1,t}))(\mathbf{m}(s_{2,t})\mu_{H,D} + (1 - \mathbf{m}(s_{2,t}))\mu_{L,D}), \quad (\text{A.35})$$

where the markdown is related to the elasticity of substitution through

$$v_D(r_t) = \frac{\mu_D(r_t)}{\mu_D(r_t) - 1}. \quad (\text{A.36})$$

## A.6 Monetary Policy

The monetary authority sets policy according according to

$$R_t = \max(R_{ZLB,t}, R_t^*), \quad (\text{A.37})$$

where  $R_t^*$  is the interest rate set in normal times according to the Taylor-type rule

$$R_t^* = R_{t-1}^{*\rho_R} \left( R^* \left( \frac{\pi_t}{\pi} \right)^{\kappa_\pi} \left( \hat{Y}_t \right)^{\kappa_Y} \right)^{1-\rho_R} \exp(\varepsilon_{R,t}), \quad (\text{A.38})$$

where  $\hat{Y}_t$  is the output gap. We use a measure of the output gap in the Taylor-type rule because growth measures of GDP do not result in a negative shadow interest rate when at the lower bound. We use the CBO's output gap as the measure that policy responds to because [Primiceri and Justiniano \(2009\)](#) show that measures of potential output from a flex-price DSGE model closely resemble official measures like the CBO's output gap. We assume that the CBO output gap can be described by the following process

$$\hat{Y}_t = \kappa_P \left( \frac{Y_t}{Y_t^P} \right) \exp(F_t), \quad (\text{A.39})$$

where  $Y_t^P$  is potential output and  $F_t$  is an exogenous process with the following law of motion

$$F_t = \rho_F F_{t-1} + \varepsilon_{F,t}. \quad (\text{A.40})$$

We set the priors on  $\rho_F$  and  $\sigma_F$  to ensure that  $F_t$  only plays a limited role in explaining the output gap. We define potential output as the level of output in an economy without pricing, wage and interest rate frictions, without the monopolist competition in the goods, labor and banking markets and without the loan-in-advance constraint. In other words,

potential output is the level that would apply in the real business cycle representation of a frictionless economy. When the economy is at the lower bound, interest rates evolve according to

$$R_{ZLB,t} = \mathbf{K} + \varepsilon_{ZLB,t}, \quad (\text{A.41})$$

where  $\mathbf{K}$  is the effective lower bound on interest rates and  $\varepsilon_{ZLB}$  is a small shock that prevents a stochastic singularity at the lower bound. which in the regime-switching setup we replace (A.37) with

$$R_t = \mathbf{z}(s_{1,t})R_{ZLB,t} + (1 - \mathbf{z}(s_{1,t}))R_t^*, \quad (\text{A.42})$$

## A.7 Fiscal Policy

Government spending follows a very simple autoregressive process

$$\frac{G_t}{Z_{Y,t}} = \left( \frac{G_{t-1}}{Z_{Y,t-1}} \right)^{\rho_G} \left( \frac{G}{Z_Y} \right)^{1-\rho_G} \exp(\varepsilon_{G,t}),$$

while the government runs balanced budgets, setting lump sum taxes equal to government expenditures

$$T_t = G_t.$$

## A.8 Market Clearing and Equilibrium

We assume a symmetric equilibrium so that:  $N_t = \int_0^1 N_t(i)di$ ,  $Y_t = \int_0^1 Y_t(h)dh$ ,  $D_t = \int_0^1 D_t(z)dz$ ,  $L_t = \int_0^1 L_t(z)dz$ ,  $J_t = \int_0^1 J_t(z)dz$ . Substituting the profit and cost functions into the budget constraint gives:

$$C_t + \frac{P_{I,t}}{P_t} I_t + G_t + D_t = \frac{D_{t-1} R_{D,t-1}}{\pi_t} + L_t - \frac{L_{t-1} R_{L,t-1}}{\pi_t} + Y_t + (1 - \omega) \frac{J_{t-1}}{\pi_t}. \quad (\text{A.43})$$

## A.9 Potential Output

The following set of equations describe the frictionless economy:

$$Y_t^P = C_t^P + I_t^P + G_t^P, \quad (\text{A.44})$$

$$K_t^P = I_t^P \left( 1 - \frac{\phi_I}{2} \left( \frac{I_t^P}{I_{t-1}^P} - \mu_I \right)^2 \right) + (1 - \delta) K_{t-1}^P, \quad (\text{A.45})$$

$$1 = Q_t^P \left[ 1 - \frac{\phi_I}{2} \left( \frac{I_t^P}{I_{t-1}^P} - \mu_I \right)^2 - \phi_I \left( \frac{I_t^P}{I_{t-1}^P} - \mu_I \right) \frac{I_t^P}{I_{t-1}^P} \right] + \dots$$

$$\dots + E_t \left\{ \mathcal{M}_{t,t+1}^P \phi_I Q_{t+1}^P \left( \frac{I_{t+1}^P}{I_t^P} - \mu_I \right) \left( \frac{I_{t+1}^P}{I_t^P} \right)^2 \right\}, \quad (\text{A.46})$$

$$Q_t^P = E_t \left\{ \mathcal{M}_{t,t+1}^P \left( \alpha \frac{Y_{t+1}^P}{K_t^P} + (1 - \delta) Q_{t+1}^P \right) \right\}, \quad (\text{A.47})$$

$$(1 - \alpha) \frac{Y_t^P}{N_t^P} = \kappa_{P,t} \frac{(N_t^P)^\eta}{\lambda_t^P}, \quad (\text{A.48})$$

$$\lambda_t^P = A_t (C_t^P - \chi C_{t-1}^P)^{-\sigma}, \quad (\text{A.49})$$

$$\mathcal{M}_{t,t+1}^P = E_t \left\{ \beta \frac{\lambda_{t+1}^P}{\lambda_t^P} \right\}, \quad (\text{A.50})$$

$$Y_t^P = Z_t (K_{t-1}^P)^\alpha (N_t^P)^{1-\alpha}, \quad (\text{A.51})$$

$$W_t^P = (1 - \alpha) \frac{Y_t^P}{N_t^P}. \quad (\text{A.52})$$

## A.10 Trends

The Cobb-Douglas production functions in the intermediate goods and investment goods producing sectors imply the following composite technology processes. The effective investment technology

$$\mathbb{Z}_{I,t} = Z_{I,t} \mathbb{Z}_{Y,t}, \quad (\text{A.53})$$

where  $\mathbb{Z}_{Y,t}$  is the as yet unknown composite technology for intermediate goods. The intermediate investment production function implies the following relationship for the effective technology in that sector

$$\mathbb{Z}_{Y,t} = Z_t (Z_{I,t} \mathbb{Z}_{Y,t})^\alpha, \quad (\text{A.54})$$

$$\mathbb{Z}_{Y,t} = Z_t^{\frac{1}{1-\alpha}} Z_{I,t}^{\frac{\alpha}{1-\alpha}}. \quad (\text{A.55})$$

Combining [A.53](#) and [A.55](#) allows us to write the effective investment technology in terms of neutral and investment specific technology

$$\mathbb{Z}_{I,t} = Z_t^{\frac{1}{1-\alpha}} Z_{I,t}^{\frac{1}{1-\alpha}}. \quad (\text{A.56})$$

## A.11 Model Equations

For the set of model variables:  $C_t, I_t, K_t, Q_t, P_{I,t}/P_t, D_t, R_{D,t}, \pi_t, W_t/P_t, \pi_{W,t}, N_t, \lambda_t, \Upsilon_{L,t}, \Phi_t, \mathcal{M}_{t,t+1}^*, R_{L,t}, Y_t, \mathbb{R}_{D,t}, \mathbb{R}_{L,t}, L_t, K_{B,t}, J_t, R_t, A_t, Z_t, Z_{I,t}, \mathbb{Z}_{I,t}, \mathbb{Z}_{Y,t}, \mathcal{A}_{Z,t}, \mathcal{A}_{Z_{I,t}}, \tilde{\pi}_t, \tilde{\pi}_{W,t}, \hat{N}_t, R_t^*, R_{ZLB,t}, \tilde{G}_t, \Delta \log Y_t, \Delta \log C_t, \Delta \log I_t, \hat{Y}_t, F_t, N_t^P, Q_t^P, Y_t^P, K_t^P, I_t^P, C_t^P, W_t^P, \mathcal{M}_t^P, \lambda_t^P, \kappa_t$ , and  $\mathbb{P}_t$ , the model is described by the following set of equations:

$$C_t + \frac{P_{I,t}}{P_t} I_t + G_t + D_t = \frac{D_{t-1} R_{D,t-1}}{\pi_t} + L_t - \frac{L_{t-1} R_{L,t-1}}{\pi_t} + Y_t + (1 - \omega) \frac{J_{t-1}}{\pi_t}, \quad (\text{A.57})$$

$$\psi I_t = L_t, \quad (\text{A.58})$$

$$K_t = I_t \left( 1 - \frac{\phi_I}{2} \left( \frac{I_t}{I_{t-1}} - \mu_I \right)^2 \right) + (1 - \delta) K_{t-1}, \quad (\text{A.59})$$

$$\begin{aligned} \frac{P_{I,t}}{P_t} = Q_t \left[ 1 - \frac{\phi_I}{2} \left( \frac{I_t}{I_{t-1}} - \mu_I \right)^2 - \phi_I \left( \frac{I_t}{I_{t-1}} - \mu_I \right) \frac{I_t}{I_{t-1}} \right] + \psi \Upsilon_{L,t} \frac{P_{I,t}}{P_t} + \dots \\ \dots + E_t \left\{ \mathcal{M}_{t,t+1}^* \phi_I Q_{t+1} \left( \frac{I_{t+1}}{I_t} - \mu_I \right) \left( \frac{I_{t+1}}{I_t} \right)^2 \right\}, \end{aligned} \quad (\text{A.60})$$

$$Q_t = E_t \left\{ \mathcal{M}_{t,t+1}^* \left( \alpha \Phi_{t+1} \frac{Y_{t+1}}{K_t} + (1 - \delta) Q_{t+1} \right) \right\}, \quad (\text{A.61})$$

$$\begin{aligned} \left( \frac{\phi_W}{v-1} \right) \pi_{W,t} [\pi_{W,t} - \tilde{\pi}_{W,t}] = \left( \frac{v}{v-1} \right) \kappa \frac{N_t^\eta P_t}{\lambda_t W_t} - 1 + \dots \\ \dots + E_t \left\{ \left( \frac{\phi_W}{v-1} \right) \mathcal{M}_{t,t+1}^* \frac{\pi_{W,t+1}^2}{\pi_{t+1}} \left( \frac{N_{t+1}}{N_t} \right) [\pi_{W,t+1} - \tilde{\pi}_{W,t+1}] \right\}, \end{aligned} \quad (\text{A.62})$$

$$\frac{W_t}{P_t} = \frac{\pi_{W,t} W_{t-1}}{\pi_t P_{t-1}}, \quad (\text{A.63})$$

$$\lambda_t = A_t (C_t - \chi C_{t-1})^{-\sigma} \mathbb{Z}_{Y,t}^{\sigma-1}, \quad (\text{A.64})$$

$$\lambda_t = E_t \left\{ \beta d_{t+1} \frac{\lambda_{t+1} R_{D,t}}{\pi_{t+1}} \right\}, \quad (\text{A.65})$$

$$1 - \Upsilon_{L,t} = E_t \left\{ \mathcal{M}_{t,t+1}^* d_{t+1} \frac{R_{L,t}}{\pi_{t+1}} \right\}, \quad (\text{A.66})$$

$$\mathcal{M}_{t,t+1}^* = E_t \left\{ \beta \frac{\lambda_{t+1}}{\lambda_t} \right\}, \quad (\text{A.67})$$

$$\begin{aligned} \left( \frac{\phi_P}{\varepsilon - 1} \right) \pi_t [\pi_t - \tilde{\pi}_t] &= \left( \frac{\varepsilon}{\varepsilon - 1} \right) \Phi_t - \exp(\mathbb{P}_t) + \dots \\ &\dots + E_t \left\{ \left( \frac{\phi_P}{\varepsilon - 1} \right) \mathcal{M}_{t,t+1}^* \frac{Y_{t+1}}{Y_t} \pi_{t+1} [\pi_{t+1} - \tilde{\pi}_{t+1}] \right\}, \end{aligned} \quad (\text{A.68})$$

$$K_{B,t} = (1 - \delta_B) K_{B,t-1} + \omega J_{t-1}, \quad (\text{A.69})$$

$$J_t = R_{L,t} L_t - R_{D,t} D_t - R_t K_{B,t}, \quad (\text{A.70})$$

$$L_t = D_t + K_{B,t}, \quad (\text{A.71})$$

$$\mathbb{R}_{D,t} = R_t, \quad (\text{A.72})$$

$$\mathbb{R}_{L,t} = R_t, \quad (\text{A.73})$$

$$Y_t = Z_t K_{t-1}^\alpha N_t^{1-\alpha}, \quad (\text{A.74})$$

$$\frac{W_t}{P_t} = (1 - \alpha) \Phi_t \frac{Y_t}{N_t}, \quad (\text{A.75})$$

$$R_t^* = R_{t-1}^{*\rho_R} \left( R^* \left( \frac{\pi_t}{\pi} \right)^{\kappa_\pi} \left( \hat{Y}_t \right)^{\kappa_Y} \right)^{1-\rho_R} \exp(\varepsilon_{R,t}), \quad (\text{A.76})$$

$$\hat{Y}_t = \kappa_P \left( \frac{Y_t}{Y_t^P} \right) \exp(F_t), \quad (\text{A.77})$$

$$F_t = \rho_F F_{t-1} + \varepsilon_{F,t}, \quad (\text{A.78})$$

$$R_{ZLB,t} = \mathbf{K} + \varepsilon_{ZLB,t}, \quad (\text{A.79})$$

$$R_t = \mathbf{z}(s_{1,t})R_{ZLB,t} + (1 - \mathbf{z}(s_{1,t}))R_t^*, \quad (\text{A.80})$$

$$\frac{G_t}{Z_{Y,t}} = \left( \frac{G_{t-1}}{Z_{Y,t-1}} \right)^{\rho_G} \left( \frac{G}{Z_Y} \right)^{1-\rho_G} \exp(\varepsilon_{G,t}), \quad (\text{A.81})$$

$$\frac{P_{I,t}}{P_t} = \frac{1}{Z_{I,t}}, \quad (\text{A.82})$$

$$\log A_t = \rho_A \log A_{t-1} + \varepsilon_{A,t}, \quad (\text{A.83})$$

$$Z_t = Z_0 \exp(g_Z t + \mathcal{A}_{Z,t}), \quad (\text{A.84})$$

$$Z_{I,t} = Z_{I,0} \exp(g_{Z_I} t + \mathcal{A}_{Z_I,t}), \quad (\text{A.85})$$

$$\begin{aligned} & \left( \frac{v_L(r_t)}{v_L(r_t) - 1} \right) \exp(\varepsilon_{L,t}) \frac{\mathbb{R}_{L,t}}{R_{L,t}} - 1 - \tilde{\phi}_L(r_t) \frac{R_{L,t}}{R_{L,t-1}} \left[ \frac{R_{L,t}}{R_{L,t-1}} - 1 \right] + \dots \\ & \dots + E_t \left\{ \tilde{\phi}_L(r_{t+1}) \mathcal{M}_{t,t+1}^* \left( \frac{1}{\pi_{t+1}} \right) \left( \frac{R_{L,t+1}}{R_{L,t}} \right)^2 \frac{L_{t+1}}{L_t} \left[ \frac{R_{L,t+1}}{R_{L,t}} - 1 \right] \right\} = 0, \quad (\text{A.86}) \end{aligned}$$

$$\begin{aligned} & 1 - \left( \frac{v_D(r_t)}{v_D(r_t) - 1} \right) \exp(\varepsilon_{D,t}) \frac{\mathbb{R}_{D,t}}{R_{D,t}} - \tilde{\phi}_D(r_t) \frac{R_{D,t}}{R_{D,t-1}} \left[ \frac{R_{D,t}}{R_{D,t-1}} - 1 \right] + \dots \\ & \dots + E_t \left\{ \tilde{\phi}_D(r_{t+1}) \mathcal{M}_{t,t+1}^* \left( \frac{1}{\pi_{t+1}} \right) \left( \frac{R_{D,t+1}}{R_{D,t}} \right)^2 \frac{D_{t+1}}{D_t} \left[ \frac{R_{D,t+1}}{R_{D,t}} - 1 \right] \right\} = 0, \quad (\text{A.87}) \end{aligned}$$

$$Y_t^P = C_t^P + I_t^P + G_t^P, \quad (\text{A.88})$$

$$K_t^P = I_t^P \left( 1 - \frac{\phi_I}{2} \left( \frac{I_t^P}{I_{t-1}^P} - \mu_I \right)^2 \right) + (1 - \delta) K_{t-1}^P, \quad (\text{A.89})$$

$$\begin{aligned} 1 = Q_t^P & \left[ 1 - \frac{\phi_I}{2} \left( \frac{I_t^P}{I_{t-1}^P} - \mu_I \right)^2 - \phi_I \left( \frac{I_t^P}{I_{t-1}^P} - \mu_I \right) \frac{I_t^P}{I_{t-1}^P} \right] + \dots \\ & \dots + E_t \left\{ \mathcal{M}_{t,t+1}^P \phi_I Q_{t+1}^P \left( \frac{I_{t+1}^P}{I_t^P} - \mu_I \right) \left( \frac{I_{t+1}^P}{I_t^P} \right)^2 \right\}, \quad (\text{A.90}) \end{aligned}$$



$$Q_t^P = E_t \left\{ \mathcal{M}_{t,t+1}^P \left( \alpha \frac{Y_{t+1}^P}{K_t^P} + (1 - \delta) Q_{t+1}^P \right) \right\}, \quad (\text{A.91})$$

$$(1 - \alpha) \frac{Y_t^P}{N_t^P} = \kappa_{P,t} \frac{(N_t^P)^\eta}{\lambda_t^P}, \quad (\text{A.92})$$

$$\lambda_t^P = A_t (C_t^P - \chi C_{t-1}^P)^{-\sigma}, \quad (\text{A.93})$$

$$\mathcal{M}_{t,t+1}^P = E_t \left\{ \beta \frac{\lambda_{t+1}^P}{\lambda_t^P} \right\}, \quad (\text{A.94})$$

$$Y_t^P = Z_t (K_{t-1}^P)^\alpha (N_t^P)^{1-\alpha}, \quad (\text{A.95})$$

$$W_t^P = (1 - \alpha) \frac{Y_t^P}{N_t^P}, \quad (\text{A.96})$$

$$\mathbb{P}_t = \rho_{\mathbb{P}} \mathbb{P}_{t-1} + \varepsilon_{\mathbb{P},t}, \quad (\text{A.97})$$

$$\kappa_t = \rho_{\kappa} \kappa_{t-1} + \varepsilon_{\kappa,t}, \quad (\text{A.98})$$

$$\tilde{\pi}_t = \pi_{t-1}^\xi \pi^{1-\xi}, \quad (\text{A.99})$$

$$\tilde{\pi}_{W,t} = \pi_{t-1}^{\xi_W} \pi^{1-\xi_W}, \quad (\text{A.100})$$

$$\hat{N}_t = \frac{N_t}{N} \exp(\varepsilon_{N,t}), \quad (\text{A.101})$$

$$\Delta \log Y_t = \log Y_t - \log Y_{t-1}, \quad (\text{A.102})$$

$$\Delta \log C_t = \log C_t - \log C_{t-1}, \quad (\text{A.103})$$

$$\Delta \log I_t = \log I_t - \log I_{t-1}, \quad (\text{A.104})$$

$$\mathcal{A}_{Z,t} = \rho_{\mathcal{A}_Z} \mathcal{A}_{Z,t} + \varepsilon_{Z,t}, \quad (\text{A.105})$$

$$\mathcal{A}_{Z_I,t} = \rho_{\mathcal{A}_{Z_I}} \mathcal{A}_{Z_I,t} + \varepsilon_{Z_I,t}, \quad (\text{A.106})$$

$$\mathbb{Z}_{Y,t} = Z_t^{\frac{1}{1-\alpha}} Z_{I,t}^{\frac{\alpha}{1-\alpha}}, \quad (\text{A.107})$$

$$\mathbb{Z}_{I,t} = Z_t^{\frac{1}{1-\alpha}} Z_{I,t}^{\frac{1}{1-\alpha}}. \quad (\text{A.108})$$

## A.12 Stochastically Detrended Model

The model is non-stationary. To make the model stationary we rewrite the set of model equations in terms of the following stochastically detrended variables:  $\tilde{C}_t = C_t/\mathbb{Z}_{Y,t}$ ,  $\tilde{I}_t = I_t/\mathbb{Z}_{I,t}$ ,  $\tilde{K}_t = K_t/\mathbb{Z}_{I,t}$ ,  $\tilde{Q}_t = Q_t Z_{I,t}$ ,  $\tilde{D}_t = D_t/\mathbb{Z}_{Y,t}$ ,  $R_{D,t}$ ,  $\pi_t$ ,  $\tilde{W}_t = \frac{W_t}{P_t \mathbb{Z}_{Y,t}}$ ,  $\pi_{W,t}$ ,  $N_t$ ,  $\tilde{\lambda}_t = \lambda_t \mathbb{Z}_{Y,t}$ ,  $\Upsilon_{L,t}$ ,  $\Phi_t$ ,  $\mathcal{M}_{t,t+1}^*$ ,  $R_{L,t}$ ,  $\tilde{Y}_t = Y_t/\mathbb{Z}_{Y,t}$ ,  $\mathbb{R}_{D,t}$ ,  $\mathbb{R}_{L,t}$ ,  $\tilde{L}_t = L_t/\mathbb{Z}_{Y,t}$ ,  $\tilde{K}_{b,t} = K_{b,t}/\mathbb{Z}_{Y,t}$ ,  $\tilde{J}_t = J_t/\mathbb{Z}_{Y,t}$ ,  $\tilde{Q}_t^P = Q_t^P Z_{I,t}$ ,  $\tilde{Y}_t^P = Y_t^P/\mathbb{Z}_{Y,t}$ ,  $\tilde{K}_t^P = K_t^P/\mathbb{Z}_{I,t}$ ,  $\tilde{I}_t^P = I_t^P/\mathbb{Z}_{I,t}$ ,  $\tilde{C}_t^P = C_t^P/\mathbb{Z}_{Y,t}$ ,  $\tilde{W}_t^P = W_t^P/\mathbb{Z}_{Y,t}$  and  $\tilde{\lambda}_t^P = C_t/\mathbb{Z}_{Y,t}$ .

The transformed set of model equations:

$$\tilde{C}_t + \tilde{I}_t + \tilde{G}_t + \tilde{D}_t = \frac{\tilde{D}_{t-1} R_{D,t-1}}{\mu_{Y,t} \pi_t} + \tilde{L}_t - \frac{\tilde{L}_{t-1} R_{L,t-1}}{\mu_{Y,t} \pi_t} + \tilde{Y}_t + (1 - \omega) \frac{\tilde{J}_{t-1}}{\mu_{Y,t} \pi_t}, \quad (\text{A.109})$$

$$\psi \tilde{I}_t = \tilde{L}_t, \quad (\text{A.110})$$

$$\tilde{K}_t = \tilde{I}_t \left( 1 - \frac{\phi_I}{2} \left( \frac{\tilde{I}_t}{\tilde{I}_{t-1}} \mu_{I,t} - \mu_I \right)^2 \right) + (1 - \delta) \frac{\tilde{K}_{t-1}}{\mu_{I,t}}, \quad (\text{A.111})$$

$$\begin{aligned} \tilde{P}_{I,t} = \tilde{Q}_t & \left[ 1 - \frac{\phi_I}{2} \left( \frac{\tilde{I}_t}{\tilde{I}_{t-1}} \mu_{I,t} - \mu_I \right)^2 - \phi_I \left( \frac{\tilde{I}_t}{\tilde{I}_{t-1}} \mu_{I,t} - \mu_I \right) \frac{\tilde{I}_t}{\tilde{I}_{t-1}} \mu_{I,t} \right] + \psi \Upsilon_{L,t} \tilde{P}_{I,t} + \dots \\ & \dots + E_t \left\{ \mathcal{M}_{t,t+1}^* \phi_I \frac{\tilde{Q}_{t+1}}{\mu_{I,t+1}} \left( \frac{\tilde{I}_{t+1}}{\tilde{I}_t} \mu_{I,t+1} - \mu_I \right) \left( \frac{\tilde{I}_{t+1}}{\tilde{I}_t} \mu_{I,t+1} \right)^2 \right\}, \quad (\text{A.112}) \end{aligned}$$

$$\tilde{Q}_t = E_t \left\{ \mathcal{M}_{t,t+1}^* \left( \alpha \Phi_{t+1} \frac{\tilde{Y}_{t+1}}{\tilde{K}_t} \mu_{Y,t+1} + (1 - \delta) \frac{\tilde{Q}_{t+1}}{\mu_{Z_1,t+1}} \right) \right\}, \quad (\text{A.113})$$

$$\begin{aligned} \left( \frac{\phi_W}{v-1} \right) \pi_{W,t} [\pi_{W,t} - \tilde{\pi}_{W,t}] &= \left( \frac{v}{v-1} \right) \kappa \frac{N_t^\eta}{\tilde{\lambda}_t \tilde{W}_t} - 1 + \dots \\ &\dots + E_t \left\{ \left( \frac{\phi_W}{v-1} \right) \mathcal{M}_{t,t+1}^* \frac{\pi_{W,t+1}^2}{\pi_{t+1}} \left( \frac{N_{t+1}}{N_t} \right) [\pi_{W,t+1} - \tilde{\pi}_{W,t+1}] \right\}, \end{aligned} \quad (\text{A.114})$$

$$\tilde{W}_t = \frac{\pi_{W,t}}{\mu_{Y,t} \pi_t} \tilde{W}_{t-1}, \quad (\text{A.115})$$

$$\tilde{\lambda}_t = A_t \left( \tilde{C}_t - \chi \frac{\tilde{C}_{t-1}}{\mu_{Y,t}} \right)^{-\sigma}, \quad (\text{A.116})$$

$$\tilde{\lambda}_t = E_t \left\{ \beta d_{t+1} \frac{\tilde{\lambda}_{t+1} R_{D,t}}{\mu_{Y,t+1} \pi_{t+1}} \right\}, \quad (\text{A.117})$$

$$1 - \Upsilon_{L,t} = E_t \left\{ \mathcal{M}_{t,t+1}^* d_{t+1} \frac{R_{L,t}}{\pi_{t+1}} \right\}, \quad (\text{A.118})$$

$$\mathcal{M}_{t,t+1}^* = E_t \left\{ \beta \frac{\tilde{\lambda}_{t+1}}{\mu_{Y,t+1} \tilde{\lambda}_t} \right\}, \quad (\text{A.119})$$

$$\begin{aligned} \left( \frac{\phi_P}{\varepsilon-1} \right) \pi_t [\pi_t - \tilde{\pi}_t] &= \left( \frac{\varepsilon}{\varepsilon-1} \right) \Phi_t - \exp(\mathbb{P}_t) + \dots \\ &\dots + E_t \left\{ \left( \frac{\phi_P}{\varepsilon-1} \right) \mathcal{M}_{t,t+1}^* \frac{\tilde{Y}_{t+1}}{\tilde{Y}_t} \mu_{Y,t+1} \pi_{t+1} [\pi_{t+1} - \tilde{\pi}_{t+1}] \right\}, \end{aligned} \quad (\text{A.120})$$

$$\begin{aligned} \left( \frac{v_L(r_t)}{v_L(r_t) - 1} \right) \frac{\mathbb{R}_{L,t}}{R_{L,t}} - 1 - \tilde{\phi}_L(r_t) \frac{R_{L,t}}{R_{L,t-1}} \left[ \frac{R_{L,t}}{R_{L,t-1}} - 1 \right] + \dots \\ \dots + E_t \left\{ \tilde{\phi}_L(r_{t+1}) \mathcal{M}_{t,t+1}^* \left( \frac{1}{\pi_{t+1}} \right) \left( \frac{R_{L,t+1}}{R_{L,t}} \right)^2 \frac{\tilde{L}_{t+1}}{\tilde{L}_t} \mu_{Y,t+1} \left[ \frac{R_{L,t+1}}{R_{L,t}} - 1 \right] \right\} = 0, \end{aligned} \quad (\text{A.121})$$

$$\begin{aligned} 1 - \left( \frac{v_D(r_t)}{v_D(r_t) - 1} \right) \frac{\mathbb{R}_{D,t}}{R_{D,t}} - \tilde{\phi}_D(r_t) \frac{R_{D,t}}{R_{D,t-1}} \left[ \frac{R_{D,t}}{R_{D,t-1}} - 1 \right] + \dots \\ \dots + E_t \left\{ \tilde{\phi}_D(r_{t+1}) \mathcal{M}_{t,t+1}^* \left( \frac{1}{\pi_{t+1}} \right) \left( \frac{R_{D,t+1}}{R_{D,t}} \right)^2 \frac{\tilde{D}_{t+1}}{\tilde{D}_t} \mu_{Y,t+1} \left[ \frac{R_{D,t+1}}{R_{D,t}} - 1 \right] \right\} = 0, \end{aligned} \quad (\text{A.122})$$

$$\tilde{L}_t = \tilde{D}_t + \tilde{K}_{B,t}, \quad (\text{A.123})$$

$$\tilde{K}_{B,t} = (1 - \delta_B) \frac{\tilde{K}_{B,t-1}}{\mu_{Y,t}} + \omega \frac{\tilde{J}_{t-1}}{\mu_{Y,t}}, \quad (\text{A.124})$$

$$\tilde{J}_t = R_{L,t} \tilde{L}_t - R_{D,t} \tilde{D}_t - R_t \tilde{K}_{B,t}, \quad (\text{A.125})$$

$$\mathbb{R}_{D,t} = R_t, \quad (\text{A.126})$$

$$\mathbb{R}_{L,t} = R_t, \quad (\text{A.127})$$

$$\tilde{Y}_t = \left( \frac{\tilde{K}_{t-1}}{\mu_{I,t}} \right)^\alpha N_t^{1-\alpha}, \quad (\text{A.128})$$

$$\tilde{W}_t = (1 - \alpha) \Phi_t \frac{\tilde{Y}_t}{N_t}, \quad (\text{A.129})$$

$$R_t^* = R_{t-1}^{*\rho_R} \left( R^* \left( \frac{\pi_t}{\pi} \right)^{\kappa_\pi} \left( \hat{Y}_t \right)^{\kappa_Y} \right)^{1-\rho_R} \exp(\varepsilon_{R,t}), \quad (\text{A.130})$$

$$\hat{Y}_t = \kappa_P \left( \frac{Y_t}{Y_t^P} \right) \exp(F_t), \quad (\text{A.131})$$

$$F_t = \rho_F F_{t-1} + \varepsilon_{F,t}, \quad (\text{A.132})$$

$$R_{ZLB,t} = \mathbf{K} + \varepsilon_{ZLB,t}, \quad (\text{A.133})$$

$$R_t = \mathbf{z}(s_{1,t}) R_{ZLB,t} + (1 - \mathbf{z}(s_{1,t})) R_t^*, \quad (\text{A.134})$$

$$\frac{G_t}{Z_{Y,t}} = \left( \frac{G_{t-1}}{Z_{Y,t-1}} \right)^{\rho_G} \left( \frac{G}{Z_Y} \right)^{1-\rho_G} \exp(\varepsilon_{G,t}), \quad (\text{A.135})$$

$$\log A_t = \rho_A \log A_{t-1} + \varepsilon_{A,t}, \quad (\text{A.136})$$

$$\log \mu_{Z,t} = g_Z + \Delta \mathcal{A}_{Z,t}, \quad (\text{A.137})$$

$$\log \mu_{Z_I,t} = g_{Z_I} + \Delta \mathcal{A}_{Z_I,t}, \quad (\text{A.138})$$

$$\log \mu_{Y,t} = \left( \frac{1}{1-\alpha} \right) (\log \mu_{Z,t} + \alpha \log \mu_{Z_I,t}), \quad (\text{A.139})$$

$$\log \mu_{I,t} = \left( \frac{1}{1-\alpha} \right) (\log \mu_{Z,t} + \log \mu_{Z_I,t}), \quad (\text{A.140})$$

$$\tilde{Y}_t^P = \tilde{C}_t^P + \tilde{I}_t^P + \tilde{G}_t, \quad (\text{A.141})$$

$$\tilde{K}_t^P = \tilde{I}_t^P \left( 1 - \frac{\phi_I}{2} \left( \frac{\tilde{I}_t^P}{\tilde{I}_{t-1}^P} \mu_{I,t} - \mu_I \right)^2 \right) + (1-\delta) \frac{\tilde{K}_{t-1}^P}{\mu_{I,t}}, \quad (\text{A.142})$$

$$\begin{aligned} 1 = \tilde{Q}_t^P & \left[ 1 - \frac{\phi_I}{2} \left( \frac{\tilde{I}_t^P}{\tilde{I}_{t-1}^P} \mu_{I,t} - \mu_I \right)^2 - \phi_I \left( \frac{\tilde{I}_t^P}{\tilde{I}_{t-1}^P} \mu_{I,t} - \mu_I \right) \frac{\tilde{I}_t^P}{\tilde{I}_{t-1}^P} \mu_{I,t} \right] + \dots \\ & \dots + E_t \left\{ \mathcal{M}_{t,t+1}^P \phi_I \frac{\tilde{Q}_{t+1}^P}{\mu_{I,t+1}} \left( \frac{\tilde{I}_{t+1}^P}{\tilde{I}_t^P} \mu_{I,t+1} - \mu_I \right) \left( \frac{\tilde{I}_{t+1}^P}{\tilde{I}_t^P} \mu_{I,t+1} \right)^2 \right\}, \end{aligned} \quad (\text{A.143})$$

$$\tilde{Q}_t^P = E_t \left\{ \mathcal{M}_{t,t+1}^P \left( \alpha \frac{\tilde{Y}_{t+1}^P}{\tilde{K}_t^P} \mu_{Y,t+1} + (1-\delta) \frac{\tilde{Q}_{t+1}^P}{\mu_{Z_I,t+1}} \right) \right\}, \quad (\text{A.144})$$

$$(1-\alpha) \frac{\tilde{Y}_t^P}{N_t^P} = \kappa \frac{(N_t^P)^\eta}{\tilde{\lambda}_t^P}, \quad (\text{A.145})$$

$$\tilde{\lambda}_t^P = A_t \left( \tilde{C}_t^P - \chi \frac{\tilde{C}_{t-1}^P}{\mu_{Y,t}} \right)^{-\sigma}, \quad (\text{A.146})$$

$$\mathcal{M}_{t,t+1}^P = E_t \left\{ \beta \frac{\tilde{\lambda}_{t+1}^P}{\mu_{Y,t+1} \tilde{\lambda}_t^P} \right\}, \quad (\text{A.147})$$

$$\tilde{Y}_t^P = \left( \frac{\tilde{K}_{t-1}^P}{\mu_{I,t}} \right)^\alpha (N_t^P)^{1-\alpha}, \quad (\text{A.148})$$

$$\tilde{W}_t^P = (1-\alpha) \frac{\tilde{Y}_t^P}{N_t^P}, \quad (\text{A.149})$$

$$\mathbb{P}_t = \rho_{\mathbb{P}} \mathbb{P}_{t-1} + \varepsilon_{\mathbb{P},t}, \quad (\text{A.150})$$

$$\kappa_t = \rho_{\kappa} \kappa_{t-1} + \varepsilon_{\kappa,t}, \quad (\text{A.151})$$

$$\tilde{\pi}_t = \pi_{t-1}^{\xi} \pi^{1-\xi}, \quad (\text{A.152})$$

$$\tilde{\pi}_{W,t} = \pi_{t-1}^{\xi_W} \pi^{1-\xi_W}, \quad (\text{A.153})$$

$$\hat{N}_t = \frac{N_t}{N} \exp(\varepsilon_{N,t}), \quad (\text{A.154})$$

$$\Delta \log Y_t = \log \tilde{Y}_t - \log \tilde{Y}_{t-1} + \log \mu_{Y,t}, \quad (\text{A.155})$$

$$\Delta \log C_t = \log \tilde{C}_t - \log \tilde{C}_{t-1} + \log \mu_{Y,t}, \quad (\text{A.156})$$

$$\Delta \log I_t = \log \tilde{I}_t - \log \tilde{I}_{t-1} + \log \mu_{I,t}, \quad (\text{A.157})$$

$$\mathcal{A}_{Z,t} = \rho_{\mathcal{A}_Z} \mathcal{A}_{Z,t} + \varepsilon_{Z,t}, \quad (\text{A.158})$$

$$\mathcal{A}_{Z_I,t} = \rho_{\mathcal{A}_{Z_I}} \mathcal{A}_{Z_I,t} + \varepsilon_{Z_I,t}, \quad (\text{A.159})$$

$$\mathbb{Z}_{Y,t} = Z_t^{\frac{1}{1-\alpha}} Z_{I,t}^{\frac{\alpha}{1-\alpha}}, \quad (\text{A.160})$$

$$\mathbb{Z}_{I,t} = Z_t^{\frac{1}{1-\alpha}} Z_{I,t}^{\frac{1}{1-\alpha}}. \quad (\text{A.161})$$

### A.13 Steady State Model

$$\tilde{\phi}_L(r_t) = \mathbf{z}(s_{1,t})\tilde{\phi}_{ZLB,L} + (1 - \mathbf{z}(s_{1,t}))(\mathbf{m}(s_{2,t})\tilde{\phi}_{H,L} + (1 - \mathbf{m}(s_{2,t}))\tilde{\phi}_{L,L}), \quad (\text{A.162})$$

$$\tilde{\phi}_D(r_t) = \mathbf{z}(s_{1,t})\tilde{\phi}_{ZLB,D} + (1 - \mathbf{z}(s_{1,t}))(\mathbf{m}(s_{2,t})\tilde{\phi}_{H,D} + (1 - \mathbf{m}(s_{2,t}))\tilde{\phi}_{L,D}), \quad (\text{A.163})$$

$$\mu_D(r_t) = \mathbf{z}(s_{1,t})\mu_{ZLB,D} + (1 - \mathbf{z}(s_{1,t}))(\mathbf{m}(s_{2,t})\mu_{H,D} + (1 - \mathbf{m}(s_{2,t}))\mu_{L,D}), \quad (\text{A.164})$$

$$\mu_L(r_t) = \mathbf{z}(s_{1,t})\mu_{ZLB,L} + (1 - \mathbf{z}(s_{1,t}))(\mathbf{m}(s_{2,t})\mu_{H,L} + (1 - \mathbf{m}(s_{2,t}))\mu_{L,L}), \quad (\text{A.165})$$

$$\frac{v_D(r_t)}{v_D(r_t) - 1} = \mu_D(r_t), \quad (\text{A.166})$$

$$\frac{v_L(r_t)}{v_L(r_t) - 1} = \mu_L(r_t), \quad (\text{A.167})$$

$$\mathcal{A}_{Z,t} = 0, \quad (\text{A.168})$$

$$\mathcal{A}_{Z_I,t} = 0, \quad (\text{A.169})$$

$$A_t = 1, \quad (\text{A.170})$$

$$\pi_t = \pi, \quad (\text{A.171})$$

$$\tilde{\pi}_t = \pi, \quad (\text{A.172})$$

$$\log \mu_{Z,t} = g_Z + \Delta \mathcal{A}_{Z,t}, \quad (\text{A.173})$$

$$\log \mu_{Z_I,t} = g_{Z_I} + \Delta \mathcal{A}_{Z_I,t}, \quad (\text{A.174})$$

$$\log \mu_{Y,t} = \left( \frac{1}{1-\alpha} \right) (\log \mu_{Z,t} + \alpha \log \mu_{Z_I,t}), \quad (\text{A.175})$$

$$\log \mu_{I,t} = \left( \frac{1}{1-\alpha} \right) (\log \mu_{Z,t} + \log \mu_{Z_I,t}), \quad (\text{A.176})$$

$$\pi_{W,t} = \mu_{Y,t} \pi_t, \quad (\text{A.177})$$

$$\tilde{\pi}_{W,t} = \pi_{W,t}, \quad (\text{A.178})$$

$$\tilde{P}_{I,t} = 1, \quad (\text{A.179})$$

$$R_{ZLB,t} = \mathbf{K} = \frac{R_{ZLB,D}}{\mu_{ZLB,D}}, \quad (\text{A.180})$$

$$R_t^* = \left( \frac{\pi_t}{\beta \mu_{N,D}} \right) \exp \left( \left( \frac{1}{1-\alpha} \right) (g_Z + \alpha g_{Z_I}) \right), \quad (\text{A.181})$$

$$R_t = \mathbf{z}(s_{1,t}) R_{ZLB,t} + (1 - \mathbf{z}(s_{1,t})) R_t^*, \quad (\text{A.182})$$

$$R_{D,t} = \mu_D(r_t) R_t, \quad (\text{A.183})$$

$$d_t = \pi_t \frac{\exp \left( \left( \frac{1}{1-\alpha} \right) (g_Z + \alpha g_{Z_I}) \right)}{R_{D,t} \beta}, \quad (\text{A.184})$$

$$\mathbb{R}_{L,t} = R_t, \quad (\text{A.185})$$

$$\mathbb{R}_{D,t} = R_t, \quad (\text{A.186})$$

$$\mathcal{M}_{t,t+1}^* = \frac{\beta}{\mu_{Y,t}}, \quad (\text{A.187})$$

$$\Upsilon_{L,t} = 1 - \frac{\beta d_t R_{L,t}}{\mu_{Y,t} \pi_t}, \quad (\text{A.188})$$



$$\tilde{Q}_t = \tilde{P}_{I,t} (1 - \psi \Upsilon_{L,t}), \quad (\text{A.189})$$

$$\Phi_t = \frac{\varepsilon - 1}{\varepsilon}, \quad (\text{A.190})$$

$$k_{-y} = \frac{\alpha \Phi \mu_{Y,t} \mu_{Z_{I,t}}}{\tilde{Q}_t \left( \frac{\mu_{Z_{I,t}}}{\mathcal{M}^*} - (1 - \delta) \right)}, \quad (\text{A.191})$$

$$i_{-y} = k_{-y} \left( 1 - \frac{(1 - \delta)}{\mu_{I,t}} \right), \quad (\text{A.192})$$

$$\varrho = \left( \frac{1}{1 - i_{-y} - g_{-y}} \right) \left( \frac{(R_{L,t} - R_{D,t}) \psi i_{-y} \left( 1 - \left( \frac{R_t - 1 + \delta_B}{\mu_{Y,t} \pi_t} \right) - \frac{1}{\pi_t} \right)}{\left( R_t - R_{D,t} + \frac{1 - (1 - \delta_B) / \mu_{Y,t}}{\omega / \mu_{Y,t}} \right)} - i_{-y} - g_{-y} + 1 \right), \quad (\text{A.193})$$

$$c_{-y} = \varrho (1 - i_{-y} - g_{-y}), \quad (\text{A.194})$$

$$n_{-y} = \left( \frac{k_{-y}}{\mu_{I,t}} \right)^{\frac{-\alpha}{1-\alpha}}, \quad (\text{A.195})$$

$$\tilde{W}_t = \frac{(1 - \alpha) \Phi_t}{n_{-y}}, \quad (\text{A.196})$$

$$l_{-y} = \psi i_{-y}, \quad (\text{A.197})$$

$$kb_{-y} = \frac{(c_{-y} + i_{-y} + g_{-y} - 1)}{1 - ((R_t - 1 + \delta_B) / (\mu_{Y,t} \pi_t)) - 1 / \pi_t}, \quad (\text{A.198})$$

$$d_{-y} = l_{-y} - kb_{-y}, \quad (\text{A.199})$$

$$j_{-y} = R_{L,t} l_{-y} - R_{D,t} d_{-y} - R_t kb_{-y}, \quad (\text{A.200})$$

$$\tilde{Y}_t = \left( \left( \frac{v - 1}{v} \right) \left( \frac{A \tilde{W}_t}{\kappa (c_{-y} - \chi c_{-y} / \mu_{Y,t})^\sigma n_{-y}^\eta} \right) \right)^{\frac{1}{\sigma + \eta}}, \quad (\text{A.201})$$

$$N_t = n_{-y}\tilde{Y}_t, \quad (\text{A.202})$$

$$\tilde{K}_t = k_{-y}\tilde{Y}_t, \quad (\text{A.203})$$

$$\tilde{I}_t = i_{-y}\tilde{Y}_t, \quad (\text{A.204})$$

$$\tilde{C}_t = c_{-y}\tilde{Y}_t, \quad (\text{A.205})$$

$$\tilde{G}_t = g_{-y}\tilde{Y}_t, \quad (\text{A.206})$$

$$\tilde{L}_t = l_{-y}\tilde{Y}_t, \quad (\text{A.207})$$

$$\tilde{K}_{B,t} = kb_{-y}\tilde{Y}_t, \quad (\text{A.208})$$

$$\tilde{D}_t = d_{-y}\tilde{Y}_t, \quad (\text{A.209})$$

$$\tilde{J}_t = j_{-y}\tilde{Y}_t, \quad (\text{A.210})$$

$$\tilde{\lambda}_t = A_t(\tilde{C}_t - \chi\tilde{C}_t/\mu_{Y,t})^{-\sigma}, \quad (\text{A.211})$$

$$\Delta \log Y_t = \log \mu_{Y,t}, \quad (\text{A.212})$$

$$\Delta \log C_t = \log \mu_{Y,t}, \quad (\text{A.213})$$

$$\Delta \log I_t = \log \mu_{I,t}, \quad (\text{A.214})$$

$$\hat{N}_t = 1, \quad (\text{A.215})$$

$$\hat{Y}_t = 1, \quad (\text{A.216})$$

$$F_t = 0, \quad (\text{A.217})$$

$$\mathbb{P}_t = 0, \quad (\text{A.218})$$

$$\kappa_t = 0, \quad (\text{A.219})$$

$$\tilde{Q}_t^P = 1, \quad (\text{A.220})$$

$$\mathcal{M}_t^P = \beta/\mu_{Y,t}, \quad (\text{A.221})$$

$$kp_{-y} = \frac{\alpha\mu_{Y,t}}{\tilde{Q}_t^P(1/\mathcal{M}_t^P - (1-\delta)/\mu_{Z_{I,t}})}, \quad (\text{A.222})$$

$$ip_{-y} = kp_{-y}(1 - (1-\delta)/\mu_{I,t}), \quad (\text{A.223})$$

$$np_{-y} = \left( \frac{kp_y}{\mu_{I,t}} \right)^{\frac{-\alpha}{1-\alpha}}, \quad (\text{A.224})$$

$$\tilde{W}_t^P = \frac{(1-\alpha)}{np_{-y}}, \quad (\text{A.225})$$

$$\tilde{Y}_t^P = \left( \frac{A_t \tilde{W}_t^P}{(\kappa_p(cp_{-y} - \chi cp_{-y}/\mu_{Y,t})^\sigma np_{-y}^\eta)} \right)^{\frac{1}{\sigma+\eta}}, \quad (\text{A.226})$$

$$N_t^P = np_{-y} \tilde{Y}_t^P, \quad (\text{A.227})$$

$$\tilde{K}_t^P = kp_{-y} \tilde{Y}_t^P, \quad (\text{A.228})$$

$$\tilde{I}_t^P = ip_{-y} \tilde{Y}_t^P, \quad (\text{A.229})$$

$$\tilde{C}_t^P = \tilde{Y}_t^P - \tilde{I}_t^P - g_{-y} \tilde{Y}_t^P, \quad (\text{A.230})$$

$$\tilde{\lambda}_t^P = A_t (\tilde{C}_t^P - \chi \tilde{C}_t^P / \mu_{Y,t})^{-\sigma}. \quad (\text{A.231})$$

### A.13.1 Omega

$$\tilde{K}_{B,t} = \frac{\tilde{C}_t + \tilde{I}_t + \tilde{G}_t - \tilde{Y}_t}{1 - \left( \frac{R_t - 1 + \delta_B}{\mu_{Y,t} \pi_t} \right) - \frac{1}{\pi_t}}, \quad (\text{A.232})$$

$$\tilde{K}_{B,t} = \frac{\varrho \left( \tilde{Y}_t - \tilde{I}_t - \tilde{G}_t \right) + \tilde{I}_t + \tilde{G}_t - \tilde{Y}_t}{1 - \left( \frac{R_t - 1 + \delta_B}{\mu_{Y,t} \pi_t} \right) - \frac{1}{\pi_t}}, \quad (\text{A.233})$$

$$\tilde{J}_t = R_{L,t} \psi \tilde{I}_t - R_{D,t} \left( \psi \tilde{I}_t - \tilde{K}_{B,t} \right) - R_t \tilde{K}_{B,t}, \quad (\text{A.234})$$

$$\omega = \tilde{K}_{B,t} \left( \frac{1 - (1 - \delta_B) / \mu_{Y,t}}{\tilde{J}_{B,t} / \mu_{Y,t}} \right), \quad (\text{A.235})$$

$$R_{L,t} \psi \tilde{I}_t - R_{D,t} \left( \psi \tilde{I}_t - \tilde{K}_{B,t} \right) - R_t \tilde{K}_{B,t} = \tilde{K}_{B,t} \left( \frac{1 - (1 - \delta_B) / \mu_{Y,t}}{\omega / \mu_{Y,t}} \right), \quad (\text{A.236})$$

$$(R_{L,t} - R_{D,t}) \psi \tilde{I}_t = \tilde{K}_{B,t} \left( R_t - R_{D,t} + \frac{1 - (1 - \delta_B) / \mu_{Y,t}}{\omega / \mu_{Y,t}} \right), \quad (\text{A.237})$$

$$\frac{(R_{L,t} - R_{D,t}) \psi \tilde{I}_t}{\left( R_t - R_{D,t} + \frac{1 - (1 - \delta_B) / \mu_{Y,t}}{\omega / \mu_{Y,t}} \right)} = \frac{\varrho \left( \tilde{Y}_t - \tilde{I}_t - \tilde{G}_t \right) + \tilde{I}_t + \tilde{G}_t - \tilde{Y}_t}{1 - \left( \frac{R_t - 1 + \delta_B}{\mu_{Y,t} \pi_t} \right) - \frac{1}{\pi_t}}, \quad (\text{A.238})$$

$$\left( \frac{(R_{L,t} - R_{D,t}) \psi \tilde{I}_t \left( 1 - \left( \frac{R_t - 1 + \delta_B}{\mu_{Y,t} \pi_t} \right) - \frac{1}{\pi_t} \right)}{\left( R_t - R_{D,t} + \frac{1 - (1 - \delta_B) / \mu_{Y,t}}{\omega / \mu_{Y,t}} \right)} - \tilde{I}_t - \tilde{G}_t + \tilde{Y}_t \right) \frac{1}{\left( \tilde{Y}_t - \tilde{I}_t - \tilde{G}_t \right)} = \varrho. \quad (\text{A.239})$$

## Appendix B Parameters

**Table 2.** Parameters description

Parameters	Description
$\kappa$	Weight on Labor in the Utility Function
$\kappa_P$	Weight on Labor in the Utility Function (Potential Model)
$\nu$	Elasticity of Substitution Between Differentiated Labor
$\epsilon$	Elasticity of Substitution Between Differentiated Intermediate Goods
$\mu_{Z,D}$	Markdown on Deposit Interest Rates in the ZLB State
$\omega$	Share of Bank Profits Paid as Dividends
$\delta_b$	Depreciation Rate of Bank Capital
$\psi$	Fraction of Investment Goods Bought Using Loans
$\delta$	Depreciation Rate of Physical Capital
$\alpha$	Capital's Share of Income
$\sigma_{ZLB}$	Standard Deviation on ZLB Shocks
$\chi$	Weight on Habit
$\eta$	Inverse of the Frisch Elasticity of Labor Supply
$\sigma$	Inverse of the Intertemporal Elasticity of Substitution
$\beta$	Time Discount Parameter
$\phi_P$	Weight on Rotemberg Adjustment Costs for Changing Prices
$\phi_W$	Weight on Rotemberg Adjustment Costs for Changing Wages
$\phi_I$	Weight on Investment Adjustment Costs
$\xi_P$	Degree of Price Indexation
$\xi_W$	Degree of Wage Indexation
$\mu_{L,D}$	Markdown of Deposit Interest Rates in the Low State
$\mu_{H,D}$	Markdown of Deposit Interest Rates in the High State
$\mu_{Z,L}$	Markup on Lending Rates in the ZLB State
$\mu_{H,L}$	Markup on Lending Rates in the High State
$\mu_{L,L}$	Markup on Lending Rates in the Low State
$\phi_{Z,L}$	Degree of Rigidity in Loan Rate-Setting at the ZLB
$\phi_{Z,D}$	Degree of Rigidity in Deposit Rate-Setting at the ZLB
$\phi_{L,L}$	Degree of Rigidity in Loan Rate-Setting in the Low State
$\phi_{L,D}$	Degree of Rigidity in Deposit Rate-Setting in the Low State

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<b>Parameters</b>	<b>Description</b>
$\phi_{H,L}$	Degree of Rigidity in Loan Rate-Setting in the High State
$\phi_{H,D}$	Degree of Rigidity in Deposit Rate-Setting in the High State
$q_{H,L}$	Transition Probability From High to Low State
$q_{L,H}$	Transition Probability from Low to High State
$\rho_r$	Interest Rate Smoothing
$\kappa_\pi$	Weight on Inflation
$\kappa_y$	Weight on the Output Gap
$\pi$	Steady State Inflation
$p_{N,L}$	Transition Probability From Normal to ZLB State
$p_{L,N}$	Transition Probability From ZLB to Normal State
$g_Z$	Neutral Technology Growth
$g_{Z_I}$	Investment Specific Technology Growth
$\rho_A$	Persistence Consumption Preference Shocks
$\rho_{\mathcal{A}_Z}$	Persistence Neutral Technology Shock
$\rho_{\mathcal{A}_{Z_I}}$	Persistence Investment Specific Technology Shock
$\rho_G$	Persistence Government Spending Shock
$\rho_\pi$	Persistence Cost-Push Shock
$\rho_\kappa$	Persistence Labor Preference Shock
$\rho_Y$	Persistence Output Gap Shock
$\sigma_A$	Std. Consumption Preference Shock
$\sigma_{\mathcal{A}_Z}$	Std. Neutral Technology Shock
$\sigma_{\mathcal{A}_{Z_I}}$	Std. Investment Specific Technology Shock
$\sigma_G$	Std. Government Spending Shock
$\sigma_P$	Std. Cost-Push Shock
$\sigma_\kappa$	Std. Labor Preference Shock
$\sigma_Y$	Std. Output Gap Shock
$\sigma_R$	Std. Monetary Policy Shock
$\sigma_L$	Std. Loan Markup Shock
$\sigma_D$	Std. Deposit Markup Shock
$\sigma_N$	Std. Labor Shock

**Table 3.** Calibrated Parameters

Parameters	Value
$\kappa$	8000
$\kappa_P$	8000
$\nu$	6
$\epsilon$	6
$\mu_{Z,D}$	1
$\omega$	0.5
$\delta_b$	0.10
$\psi$	1
$\delta$	0.025
$\alpha$	0.35
$\sigma_{ZLB}$	0.0001

Table 4. Estimated parameters

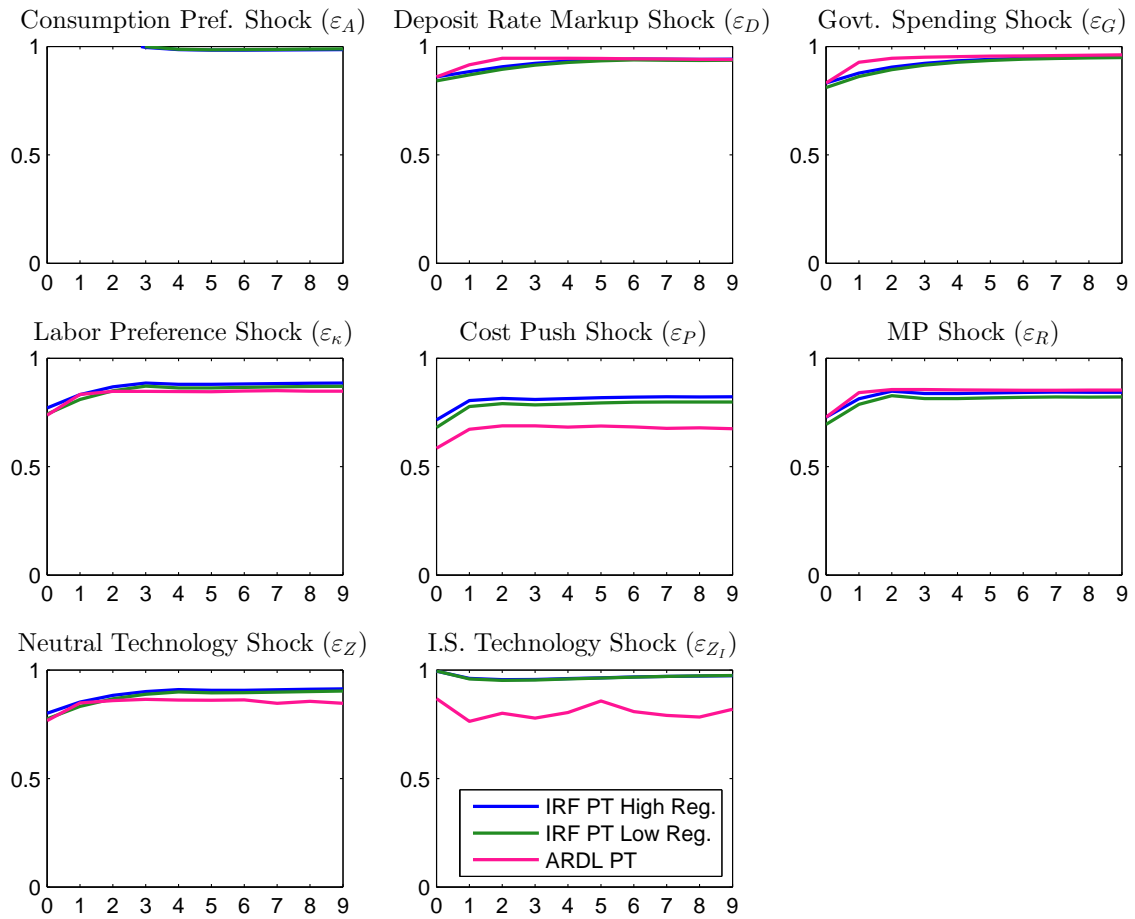
Param	Distrb	Mean	Std Dev	Post Mode	Post Mean	5%	95%
$\chi$	beta	0.7000	0.0050	0.7043	0.7003	0.6907	0.7126
$\eta$	normal	2.0000	0.2500	1.0099	1.0084	1.0010	1.0169
$\sigma$	normal	2.0000	0.2500	1.8522	1.8605	1.8516	1.8703
$\beta$	uniform	0.9988	0.0004	0.9995	0.9994	0.9991	0.9995
$\phi_P$	gamma	10.000	0.5000	12.013	11.982	11.891	12.106
$\phi_W$	gamma	10.000	0.5000	11.023	10.978	10.861	11.115
$\phi_I$	gamma	3.0000	0.5000	1.8650	2.0090	1.7030	2.4680
$\xi_P$	beta	0.5000	0.1500	0.0339	0.0383	0.0222	0.0517
$\xi_W$	beta	0.5000	0.1500	0.0914	0.0926	0.0804	0.1069
$\mu_{L,D}$	normal	0.9980	0.0003	0.9980	0.9979	0.9975	0.9983
$\mu_{H,D}$	normal	0.9930	0.0003	0.9935	0.9934	0.9931	0.9938
$\mu_{Z,L}$	normal	1.0110	0.0003	1.0110	1.0111	1.0107	1.0115
$\mu_{H,L}$	normal	1.0080	0.0003	1.0080	1.0078	1.0074	1.0082
$\mu_{L,L}$	normal	1.0110	0.0003	1.0104	1.0105	1.0102	1.0109
$\tilde{\phi}_{Z,L}$	right triang	0.0000	1.5000	0.4153	0.4180	0.3998	0.4360
$\tilde{\phi}_{Z,D}$	right triang	0.0000	1.5000	0.1374	0.1411	0.1272	0.1600
$\tilde{\phi}_{L,L}$	right triang	0.0000	1.5000	0.8792	0.8735	0.8660	0.8808
$\tilde{\phi}_{L,D}$	right triang	0.0000	1.5000	0.2800	0.2770	0.2672	0.2911
$\tilde{\phi}_{H,L}$	right triang	0.0000	1.5000	0.8163	0.8298	0.8152	0.8491
$\tilde{\phi}_{H,D}$	right triang	0.0000	1.5000	0.2739	0.2612	0.2377	0.2739
$q_{H,L}$	beta	0.1250	0.0400	0.1064	0.1147	0.1040	0.1327
$q_{L,H}$	beta	0.1250	0.0400	0.0653	0.0516	0.0346	0.0674
$\rho_r$	beta	0.7000	0.0050	0.7055	0.7084	0.6991	0.7201
$\kappa_\pi$	normal	1.5000	0.2500	2.0100	2.0060	1.9918	2.0192
$\kappa_y$	normal	0.1200	0.0500	0.2652	0.2679	0.2594	0.2789
$\pi$	uniform	1.0055	0.0026	1.0026	1.0025	1.0012	1.0040
$p_{N,Z}$	beta	0.1250	0.0400	0.0324	0.0317	0.0196	0.0428
$p_{Z,N}$	beta	0.1250	0.0400	0.3162	0.3168	0.3015	0.3304
$g_Z$	uniform	0.0050	0.0029	0.0000	0.0002	0.0000	0.0006
$g_{Z_I}$	uniform	0.0050	0.0029	0.0031	0.0030	0.0023	0.0037
$\rho_A$	beta	0.5000	0.1500	0.9887	0.9780	0.9463	0.9937

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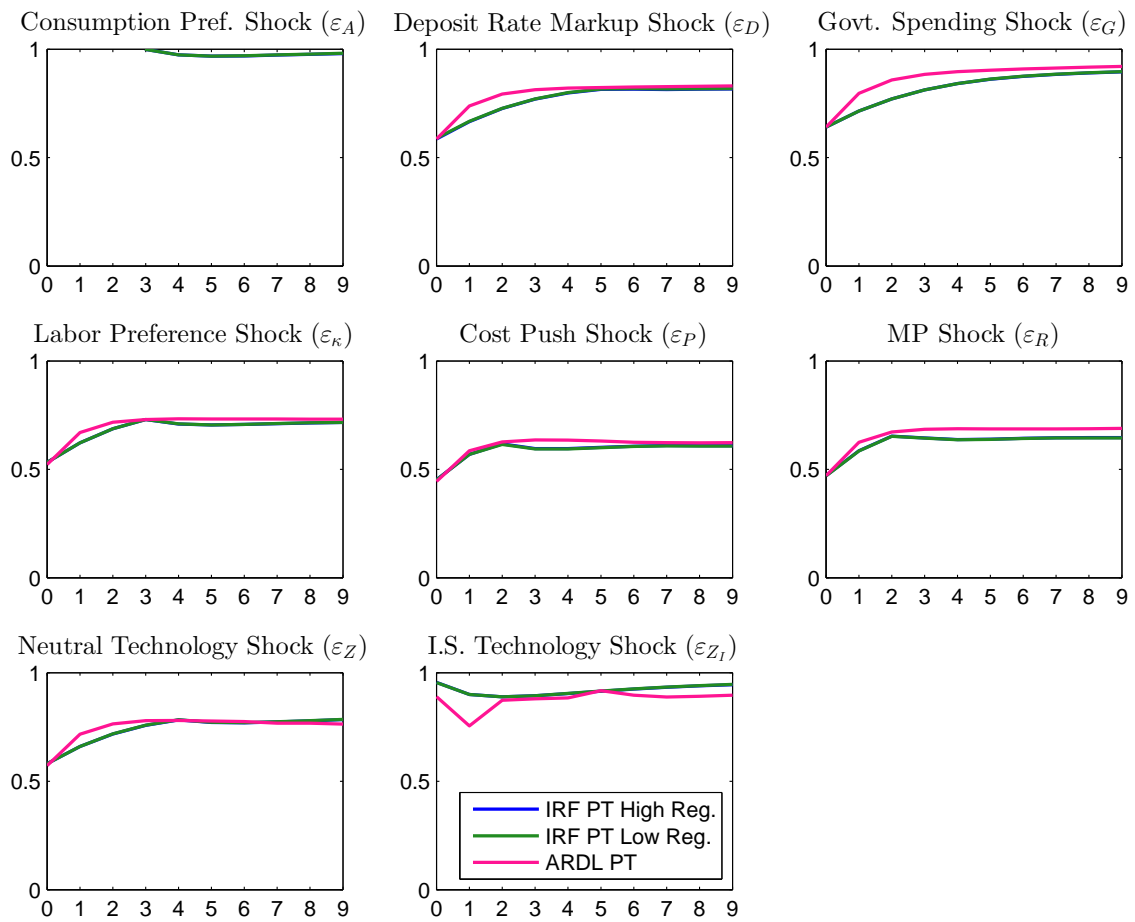
Param	Distrb	Mean	Std Dev	Post Mode	Post Mean	5%	95%
$\rho_{\mathcal{A}_Z}$	uniform	0.5000	0.2887	0.9771	0.9726	0.9510	0.9842
$\rho_{\mathcal{A}_{Z_I}}$	uniform	0.5000	0.2887	0.7751	0.7537	0.7195	0.7815
$\rho_G$	beta	0.5000	0.1500	0.9330	0.9323	0.9208	0.9438
$\rho_\pi$	beta	0.7000	0.0500	0.4761	0.4627	0.4299	0.4780
$\rho_\kappa$	beta	0.5000	0.1500	0.4201	0.4127	0.4040	0.4198
$\rho_Y$	right triang	0.0000	0.1000	0.1358	0.1248	0.1150	0.1372
$\sigma_A$	inverse gamma	0.1000	2.0000	0.0546	0.0460	0.0378	0.0562
$\sigma_{\mathcal{A}_Z}$	inverse gamma	0.1000	2.0000	0.0059	0.0060	0.0051	0.0070
$\sigma_{\mathcal{A}_{Z_I}}$	inverse gamma	0.1000	2.0000	0.0231	0.0255	0.0215	0.0319
$\sigma_G$	inverse gamma	0.1000	2.0000	0.0260	0.0245	0.0216	0.0275
$\sigma_P$	inverse gamma	0.1000	2.0000	0.0425	0.0438	0.0381	0.0526
$\sigma_\kappa$	inverse gamma	0.1000	2.0000	0.0314	0.0330	0.0289	0.0379
$\sigma_Y$	right triang	0.0000	0.1000	0.0156	0.0154	0.0136	0.0174
$\sigma_R$	inverse gamma	0.1000	2.0000	0.0038	0.0039	0.0038	0.0041
$\sigma_L$	inverse gamma	0.1000	2.0000	0.0038	0.0038	0.0038	0.0040
$\sigma_D$	inverse gamma	0.1000	2.0000	0.0038	0.0038	0.0038	0.0039
$\sigma_N$	inverse gamma	0.1000	2.0000	0.0038	0.0042	0.0038	0.0050



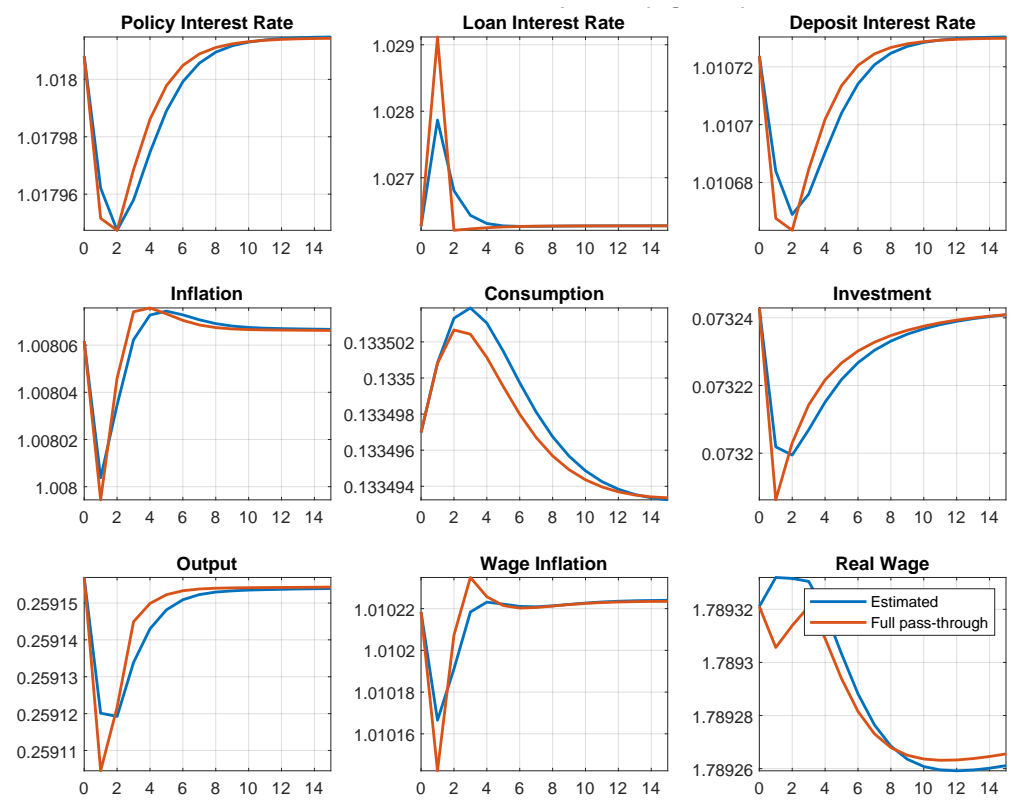
## Appendix C Additional results



**Figure 11.** Deposit rate pass-through: Alternative measures based on a more direct computation of the impulse responses



**Figure 12.** Loan rate pass-through: Alternative measures based on a more direct computation of the impulse responses



**Figure 13.** Simulation exercise to Loan markup shock - Estimated model and Full pass-through

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Centre for Applied Macro - Petroleum economics (CAMP)  
N-0442 Oslo

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