New-Keynesian Open-Market Operations: A Reassessment of the Role of Money*

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Abstract

Most quantitative New-Keynesian models omit a medium of exchange, on the grounds that money plays no quantitative role in monetary policy transmission or optimal policy. This paper reassesses that view. Empirically, I construct a new series of Federal Reserve permanent open-market operations (OMOs) from weekly reports (1979–2008) and show, in VAR-IV and recursive VARs with high-frequency identified shocks, that OMOs respond significantly to monetary policy shocks within a month and, contrary to existing evidence, more strongly after the Fed began announcing its target rate. I then build a heterogeneous-agent New-Keynesian model with corporate debt and cash-in-advance constraints under which the central bank must conduct OMOs to enforce its interest-rate target. Calibrated to business-cycle moments, the model reproduces the impact and persistence of the estimated OMO response. Relative to a cashless benchmark, investment responds up to 30% more, and savings twice as much to a monetary shock, because the central bank accommodates liquidity needs via OMOs. Though the optimal Taylor rule is similar in both economies, welfare costs of deviating from it are up to ten times larger with money, where consumption volatility responds strongly to inflation and OMO volume. Extensions show that information frictions explain the weaker pre-announcement response, and that the cashless benchmark amplifies shocks through a within-period income–spending feedback loop that a cash-in-advance constraint breaks.

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1 Introduction

Most quantitative monetary models of the last two decades do not feature a medium of exchange. This followed an empirical and theoretical literature suggesting a limited quantitative role.[1] Money has not, however, ceased to matter for prices. Money growth and inflation have long been documented to move together over long horizons.[2] The years after the pandemic offered a reminder of a different kind. Inflation returned after a period of substantial money growth, and the Federal Reserve then spent two years absorbing close to two trillion dollars of excess liquidity a day to keep it from flowing back into the economy.[3] Money has also been shown to affect monetary policy rates and transmission. Unexpected changes in the supply of reserves move the federal funds rate,[4] and balance-sheet liquidity affects how lending and investment respond to monetary shocks.[5] Money, then, remains visible in the data in ways that bear on monetary policy.

Recent improvements in the identification of monetary policy shocks and in the underlying vector autoregression machinery create grounds for revisiting the role of open market operations in enforcing monetary policy at horizons long enough for general-equilibrium effects to unfold. On the theoretical front, recent advances in heterogeneous-agent New Keynesian (HANK) modelling allow for a new angle on how money can affect monetary policy discussions. This is relevant because household heterogeneity and income risk have been shown to shape the demand for money and to be consequential for monetary policy implementation.[6] Against this backdrop, this paper asks whether, in such an environment, money matters for the transmission of monetary policy and for optimal policy design.

My framework is consistent with the empirical finding that monetary aggregates carry no information about output and prices beyond that contained in the interest rate (Sims, 1980; Friedman and Kuttner, 1992; Estrella and Mishkin, 1997), yet money remains consequential for monetary policy. Intuitively, in an economy with money, the interest rate set by the central bank in general differs from the rate that would clear the bond market, generating nonzero excess demand for bonds and, by Walras' law, an offsetting excess demand in the money market, a gap I call the textit enforcement wedge henceforth. Open-market operations (OMOs) close this wedge through a joint intervention in the

[1] Section 2 reviews the empirical evidence.

[2] McCandless and Weber (1995), Sargent and Surico (2011).

[3] Daily overnight reverse repurchase agreements averaged 1.87 trillion USD between 2022 and 2023. On money growth over the preceding period, see Hall and Sargent (2022), and on its relation to forecast errors, see Borio et al. (2023).

[4] Hamilton (1997); Carpenter and Demiralp (2006)

[5] Jeenas (2023), Kashyap and Stein (2000).

[6] Rocheteau et al. (2018), Herrenbrueck (2019).

bond and money markets. OMO volume is therefore determined by whatever shifts the demand for bonds and money, and explains nothing beyond it. What shapes the response to shocks is not the volume but the environment in which it operates: the frictions that require money to be held in advance of transactions, and the central bank's institutional commitment to intervene in the open market to ensure clearing. These frictions reinforce the real wage distortions created by wage rigidities and make investment sensitive to debt-servicing costs, while OMOs redistribute real balances between households and investors.

First, I use structural VARs to investigate the role of open-market operations in monetary policy enforcement. For this, I rely on large language models to build a series of permanent OMOs out of weekly scanned reports by the Federal Reserve of the United States. Then, using high-frequency identified (HFI) monetary policy shocks from a series of papers (Swanson, 2021; Jarociński and Karadi, 2020; Miranda-Agrippino and Ricco, 2021) as instruments on a set of monthly VAR-IV regressions, I show that OMOs are significantly affected by monetary policy shocks. These effects stay significant and become larger after 1994, when the Fed started to announce the interest rate target publicly.

With this evidence at hand, I build a heterogeneous agents New Keynesian (HANK) model with open market operations. The model features households that are subject to idiosyncratic labor income shocks and can purchase securities to save, a capital firm that holds all the capital in the economy and issues corporate bonds to invest, and a bank that bundles government and corporate bonds into the securities purchased by households. I compare an economy where money is needed as a medium of exchange to a standard cashless benchmark with firm borrowing. Unlike the cashless economy, the central bank must conduct open-market operations in the former (henceforth, referred to as *"cash economy"* for short) to ensure market clearing at the interest rate it sets.

I show that the calibrated model can match the untargeted initial response in OMO volume to a monetary policy shock. I also show that the two economies behave differently: given a baseline calibration, the peak in investment is 30% higher in the cash economy than in the cashless economy, while savings fall twice as much after an exogenous interest rate cut. I show that these wedges are produced by the frictions associated with the need to hold money in advance of transactions. On the investment side, firms also react to monetary shocks through a variation in their costs of servicing the debt, a channel that is absent in the cashless model. On the consumer side, the loss of value on wages at the end of the previous period enhances dissaving by all households, especially poorer ones. I also show that, in the cash economy, investment and savings can only go in opposite directions because of open-market operations. In this sense, the stock of government debt serves as a buffer that can be leveraged by the central bank to absorb shocks and allow investment to, for instance, expand in the face of contracting savings.

I then turn to the study of optimal policy. To a second-order approximation, I show that welfare is maximized by setting the inflation coefficient in the Taylor rule at 1.375 in both economies in the case where inflation, the real interest rate, and output targets are set at the deterministic steady state level. The optimal output coefficient is zero in the cash economy and 0.05 in the cashless economy. Despite the similarity, the two economies react very differently to deviations from optimal policy, with the cash economy predicting substantially higher losses. These differences are due to 1) higher costs in the cash economy of inflation volatility, which affects the value of holding money and OMO volume; and 2) OMO volatility producing substantial redistribution between households and capital firms. If the Taylor rule targets are allowed to reflect the stochastic steady state means, the optimal inflation coefficient is 2 in both economies, but welfare is maximized in the cashless economy by reacting strongly to output, whereas the cash economy requires no output response at all.

By means of extensions, I show additional results. First, by changing the fiscal rule to strict debt targeting, where government spending varies to keep debt on target at all times, the surplus in the government budget caused by an interest rate cut leads to a large fiscal multiplier. This is because of a feedback loop, whereby higher spending increases output and, therefore, taxes, which in turn increase spending. I argue that this feedback loop is an inherent amplification mechanism in cashless models, which is broken in the cash economy by the presence of cash-in-advance constraints. Second, I study alternative money injection technologies in the form of proportional and lump-sum helicopter drops. I show how lump-sum expansionary helicopter drops generate a stronger consumption response by favoring households with high marginal propensity to consume, but the response in investment is weaker. Lastly, I develop an extension that features sticky expectations about the interest rate and myopia regarding future trajectories for all variables to capture the economy's behavior prior to public announcements of the interest rate target by the central bank. I show that the model with imperfect information produces a weaker impact response in OMO volume to a monetary policy shock, which is aligned with my empirical findings.

All in all, the framework presented in this paper predicts different implications between cash and cashless models for monetary policy transmission and for the costs of deviating from optimal policy. This framework is compatible with existing evidence on the low informational content of monetary aggregates relative to other variables, such as short rates; it is mechanically compatible with the findings on the long-run co-movement between prices and money, and is supported by novel empirical evidence on the monthly-frequency response of open market operations to monetary policy shocks. The structure of the paper goes as follows. Section 2 contains a brief literature review. In Section 3,

I present my empirical approach and my results. In Section 4, I introduce the model environment, and the quantitative analysis on the calibrated model is conducted in Section 5. Section 6 discusses the policy implications of the model, while section 7 explores extensions. Finally, Section 8 concludes.

2 Related Literature

This paper contributes to the literature on the role of money in monetary models. The view that money plays no independent role in monetary policy transmission was built over three decades of time-series evidence. Goldfeld et al. (1976) documented the breakdown of standard money demand equations in the mid-1970s. Sims (1980) showed that, once a short-term interest rate is included in a VAR, money loses most of its predictive power for output in the postwar period. Similarly, Friedman and Kuttner (1992) show that movements in monetary aggregates ceased to predict movements in real and nominal GDP as well as prices after 1970, and Estrella and Mishkin (1997) found that monetary aggregates are unreliable information variables for policy after 1979.

On the theory side, Woodford (1998) showed that price determination is possible in models without money through a policy rule that makes real quantities dependent on the price level, which became an important building block of the New Keynesian framework. Furthermore, as the economy approaches a scenario where credit-based transactions can fully substitute money, the importance of the latter in explaining dynamics vanishes. McCallum (2001) argues that, although a model without money is misspecified, the error introduced is negligible.

Estimated models reinforced this conclusion: Ireland (2004) estimates, using maximum likelihood on U.S. data, a model with non-separable money in utility, yielding a small and statistically insignificant role for money in monetary business cycle dynamics. Andrés et al. (2006) reach a similar conclusion for the euro area. Lastly, from a quantitative standpoint, Schmitt-Grohé and Uribe (2007), henceforth referred to as SGU, showed that a representative agent, standard NK model with money produces the same policy implications as a cashless one. As a consequence of these results, the NK literature became vastly dominated by cashless models.

The models above still allow for transactions to be (at least partially) conducted by anticipating end-of-the-period revenues through a form of credit that is not supplied by formal financial institutions. Money then enters the utility function (Ireland, 2004; Andrés et al., 2006), through transaction costs (McCallum, 2001) or through a cash-in-advance constraint that does not require agents to hold money prior to transactions (Woodford, 1998; Schmitt-Grohé and Uribe, 2007). Although the latter is a common

way of introducing money to back transactions, as I will show, the existence of a lag between the moment in which money is received and used in transactions is necessary to 1) generate investors' sensitivity to debt-servicing costs, 2) produce an actual lack of access to credit for hand-to-mouth households, 3) remove shock amplification via a within-quarter feedback loop between incomes and spending, and 4) produce empirically plausible OMO volume responses to monetary shocks. These elements are important for the question of whether an economy with money behaves as a cashless one.

Moreover, the models above assume that money enters the households' budget as transfers, which is a form of helicopter drops in a representative agent framework. However, when households are heterogeneous, helicopter drops have been shown to not be equivalent to open-market operations (Rocheteau et al., 2018; Herrenbrueck, 2019). I, therefore, contribute to this literature by studying the role of money in a heterogeneous agents model that incorporates the needed cash-in-advance frictions, creating a meaningful role for open-market operations to be a distinctive technology for adjusting the supply of base money.

Another literature this paper contributes to is the one on monetary policy implementation and open-market operations. As stated in the introduction, Hamilton (1997) and Carpenter and Demiralp (2006) find evidence for a liquidity effect on daily open-market operations. Still, Demiralp and Jorda (2001) find evidence of an announcement effect after 1994, when the Fed started to announce the target for the federal funds rate. They show that OMOs' response to monetary policy shocks within days of the announcement then becomes insignificant.

This ability to affect the interest rate through announcements has been named *open mouth operations* by Guthrie and Wright (2000), who attribute it to the threat of actual OMOs. Taylor et al. (2001) argues, along similar lines, that if, for instance, the central bank announces an increase in the target federal funds rate, banks would demand more Fed balances on the announcement day, which would push the federal funds rate towards the target without actual OMOs.

The papers above focus on daily variations in open-market operation volume after announcements. In the context of the U.S., this corresponds to focusing on the maintenance period, a time frame of two weeks, or ten working days, in which banks need to meet reserve requirements on average. My contribution is to study the effect of monetary shocks on open-market operation volumes at lower frequency, where any possible general equilibrium effect is more likely to show up. My results indicate that these general equilibrium effects exist: despite any possible announcement effect at higher frequencies, I show that the effect of monetary policy shocks on OMO volumes within a month of the

announcement *increased* after 1994, which goes directly against the existing evidence. By means of an extension, presented in Section 7, I discuss a potential mechanism.

Lastly, I contribute to the HANK literature by developing a framework where households need to carry cash in advance of transactions that ultimately collapses into the same number of state variables for the household problem as in a standard one-asset HANK. It borrows inspiration from Geromichalos and Herrenbrueck (2022) in splitting the bond market into two moments—in a way compatible with the New-Keynesian framework—and defining open-market operations as a secondary market intervention. This framework produces very different findings on the importance of money than previous representative agent frameworks where money is injected via transfers from the Treasury. It also allows for the study of the effects of different money injection technologies in the context of a New-Keynesian DSGE.

3 Empirical Evidence

In this section, I will investigate whether 1) monetary policy shocks affect the volume of open-market operations conducted by the Fed's Trading Desk, and 2) OMOs have real effects. I will concentrate on the period before September 2008, when excess reserves were virtually zero in the United States. Under this scarce reserve regime, the banks needed to resort to the Trading Desk to increase reserves in general.[7]

3.1 Data

I build OMOs data from weekly scanned reports in the FRASER library of *U.S. government securities bought outright* between January 1979 and August 2008. I use large language models to parse the data and audit it. The resulting series then contains all the weekly developments on the stock of government bonds held by the central bank. I validate the series by comparing it with annual outright operations, stated in the *"Domestic Open Market Operations"* annual reports, which yields a correlation of approximately 0.99 with the weekly OMOs series just described.

I aggregate the series to a monthly frequency by keeping the stock at the end of the month. I also seasonally adjust it by applying the Seasonal-Trend decomposition procedure based on Loess, henceforth STL, by Cleveland et al. (1990).[8] This is a non-

[7]While retail sweeps provided another option since the mid-1990s, by allowing banks to reclassify money across their customers' accounts based on their different reserve requirements, the sample considered here covers the relevant period. This can lower the need for actual open-market operations.

[8]Taylor et al. (2001) also assumes a seasonally adjusted theoretical construct for his theory-based analysis, as seasonal variation in demand for Fed balances can generate offsetting OMOs by the Fed's Trading Desk.

parametric procedure that is well suited for series that are not well-fitted by an ARIMA. Since this is a nominal variable, and the first difference (the OMO flow) can be negative, the open-market operations measure is built by taking log differences instead of the log of the first difference.

For the monetary shock series, I use the monthly series provided by Swanson (2021), available from July 1991, because it allows me to concentrate on the component of the monetary policy surprises attributable to the target rate change, and orthogonal to large asset purchases and forward guidance. He recovers the target component of FOMC announcements by orthogonally rotating the first three principal components of high-frequency changes in federal funds futures, Eurodollar futures, and Treasury yields. I then use the orthogonalization procedure in Bauer and Swanson (2023) by regressing the target component on the same series of macroeconomic and financial variables known before the announcement as in their paper, henceforth BS shocks.[9]

As a robustness check, I also consider the shock series provided by Jarociński and Karadi (2020), henceforth JK, and Miranda-Agrippino and Ricco (2021), henceforth MAR, available from February 1990 and January 1991, respectively. For the former, I use the three-month ahead federal funds futures, where the monetary policy surprise component is computed by considering only the months in which the futures market surprises moved in the opposite direction of the stock market surprises (for the remaining months, the shock is set to zero).[10] Miranda-Agrippino and Ricco (2021), on the other hand, orthogonalize their series by regressing the surprises on the Fed's own Greenbook forecasts and forecast revisions, and then removing the autoregressive component of the resulting monthly series.

3.2 Empirical Approach

To evaluate whether OMOs react to monetary policy shocks, I employ a VAR-IV specification. In particular, given coefficient matrices $\boldsymbol{A}$ and $\boldsymbol{C}_\ell$ with $\ell \in \{1, 2, ..., p\}$, the vector of intercepts $\boldsymbol{c}$, and a vector of structural white noise shocks $\boldsymbol{\epsilon}_t$, the structural form of the VAR is given by:

$$\boldsymbol{A}\boldsymbol{Y}_t = \boldsymbol{c} + \sum_{\ell=1}^{p} \boldsymbol{C}_\ell \boldsymbol{Y}_{t-\ell} + \boldsymbol{\epsilon}_t, \tag{1}$$

where $\boldsymbol{Y}_t = (\, FFrate_t,\ OMO_t,\ \log IP_t,\ \log CPI_t \,)'$, containing, respectively, the federal funds rate, the OMOs variable, the industrial production index (IPI), and the consumer

[9] Not to be confused with the shocks used in Bauer and Swanson (2023), which do not isolate the pure target change component. I name it after the orthogonalization method.

[10] This specification is used instead of their baseline, because it produces similar IRFs and does not require all the assumptions needed for the Bayesian set-identification machinery.

price index. As in Gertler and Karadi (2015), I select July 1979 as a starting date, as it marks the beginning of Paul Volcker's tenure as the Federal Reserve chair and a new monetary policy regime. To concentrate on the scarce reserves regime, I select August 2008 as the end date, as excess reserves become positive and significant afterwards. Additionally, I run regressions starting in February 1994. This marks the beginning of the Fed's policy of announcing the federal funds rate target, during Alan Greenspan's tenure as the chair. This allows me to evaluate whether OMOs remain relevant in that period, despite the findings of Demiralp and Jorda (2001).

The estimation procedure follows Miranda-Agrippino and Ricco (2021). First, I estimate the reduced-form VAR:

$$\boldsymbol{Y}_t = \boldsymbol{b} + \sum_{\ell=1}^{p} \boldsymbol{B}_\ell \, \boldsymbol{Y}_{t-\ell} + \boldsymbol{u}_t, \tag{2}$$

where $\boldsymbol{b} = \boldsymbol{A}^{-1}\boldsymbol{c}$, $\boldsymbol{B}_\ell = \boldsymbol{A}^{-1}\boldsymbol{C}_\ell$ and $\boldsymbol{u}_t = \boldsymbol{A}^{-1}\boldsymbol{\epsilon}_t$. The reduced form regression is estimated on a sample running from July 1979 through August 2008. Let $\hat{u}_t^{FF}$ be the estimated residual for the federal funds rate equation, and $\hat{\boldsymbol{u}}_t^i$, the vector of residuals for variables $i \neq FF$. Then, I perform a two-stage least squares regression of $\hat{\boldsymbol{u}}_t^i$ on $\hat{u}_t^{FF}$ using the monetary shocks as an instrument, which restricts the sample for this step to the period in which the instrument is available. This identifies one column in $\boldsymbol{A}^{-1}$ up to a scale with no need for further restrictions beyond those that make the instrument valid, that is, for the surprise m_t^{FF} and for $i \neq FF$:

$$cov(m_t^{FF}, \epsilon_t^{FF}) \neq 0 \tag{3}$$

$$cov(m_t^{FF}, \epsilon_t^{i}) = 0. \tag{4}$$

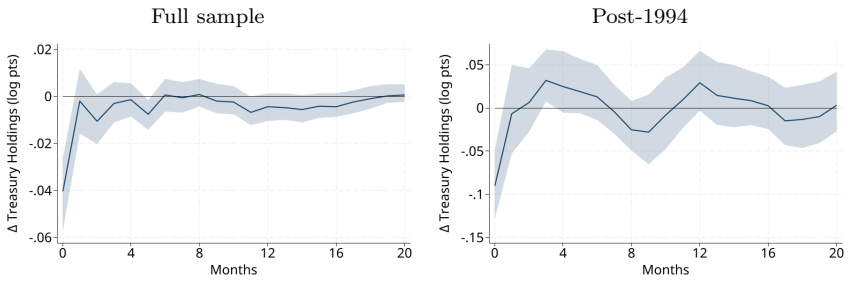
I use 12 lags as is standard in monetary economics for regressions on monthly data. I run a regression for the full sample (starting in 1979) and another for the post-1994 sample alone. I use wild bootstrap as in Mertens and Ravn (2013) and Gertler and Karadi (2015), which is appropriate under heteroskedasticity and strong instruments. Lastly, ADF tests are conducted, and first differences are taken for the logarithm of IPI and CPI, which are found to be integrated of first order.

3.3 Results

Figure 1 shows the IRFs of Treasury holdings to a 100 basis points contractionary monetary policy Swanson (2021). Treasury purchases by the central bank significantly fall on impact after the shock even in the post-1994 subsample, and return to zero in the second month. Surprisingly, the impact response is stronger after the federal funds rate target

started to be announced. I will examine this point more formally in Section 7, but, intuitively, if investment and savings respond less to monetary shocks that are unannounced, the wedge in the credit market that open-market operations are hypothesized to close would be smaller. While these responses seem transitory, they correspond to outright bond sales, which are not reversed, indicating a persistent effect in the central bank's portfolio.

Figure 1: Response of Treasury holdings to a contractionary monetary policy shock



Notes: Swanson (2021) shocks, orthogonalized with the method by Bauer and Swanson (2023). Responses in percentage points of monthly growth of Treasury holdings to a 100 basis points contractionary monetary policy shock. Frequentist VAR-IV; 90% confidence intervals.

For robustness, I run additional regressions. Figure A1 shows the results corresponding to JK and MAR shocks. I also show Bayesian VAR-IV results in Figure A2. Furthermore, Appendix B presents a Bayesian recursive VAR specification and discusses its results. In all specifications, OMO fall significantly after the contractionary interest rate shock, with a stronger response in the post-1994 sample.

The empirical results indicate, across all specifications, a robust initial response in the volume of open-market operations, which dies out within a few months. This goes in the opposite direction of previous findings, which concentrated on the management of reserves by banks after monetary policy announcements within a maintenance period. The results presented here, instead, focus on general equilibrium responses to monetary and open-market operations shocks, which may take a while longer to take place than previous papers allowed. Therefore, the results above justify building a general equilibrium framework with built-in open-market operations.

4 Model

In this section, I present the model economy. I consider two variations of this economy. In the first, all transactions are conducted by means of a specific form of credit that enables agents to settle transactions at the end of the period regardless of the timing of those transactions. This is the *cashless* benchmark. In the other variation, money must

be held in advance to serve as a means of payment in every transaction in the goods market, and credit can only operate through financial intermediaries. I will refer to this as the *cash economy*.[11]

I present the model in a way that nests both cash and cashless economies. To maintain generality, the cashless economy is built as a standard one-asset HANK, augmented to include corporate debt. The cash model only builds cash-in-advance constraints, a money market and a money injection technology (OMOs) on top of the cashless baseline structure. As the primary function of open market operations in my framework is to close the enforcement wedge—defined in the Introduction,— I model corporate debt to ensure there are optimizing agents on both sides of the bonds market. This assumption is extended to the cashless economy to preserve equivalence.

4.1 Model Environment

Time is discrete, and the economy is populated by a representative final good firm, capital good firm, and bank. Moreover, there is a unit mass of households, unions, and intermediate goods firms. The government is divided into a monetary authority, henceforth the central bank (CB), and a fiscal authority, henceforth the Treasury.

Households are subject to idiosyncratic income process, $e_{i,t}$ for $i \in [0,1]$, and choose how much to consume, $c_{i,t}$, and save in securities, $a_{i,t}$. There is a continuum of tasks that workers perform, and a monopolistic union for each task $k \in [0,1]$, which chooses the wage, $\omega_{k,t}$, and hours worked, $n_{i,k,t}$, on that task subject to a Rotemberg wage-setting friction. Households participate in all of the unions, and a labor packer aggregates the different tasks into a homogeneous labor supply, $\bar{N}_t$. Intermediate goods firms have identical technology, and hire labor from the labor packer and capital from capital firms. Furthermore, they face price-setting frictions *a la* Calvo. The representative final good firm uses intermediate goods to produce and operates in a competitive market.

The capital firm accumulates capital, k_t, by investing through final good purchases, subject to investment adjustment costs. It operates in a competitive capital input market and, due to financial frictions, must borrow from banks to invest. I assume that the profits from both capital[12] and intermediate goods firms are paid to households and subject to the income process, $e_{i,t}$. The bank also operates in a competitive market, demanding government, $\mathcal{B}_t$, and corporate bonds, B_t, issued by capital firms, and bundling them into the securities it sells to households, $a_{i,t}$.

[11] The name choice should not be taken to mean that money corresponds to cash alone. Any asset that can serve as a means of exchange can satisfy the definition.

[12] For the capital firm, operating in a competitive market means only that they are price takers, but since their current capital stock is a state variable, their choice cannot affect their contemporaneous revenue, meaning that they can make profits in equilibrium

The Treasury levies a payroll tax from workers and chooses government spending, G_t, and the path for its debt. The central bank chooses the interest rate, i_t, and enforces its policy by intervening in the credit market if necessary (more details on this point are given below). It also chooses the amount of government debt it holds, $\mathcal{B}_t^{CB}$.

In the cashless economy, price determination happens through the Taylor rule. In the cash economy, the presence of a medium of exchange means that all prices can be pinned down in terms of money.[13] Since the market-clearing interest rate, given a money and government bond supply, in general does not coincide with the one produced by the Taylor rule,[14] shocks produce excess demand in the bond market and, by Walras' law, excess demand of opposite sign in the money market. This enforcement wedge is assumed to be closed by the commitment of the central bank to intervene in both markets by conducting open market operations.

OMOs enforce the interest policy through two channels. First, a change in the money supply affects the interest rate through a liquidity effect. Second, the government changes the stock of government bonds traded in the credit market, affecting thereby the rate at which corporate bonds are traded at the margin. This requires that the interest rate be affected by the stock of public and private debt available for purchase, which cannot be accomplished in a representative agent model (Campos et al., 2024), motivating the HANK environment that I study. Before outlining the problem faced by each agent, I will discuss the timing and get into details on the implementation of OMOs.

4.2 Timing

The timing within each period goes as follows:

1. Aggregate shocks are realized, and the CB announces the nominal interest rate, i_t;
2. The bonds market opens;
3. Primary bonds market: all bonds reach maturity, and the government issues new bonds;
4. Secondary bonds market: the CB trades government bonds with the bank, while households and the capital firm adjust their asset/debt position;
5. The bonds market closes;

[13] Formally, since the price in, for instance, dollars of one dollar is always one, the price of money can always be normalized to one, meaning that, given a money endowment, all nominal prices are pinned down in general equilibrium.

[14] Even if the market-clearing interest rate can be written in a similar functional form as the Taylor rule, equivalence would require the coefficients to be the same, which is a knife edge condition.

6. Unions set wages, and intermediate goods firms set prices;

7. The goods markets open;

8. Households buy consumption goods, capital firms invest, and the government buys final good;

9. The goods markets close;

10. Wages and profits are paid to households, capital rents are paid to firm, and the government levies taxes.

As can be seen above, I assume that the bonds market is divided into two consecutive sub-markets. This is needed to pin down the equilibrium amount of OMOs, which are defined as secondary bond market interventions conducted by the central bank (Geromichalos and Herrenbrueck, 2022). To make this point clearer, I begin by defining the primary market as the one in which the Treasury rolls over its debt. The timing within the primary bond market goes as follows:

(i) Government and corporate bonds, $\mathcal{B}_{t-1}$ and B_{t-1}, reach maturity;

(ii) The Treasury sells $\mathcal{B}_t$ for a unit price Q_t;

(iii) The CB repurchases the Treasury bonds it held in the previous period, $\mathcal{B}_{t-1}^{CB}$, and remits its profits, Π_t^{CB}.

(iv) The bank purchases the rest, $\mathcal{B}_t - \mathcal{B}_{t-1}^{CB}$.

By assumption, the central bank repurchases the same amount of government bonds as in the previous period automatically.[15] This keeps the stock of government debt held by the central bank constant if no open market operations occur, as these are the only means whereby the CB can adjust its portfolio in the model.

Two important notes regarding the cash economy are needed. First, the Treasury can finance the payment of maturing debt by issuing new debt, but it must hold money to pay the difference $\mathcal{B}_{t-1} - Q_t\mathcal{B}_t - \Pi_t^{CB}$, that is, the part of maturing government debt held by the public that is not rolled over.[16] Second, capital firms do not enjoy the same benefit. As in Schmitt-Grohé and Uribe (2007), I assume that firms empty their pockets in the primary bonds market, meaning that they must pay outstanding debt with liquidity. Then, they must acquire new liquidity in the secondary market in order to invest.

[15]The analogous assumption regarding the bank is not restrictive, since the amount of government bonds held by the public must be fully purchased by households under market clearing in any model.

[16]Since all interest payments on maturing government debt held by the CB are remitted back to the Treasury in the form of profits, no money is needed to cover them.

In the secondary market, households purchase securities from the bank. The CB, then, conducts OMOs by issuing (removing) $O_t = Q_t(\mathcal{B}_t^{CB} - \mathcal{B}_{t-1}^{CB})$ units of money to buy (sell) government bonds from the bank. These operations are conducted until households' security purchases suffice to provide capital firms with the credit they demand under bond prices Q_t. Finally, capital firms sell corporate bonds to the bank.

Importantly, notice that households demand bonds in the secondary market *after* aggregate shocks are realized and *prior* to the goods market, where money is needed. As a result, bonds are more liquid than in most models, and the total amount of money households demand in a given period is endogenous in spite of the cash-in-advance constraint, and the CB ensures that this money demand is fully met.

To better illustrate this point, Figure A7 and Figure A8 in Appendix A summarize cash flows both in the goods market at period t and the bonds market at period $t+1$. If, for instance, the central bank *lowers* the interest rate, households demand fewer bonds, while capital firms supply more. Absent any bonds market intervention, this results in 1) excess demand for credit, and 2) higher demand for money, as households increase the money-to-bonds ratio, and capital firms borrow more liquidity. Then, the CB must simultaneously 1) promote equilibrium in the credit market by buying enough government bonds, and 2) inject enough money to meet excess demand from both households and capital firms. I now consider the problems faced by each agent in this economy.

4.3 Households

The household $i \in [0,1]$ solves:

$$\max_{\{c_{i,t},a_{i,t},m_{i,t}\}_{t=0}^{\infty}} \mathbb{E}_t\left[\sum_{t=0}^{\infty} \beta^{t-1} u(c_{i,t}) - v(n_{i,t})\right] \tag{5}$$

$$\text{subject to} \quad m_{i,t} + P_t c_{i,t} + Q_t a_{i,t} \leq m_{it-1} + a_{it-1} + \hat{e}_{i,t}[(1-\tau)P_t\omega_t n_{i,t} + \Pi_t] \tag{6}$$

$$P_t c_{i,t} + Q_t a_{i,t} \leq m_{it-1} \ + a_{it-1} \tag{7}$$

$$c_{i,t}, a_{i,t} \geq 0 \tag{8}$$

where m_{it-1} and a_{it-1} are, respectively, the households' monetary and security holdings at the beginning of the period, τ is the payroll tax rate, $(1-\tau)P_t\omega_t$ is the (average) net nominal wage, and $\Pi_t \coloneqq \Pi_t^I + \Pi_t^K$ is the sum of, respectively, intermediate and capital goods firms' profits. Notice that, as is common in the HANK literature, I assume that (i) households cannot short securities, meaning that $a_{i,t} \geq 0$; and (ii) $n_{i,t} = N_t$ $\forall i \in [0,1]$ is chosen by the set of all unions. Moreover, $u(\cdot)$ and $v(\cdot)$ are twice continuously differentiable and satisfy $u'(\cdot)$, $v'(\cdot) > 0$, $u''(\cdot) < 0$, $v''(\cdot) > 0$, and $\lim_{c\to 0} u'(c) = \infty$.

By the budget constraint, (6), households demand money, consumption goods, and bonds using resources from their labor and profit income, maturing bonds, and money carried from the previous period. Equation (7) represents the cash-in-advance constraint of the household. In my framework, agents can relax their cash-in-advance constraint through the contemporaneous bond demand choice, but not through contemporaneous revenues.[17] This matters, because hand-to-mouth households play an important role in monetary transmission given that their marginal propensity to consume equals one. The lack of access to credit limits contemporaneous effects of monetary policy over their consumption choices.

To allow households to acquire more (less) money by demanding fewer (more) bonds, I introduce bonds in the cash-in-advance constraint. This relates to the aforementioned assumption that households can trade securities in the secondary market. In cashless HANK models, including the one presented here, even households at the bottom of the wealth distribution can pledge their end-of-the-period revenues against their current spending. As a result, even though they cannot become indebted by choosing $a_{i,t} < 0$, they still have access to some form of credit. In the cash economy, poor households are constrained by the incomes earned in the previous period, which arguably better captures the empirical distribution of access to credit.

Moreover, $\hat{e}_{i,t}$ is a first-order idiosyncratic Markov income shock affecting total income, which satisfies $\int_0^1 \hat{e}_{i,t} = 1$. I assume that the shock is known *after* receiving the paycheck and dividends.[18] Now, let $e_{i,t}$ be the shock the affects the *income earned* in period t. By the assumption above, $e_{i,t} = \hat{e}_{i,t}$ in the cashless economy and $e_{i,t} = \hat{e}_{it-1}$ in the cash economy. This assumption is needed to ensure that, in the cash economy, an individual household cannot know the income they will have available in the next period even if, under perfect foresight for aggregate variables, profit earnings are fully known. This preserves the fundamental idiosyncratic uncertainty affecting them.

In the cashless economy, where $m_{i,t} = 0 \ \forall t$ and the cash-in-advance constraint is absent, the budget constraint implies that:

$$P_t c_{i,t} + Q_t a_{i,t} \leq a_{it-1} + e_{i,t}[(1-\tau)P_t \omega_t n_{i,t} + \Pi_t],$$

[17] In contrast, Woodford (1998) assumes that credit transactions are settled *prior* to cash-based transactions in every period. Likewise, Schmitt-Grohé and Uribe (2007) also allow contemporaneous earnings to relax the cash-in-advance constraint, which works as a collateral constraint, required to back part of households' and firms' spending.

[18] In the cashless economy, since the household can use their contemporaneous income for consumption, the paycheck and dividends for period t are available from the beginning of the period. In the cash economy, however, wages are earned only at the end of the period.

which is a standard formulation of the budget constraint in HANK models. In the cash economy, by the cash-in-advance constraint:

$$P_t c_{i,t} + Q_t a_{i,t} \leq a_{it-1} + e_{i,t}[(1-\tau)P_{t-1}\omega_{t-1}n_{it-1} + \Pi_{t-1}],$$

that is, all incomes are lagged. As already mentioned, unions choose wages, subject to Rotemberg frictions, and labor supply for each task, which is aggregated by a labor packer. The problems faced by the unions and labor packer are standard and are described in Appendix A.

4.4 Capital Firm

The representative capital firm rents capital in a competitive market and makes investment decisions subject to financial frictions and capital adjustment costs. As mentioned before, I assume that firms must issue bonds to invest in both economies. This is a common assumption in (cashless) New-Keynesian models of quantitative easing (Gertler and Karadi, 2011; Carlstrom et al., 2017; Sims and Wu, 2021). Furthermore, I assume that all the capital is held by these companies, so there is no non-arbitrage condition between bonds and capital. This means that the capital stock does not need to adjust enough to yield nominal returns equal to the interest rate target set by the CB. The firm maximizes the sum of future discounted dividend payments:

$$\max_{\{\bar{K}_{t+1},\bar{B}_t,X_t,M_t^K\}_{t=0}^{\infty}} \mathbb{E}_t\left[\sum_{s=t}^{\infty} Q_{t,s}\Pi_s^K\right] \tag{9}$$

$$\text{subject to} \quad \Pi_s^K + M_s^K + \bar{B}_{s-1} + P_s X_s\left(1 + s\left(\frac{X_s}{X_{s-1}}\right)\right) \leq P_s r_s^K \bar{K}_s + Q_s \bar{B}_s + M_{s-1}^K \tag{10}$$

$$P_s X_s\left(1 + s\left(\frac{X_s}{X_{s-1}}\right)\right) \leq Q_s \bar{B}_s \tag{11}$$

$$\bar{K}_{s+1} = (1-\delta)\bar{K}_s + X_s \tag{12}$$

$$\bar{B}_{s-1} \leq M_{s-1}^K, \tag{13}$$

where r_s^K corresponds to capital rents, M_{s-1}^K are money holdings from the previous period, $\bar{B}_t$ is corporate bond supply, X_s is investment, and $s(\cdot)$ is its adjustment cost.

Constraint (10) is the capital firm's budget constraint, which states that capital rents, bond sales, and money carried from the previous period are used to pay for investment and maturing bond obligations, demand money for the next period, and distribute dividends to households. Equation (11) works as an external financing constraint, forcing firms to issue bonds to meet investment costs. Lastly, (13) is the cash-in-advance constraint,

which follows from the assumption that the capital firm empties its pocket in the primary bonds market, enforcing the need for external financing through bond issuance in the cash economy. It is needed to ensure the bank leaves the primary bonds market with enough liquidity to buy corporate bonds and pay interest to households in the next period.

In the cash economy, the constraints imply that:

$$\Pi_t^K = P_t r_t^K \bar{K}_t - P_t X_t \left(1 + s\left(\frac{X_t}{X_{t-1}}\right)\right) + Q_t \bar{B}_t - \bar{B}_t, \tag{14}$$

that is, before paying dividends, the firm must set money aside to pay maturing bonds in the beginning of the next period, B_t. This contrasts with the cashless economy, in which the budget constraint becomes:

$$\Pi_t^K = P_t r_t^K \bar{K}_t - P_t X_t \left(1 + s\left(\frac{X_t}{X_{t-1}}\right)\right) + Q_t \bar{B}_t - \bar{B}_{t-1}, \tag{15}$$

meaning that the face value of maturing bonds from the previous period, $\bar{B}_{t-1}$, is paid for with *contemporaneous* income. Importantly, as shown in the solution presented in Appendix B, the cashless first-order conditions of the firm are the same as those that would hold in a model without the borrowing constraint (11). Therefore, the assumption that firms need to borrow to invest, in the cashless economy, does not affect firm decisions directly, but makes corporate bonds available to households. The problem faced by final and intermediate goods firms is standard and is presented and solved in Appendix B.

4.5 Government

I assume, as in Campos et al. (2024), that the Treasury chooses its spending according to the fiscal rule:

$$G_t = \overline{G} - \theta_G(\mathcal{B}_{t-1} - \overline{\mathcal{B}}), \tag{16}$$

where G_t is government spending, $\bar{G}$ is its target, and $\overline{\mathcal{B}}$, the target for government debt. Moreover, the budget constraint faced by the Treasury is given by:

$$G_t + M_t^G + \mathcal{B}_{t-1} \leq T_t + M_{t-1}^G + Q_t \mathcal{B}_t + \Pi_t^{CB}, \tag{17}$$

where $\Pi_t^{CB} = (1 - Q_t)\mathcal{B}_{t-1}^{CB}$ are interest payments to the CB on maturing government debt, assumed to be fully remitted to the Treasury. It states that the Treasury uses resources obtained from tax levies, issued bonds, the central bank's profits, and money carried forward from the previous period to pay for maturing bonds, demand money for the next period, and buy final goods. Moreover, the Treasury faces a cash-in-advance

constraint:

$$G_t + \mathcal{B}_{t-1} - Q_t \mathcal{B}_t \leq M^G_{t-1} + \Pi^{CB}_t. \tag{18}$$

Since the Treasury does not solve an optimization problem, the purpose of its cash-in-advance constraint is simply to ensure consistency in money flows, that is, to ensure that taxes levied do not disappear, but flow back to the final good firm and households in the form, respectively, of government spending and interest payments in accordance with the timing presented above. As before, these constraints imply that, in the cash economy:

$$G_t + \mathcal{B}_{t-1} - Q_t \mathcal{B}_t - \Pi^{CB}_t = T_{t-1},$$

meaning that spending is financed with taxes levied in the previous period. Naturally, in the cashless economy, contemporaneous taxes, T_t, are used.

The CB follows the Taylor rule:

$$i_t = \max\left\{(1+i_{t-1})^{\rho_i}\left[(1+\overline{r})(1+\overline{\pi})\left(\frac{1+\pi_t}{1+\overline{\pi}}\right)^{\theta_\pi}\left(\frac{Y_t}{\overline{Y}}\right)^{\theta_Y}\right]^{1-\rho_i}(1+\epsilon^i_t), 0\right\} - 1, \tag{19}$$

where $\overline{\pi}$ is the inflation rate target, $\overline{Y}$ is the steady state level of output,[19] and ϵ^i_t is the monetary policy shock. Notice that the max operator enforces the zero lower bound. Moreover, the central bank faces the budget constraint:

$$\bar{M}_{t-1} + Q_t \mathcal{B}^{CB}_t + \Pi^{CB}_t \leq \bar{M}_t + \mathcal{B}^{CB}_{t-1}, \tag{20}$$

which states that the central bank finances its profit remittances and bond purchases with interest earnings on its Treasury bond holdings and the issuance of money. Given the definition of open-market operations,[20] the budget constraint above implies that the money supply evolves according to the law of motion $\bar{M}_t = \bar{M}_{t-1} + O_t$.

[19] Schmitt-Grohé and Uribe (2007) also specify the output part component of the Taylor rule as a deviation of the (lagged) output with respect to the (deterministic) steady state value. Here, I use the current output instead.

[20] In a cashless economy, $\bar{M}_t = O_t = 0$ since there is no medium of exchange whose stock needs to be managed to enforce the interest rate policy. As a result, $\mathcal{B}^{CB}_t = \mathcal{B}^{CB}_{t-1}\ \forall t$. This makes the budget constraint of the CB redundant. Moreover, government debt held by the CB never differs from its target, meaning that the fiscal policy rule is a function of only the wedge between public debt held by the public and its target, as in the standard New-Keynesian framework.

4.6 Bank

Lastly, the representative bank securitizes government and corporate debt and sells the resulting debt bundles to households. its budget constraint is given by:

$$\int_0^1 a_{it-1}di + Q_t\mathcal{B}_t^F + Q_tB_t \leq \mathcal{B}_{t-1}^F + B_{t-1} + Q_t\int_0^1 a_{i,t}di, \tag{21}$$

where $\mathcal{B}_{t-1}^F$ is the beginning-of-the-period holdings of government bonds by the financial sector, namely, the bank. Naturally, corporate bonds and private bonds held by the public sum up to the amount of securities sold to households, $A_t \coloneqq \int_0^1 a_{i,t}di = \mathcal{B}_t^F + B_t$, and total government debt is divided in the holdings of the financial sector and the CB, *i.e.*, $\mathcal{B}_t = \mathcal{B}_t^F + \mathcal{B}_t^{CB}$. By using the definition of OMOs, we obtain:

$$\int_0^1 a_{it-1}di + Q_t(\mathcal{B}_t - \mathcal{B}_{t+1}^{CB}) + Q_tB_t \leq \mathcal{B}_{t-1}^F + B_{t-1} + Q_t\int_0^1 a_{i,t}di + O_t,$$

meaning that OMOs increase the amount of resources available to the bank to buy corporate bonds.

To complete the model, notice that, at the end of the period, cash flows satisfy:

$$M_t = B_t + P_t\omega_tN_t + \Pi_t^K + \Pi_t, \tag{22}$$

that is, money is held by (i) the capital firm in the amount needed to pay maturing bonds, (ii) the government in the form of taxes levied, and (iii) households in the form of net labor income and dividends paid by goods and capital firms.

4.7 Competitive Equilibrium

Given the setup presented above, we can define the competitive equilibrium of this economy as follows:

Definition 1 (Competitive Equilibrium)**.** *A competitive equilibrium is a sequence of prices* $\{P_t, \omega_t, r_t^K, Q_t\}_{t=0}^{\infty}$*, household allocations* $\{c_{i,t}, a_{i,t}, m_{i,t}\}_{i\in[0,1],t=0}^{\infty}$*, union and labor packer choices* $\{\omega_{k,t}, N_{k,t}, \bar{N}_t\}_{k\in[0,1],t=0}^{\infty}$*, capital firm choices* $\{\bar{K}_{t+1}, \bar{B}_t, X_t, M_t^K\}_{t=0}^{\infty}$*, intermediate and final good firm choices* $\{\{P_{j,t}, N_{j,t}, K_{j,t}, \bar{Y}_{jt}, Y_{j,t}\}_{j\in[0,1]}, Y_t\}_{t=0}^{\infty}$*, bank choices* $\{\mathcal{B}_t^F, B_t\}_{t=0}^{\infty}$*, and government policies* $\{G_t, \mathcal{B}_t, \mathcal{B}_t^{CB}, i_t, O_t\}_{t=0}^{\infty}$ *such that, given initial conditions, for every period* $0 < t < \infty$*:*

1. ***Households:*** *Given prices and unions choices,* $\{c_{i,t}, a_{i,t}, m_{i,t}\}$ *solves the problem of the household* $i \in [0, 1]$*,* (5)*.*

2. ***Unions:*** *Given prices,* $\{\omega_{k,t}, N_{k,t}\}$ *solves the problem of the union for task* $k \in [0,1]$, (B1).

3. ***Capital Firm:*** *Given prices,* $\{\bar{K}_{t+1}, \bar{B}_t, X_t, M_t^K\}$ *solves the representative capital firm's problem,* (9).

4. ***Intermediate Goods Firm:*** *Given prices and the final good firm's demand schedule,* $\{P_{j,t}, N_{j,t}, K_{j,t}, \bar{Y}_{jt}\}$ *solves the problem of the firm that produces the intermediate good* $j \in [0,1]$, (B7).

5. ***Final Good Firm:*** *Given prices,* $\{Y_t, \{Y_{j,t}\}_{j\in[0,1]}\}$ *solve the representative final good firm's problem.*

6. ***Bank:*** *The representative bank demands* $\{\mathcal{B}_t^F, B_t\}_{t=0}^{\infty}$ *and satisfies its budget constraint,* (21).

7. ***Treasury:*** *The Treasury sets* G_t *according to the policy rule* (16) *and satisfies its budget constraint,* (17)*, and, in the cash economy, its cash-in-advance constraint,* (18).

8. ***Central Bank:*** *The Central Bank sets* i_t *following its Taylor rule* (19)*, enforces it via open-market operations* O_t*, and satisfies its budget constraint* (20).

9. ***Market Clearing:***

   (a) *Goods markets:* $\int_0^1 Y_{j,t}dj = Y_t = \int_0^1 c_{i,t}di + X_t\left(1 + s\left(\frac{X_t}{X_{t-1}}\right)\right) + G_t$.

   (b) *Labor:* $\bar{N}_t = \int_0^1 N_{j,t}dj$.

   (c) *Capital:* $\bar{K}_t = \int_0^1 K_{j,t}dj$.

   (d) *Corporate bonds:* $\bar{B}_t = B_t$.

   (e) *Government bonds:* $\mathcal{B}_t = \mathcal{B}_t^F + \mathcal{B}_t^{CB}$.

   (f) *Money:* $\bar{M}_t = \bar{B}_t + P_t\omega_t N_t + \Pi_t^K + \Pi_t$.

5 Post-Monetary Shock Dynamics

This section discusses the calibration strategy for the model, its data fit, and presents the results. Given my research question, I will concentrate on monetary policy transmission and on the differences between cash and cashless economies along that dimension. This involves showing and decomposing the model dynamics after a monetary policy

shock. Before presenting the calibration procedure, I will make some functional form assumptions.

$$u(c_{i,t}) = \left(\frac{c_{i,t}^{1-\sigma} - 1}{1-\sigma} \right) \quad and \quad v(n_{i,t}) = \varphi \frac{n_{i,t}^{1+\nu}}{1+\nu}, \tag{23}$$

where σ is the inverse of the intertemporal elasticity of substitution (IES), and ν, the inverse Frisch elasticity of labor supply. Investment adjustment costs are given by:

$$s\left(\frac{X_t}{X_{t-1}}\right) := \frac{\phi}{2}\left(\frac{X_t}{X_{t-1}} - 1\right)^2, \tag{24}$$

where ϕ governs the extent of investment adjustment costs.

I solve the model using the sequence Jacobian method in Auclert et al. (2021). The method solves for perfect foresight paths for aggregate variables while recursively computing the transition of the joint income-asset distribution. I employ a linear solution to ensure the perfect foresight solution approximates the stochastic economy's transition to first order. For further details on the method, I refer the reader to the original paper.

5.1 Calibration

Given that the model was not written to match empirical IRFs, I adopt a calibration strategy to pin down parameters that cannot be reliably set from prior literature. The parameters are divided into three blocks. The first block corresponds to parameters that are fixed. The parameters in the second block are calculated to match long-run empirical moments in the steady state. Lastly, the parameters in the third block govern the response of the economy when it deviates from the steady state. They are computed by matching business cycle moments. The parameters are calibrated to the cash economy and will be imposed on the cashless economy for the results that follow. Table 1 shows all the parameters, and I will discuss each block in turn.

In the first block, I use log utility, as is standard. For the Frisch elasticity of labor supply, I follow Kaplan et al. (2018) in setting it to 1, just above the empirical estimate of 0.82 in Chetty et al. (2011) to account for intensive/extensive margin adjustment. I set the persistence of the income shock process, $\rho_e = 0.966$, as in Auclert et al. (2021). The standard deviation of the idiosyncratic shocks is set to $\sigma_e = 0.92$ as in Campos et al. (2024). This value approximates the modeled[21] wealth, earnings and income distribution moments in the US in Floden and Lindé (2001) (FL) for the period between 1988 and 1992. The cash model's fit with the data and with FL's model is presented in Table 2. The cashless economy produces similar distributional moments, so I omit its table for

[21] The empirical distribution is hard to match with a model for its extreme skewness and wealth on the tails. Hence, I concentrate on matching the model.

brevity. Since the income shock assumed in my framework hits labor earnings and profits, the model cannot differentiate between income and earnings inequality. However, its distribution sits between their modeled income and earnings distributions.

The elasticity of substitution between goods is set to $\varepsilon = 11$ to obtain 10% markups. As is common in the literature, the elasticity of substitution among labor varieties is given the same value. The capital share is equal to 0.3. With respect to the good price-setting frictions, Nakamura and Steinsson (2008) report a median monthly frequency of nonsale price adjustment stays within 9–12%, indicating a median quarterly probability of not adjusting prices of 68–75.4%. Thus, I set the Calvo probability to $\eta = 0.72$ to stay near the middle of the range. For wage-setting frictions, there is more estimate variability in the literature and, hence, I will calibrate it as part of the third block.

The Taylor rule coefficient of inflation is set to $\theta_\pi = 1.5$ and $\theta_Y = 0$ as is standard, and the interest rate smoothing coefficient is set to $\rho_i = 0.8$ to roughly match the estimates in Clarida et al. (2000) for the Volcker-Greenspan era. The fiscal rule coefficient is set to the standard value of $\theta_G = 0.1$, and the steady-state real interest rate is set to $\overline{r} = 0.005$, meaning roughly a 2% annual real interest rate.

The government's spending target is set at $\overline{G} = 0.2$ to match the average share of government consumption expenditure and gross investment in GDP in the period between 1979 and 2008. The debt target is fixed at $\overline{B} = 1.6$ to match the ratio of debt to annual GDP of 40% usually used in the literature, which also roughly matches the average value in the period. The central bank's holdings of bonds is set to $\overline{B}^{CB} = 0.208$ to match the average Fed's holdings as a share of total public debt of 13% in the period. Lastly, the inflation target is, as usual, set to $\overline{\pi} = 0$, meaning a zero-inflation steady state. This is needed here, because a 2% annual inflation rate would require the central bank to hold $\overline{B}^{CB} \approx 1$, roughly five times larger than the steady state variable.

Table 1: Model parameters

Parameter		Value	Source / target
		Fixed	
Households and unions			
$1/\sigma$	IES	1	Standard
$1/\nu$	Frisch elasticity	1	Kaplan et al. (2018)
ρ_e	Persistence of income process	0.966	Auclert et al. (2021)
σ_e	Std. dev. of idiosyncratic shock	0.92	Floden and Lindé (2001)
ε_N	Elasticity of subst. for labor	11	Standard

Parameter		Value	Source / target
Firms			
ε	Elasticity of subst. for goods	11	Standard
η	Calvo price stickiness	0.72	Nakamura and Steinsson (2008)
α	Capital share	0.3	Standard
Policy			
θ_π	Taylor-rule coefficient of inflation	1.5	Standard
θ_Y	Taylor-rule coefficient of output	0	Standard
ρ_i	Taylor-rule smoothing	0.8	Clarida et al. (2000)
θ_G	Fiscal-rule coefficient	0.1	Standard
$\overline{r}$	Real rate	0.005	Standard: 2% annual
$\overline{\pi}$	Inflation target	0	Zero-inflation steady state
$\overline{G}$	Government spending target	0.2	Gov. Spending-to-GDP[a]
$\overline{B}$	Debt target	1.6	Standard: debt-to-GDP of 40%
B^{CB}	Bonds held by the CB	0.208	13% of Debt held by the public[b]
	Calibrated steady-state		
β	Discount factor	0.9693	Bond market clearing
φ	Labor-disutility scale	0.6329	Hours $N = 1$
Θ	TFP level	0.5012	Output $Y = 1$
δ	Depreciation rate	0.0221	$K/Y = 10$ (quarterly)
τ_N	Labor-income tax rate	0.3252	Government budget
	Calibrated to business cycle moments		
ξ	Investment adjustment cost	1.7971	King and Rebelo (1999): $\mathrm{sd}(\log I)/\mathrm{sd}(\log Y) = 2.93$
κ_W	Wage Phillips-curve slope	0.02	King and Rebelo (1999): $\mathrm{sd}(\log w) = 0.0068$
ρ_Z	Persistence of TFP	0.7175	McKay and Reis (2016): $\mathrm{autocorr}(\log Y) = 0.864$
σ_Z	S.d. of the TFP innovation	0.0203	McKay and Reis (2016): $\mathrm{sd}(\log Y) = 0.015$

[a] U.S. Bureau of Economic Analysis, 1979–2008.

[b] U.S. Office of Management and Budget, 1979–2007. Most of 2007 and 2008 are excluded due a substantial drop in Treasury debt holdings by the central bank in 2007Q2.

Turning now to the parameters in the second block, the rate of time discount is calibrated to clear the bond market given the fixed debt target $\overline{B}$, yielding $\beta = 0.9694$. This is calibrated because, in HANK models, as shown by Campos et al. (2024), savings are increasing in the real interest rate, and the demand for bonds is directly affected by impatience. The labor disutility parameter and the TFP level are calibrated to enforce the normalizations $Y = N = 1$, resulting in $\varphi = 0.6545$ and $\Theta = 0.5012$. The depreciation rate is set at $\delta = 0.0223$ to obtain a capital-to-GDP ratio of 10. Lastly, the labor-income tax rate is calibrated to satisfy the government's budget, which yields $\tau_N = 0.3359$.

For the third block, I retrieve business cycle moments by using a TFP shock only. These moments are computed as the theoretical moments of the first-order approximation. By not including monetary policy shocks, I can keep the responses to these shocks entirely untargeted and do not need to make any further identification assumptions. The two primary parameters to be obtained are the investment adjustment cost scale, ξ, and the slope of the wage-Phillips curve, κ_ω. For this, I specify a Markovian productivity process:

$$z_t = \rho_Z z_{t-1} + \epsilon_{z,t}, \tag{25}$$

where $\epsilon_{z,t} \sim \mathcal{N}(0, \sigma_\epsilon)$ is i.i.d., and TFP is given by $\Theta_t = e^{z_t}\Theta$. I calibrate ρ_Z and σ_ϵ. Because the underlying moments were computed by the original sources with the use of a Hodrick-Prescott (HP) filter, as usual, I will also apply it to the model to remove low-frequency variation following the procedure in Uhlig (1995). Table 1 lists the parameters, the targeted moment for each, and the moment source.

Two notes are in order. First, although the parameters that govern the TFP shock process are reported in Table 1, the calibration's purpose is not to identify them, since they are likely to be far off the mark, as the procedure I follow attributes a lot of variation in output to TFP shocks alone. The goal is to compute investment adjustment costs and wage-setting frictions that produce a reasonable covariance between output, investment, and wages. Second, in the next subsection, I will compare the cash and cashless economies against the data following the exact same calibration method for both. However, in the cashless economy, the moment that κ_ω is adjusted to match is flat on the relevant interval and above the target. So, I set the value to $\kappa_\omega = 0.02$, which keeps the two economies close to one another in match and solve for an exact match on the remaining moments.

Using the formula in Born and Pfeifer (2020) for the slope of the wage-Phillips curve implied by a Calvo-type of friction, the value I use corresponds to a probability of adjusting wages in a quarter of around 9.4%. This is below the empirical estimates in

Table 2: Distribution of wealth, earnings and income: cash economy

			Share held by (%)			
		Gini	Bottom 40%	Top 20%	Top 10%	Top 1%
Wealth	U.S. data	0.78	1.4	79.5	66.1	29.5
	FL model	0.65	2.3	65.2	44.5	8.6
	Model	0.79	0.1	83.1	62.4	14.7
Earnings	U.S. data	0.63	2.8	61.4	43.5	14.8
	FL model	0.50	10.1	53.5	34.2	6.7
	Model	0.47	12.5	50.4	34.9	6.3
Income	U.S. data	0.57	8.8	59.9	45.2	18.6
	FL model	0.42	14.6	48.4	30.3	5.8
	Model	0.47	12.4	50.6	35.0	6.4

Notes: U.S. data and FL model are from Floden and Lindé (2001), Table VI; the U.S. data are from Díaz-Giménez, Quadrini and Ríos-Rull (1997) and refer to households. Model: stationary distribution of the cash steady state. Earnings are pre-tax labor income; income is total pre-tax income, including capital income.

Barattieri et al. (2014) (21.1–26.6%), but close to the 10% estimated by IRF-matching in Auclert et al. (2020). As for the remaining parameters, the investment adjustment cost is $\xi = 1.7871$, which is below the usual literature value but close to the value of 2 in Sims and Wu (2021), which also assumes that firms need to issue bonds (in the form of perpetuities in their framework) to finance (part of) their investment. The persistence of the TFP process is aligned with the literature, although the standard deviation is higher, but close to SGU. Now, I briefly discuss the data fit across cash and cashless models.

Figure 2: Untargeted fit to the OMOs impulse response

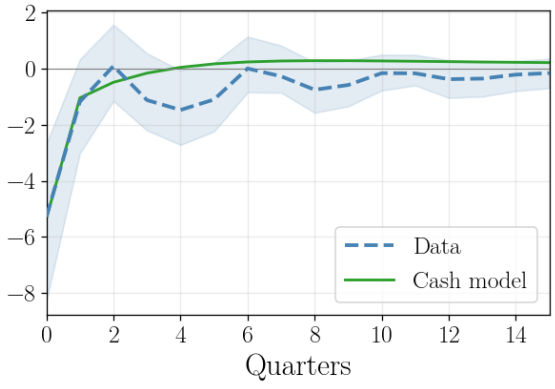


Figure 2 plots the untargeted fit of the OMO impulse-response produced by the calibrated cash model relative to its empirical counterpart from Section 3. I concentrate on the full sample IRF and turn it into a quarterly frequency by summing monthly variations within a quarter.[22] To preserve construct equivalence, the cash model IRF is computed as

[22]For the confidence intervals, I perform the same procedure for each bootstrap replication.

the percentage deviation in bond holdings by the central bank, $\mathcal{B}_t^{CB}$. As can be seen, the model matches the empirical impact response exactly, and along most of the transition, the model IRF remains within the confidence intervals. Given that OMO measure the enforcement wedge directly in the model, this result reinforces the interpretation that OMO are needed for enforcing the interest rate policy of the central bank. In Appendix B, I discuss the fit of both cash and cashless models in more detail.

5.2 Monetary Policy Transmission

In this subsection, I will discuss the different dynamics produced by cash and cashless economies to an expansionary monetary policy shock. Without loss of generality, I take the parameters calibrated to the cash economy (shown in Table 1) and impose them on the cashless economy as well. Unlike the fit discussion above, where the purpose was to discuss how both models perform as alternative estimators for deep parameters, I now turn to the discussion of the shock responses of two economies differing only in the requirement of a medium of exchange to back transactions and the need for OMOs.

Figure 3: Impulse response to an expansionary monetary policy shock

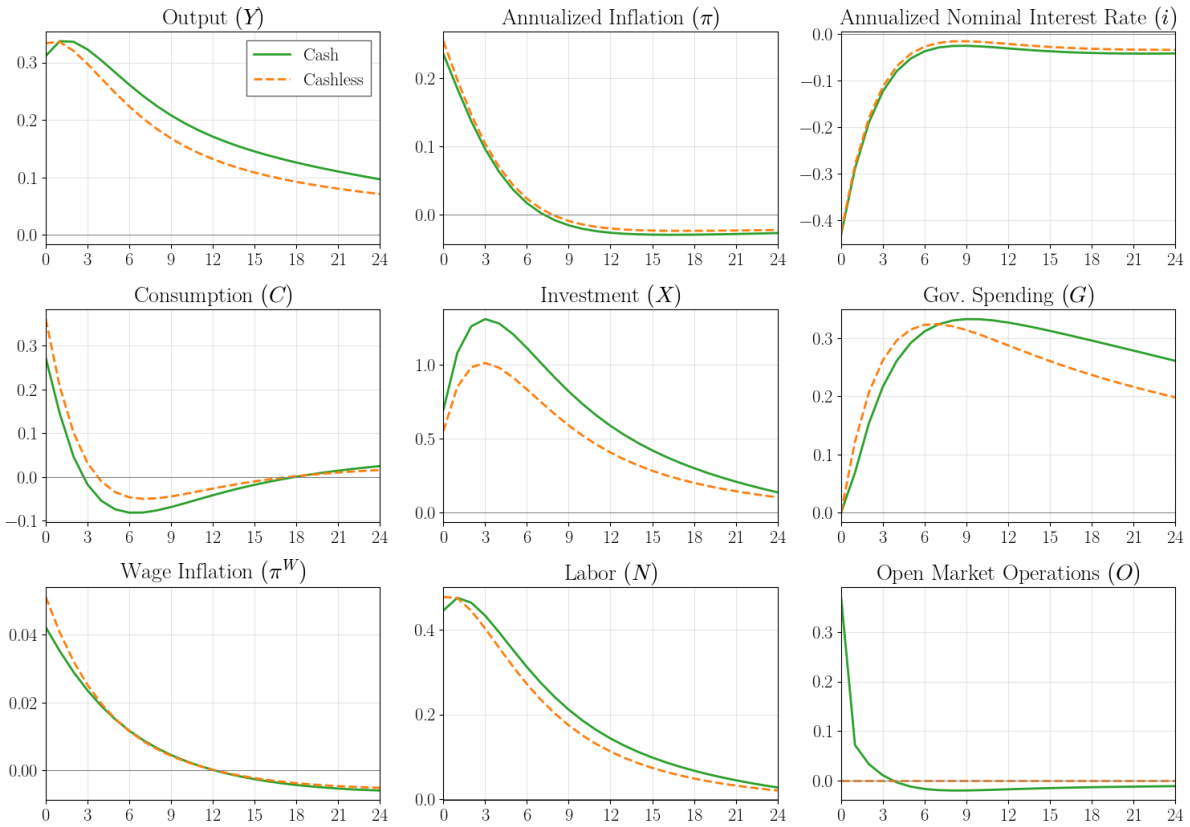


Figure 3 plots the IRFs to the expansionary monetary policy shock. The cash model IRFs are plotted in full green lines, while the cashless ones are dashed and orange. The

inflation and the interest rate paths are very close across the two economies. Output displays a bit more persistence in the cash economy, though the wedge is not substantial. Labor matches the pattern, though with a smaller wedge between the two economies. The main wedge is in the investment trajectory, where the cash economy's peak is roughly 30% higher than in the cashless economy, although they converge around the 25^{th} quarter. I will return to this point later. Government spending is more persistent in the cash economy, which is the main driving force behind the higher persistence in output, and is also reinforced by the output persistence through higher taxation.

On impact, the consumption response is around 30% higher in the cashless economy, and, although the wedge persists between the two, the effects on consumption are very transient and flip sign in the third quarter. The initially weaker consumption response in the cash economy is due to the fact that, although wages increase on impact after the shock, liquidity-constrained households still consume out of their initial, lower wages. To understand the wage path, note that, in the cash economy, the wage-Phillips curve, derived in Appendix B, has the form:

$$\log\left(\frac{1+\pi_t^{\omega}}{1+\overline{\pi}}\right) = \kappa\left[-\Omega\mathbb{E}_t\left(\beta\frac{\int_0^1 u'(c_{i,t+1})di}{1+\pi_{t+1}} + v'(N_t)\right)\right]N_t + \beta\mathbb{E}_t\left[\log\left(\frac{1+\pi_{t+1}^{\omega}}{1+\overline{\pi}}\right)\right],$$

where Ω is a constant. In the cashless economy, $\beta\mathbb{E}_t\left(\frac{\int_0^1 u'(c_{i,t+1})di}{1+\pi_{t+1}}\right)$ is replaced with $u'(c_{i,t})di$, both capturing the marginal value of earning a wage. The difference in timing reflects the fact that wages in the cash economy are used for consumption only in the consecutive period. Since real wages fall in both models, but more in the cash economy, and, besides, the labor response is close but slightly stronger in the cash economy, then its weaker nominal wage inflation response must be due to the marginal value of earning the wage. Still, the increase in hours makes total earnings increase in both economies.

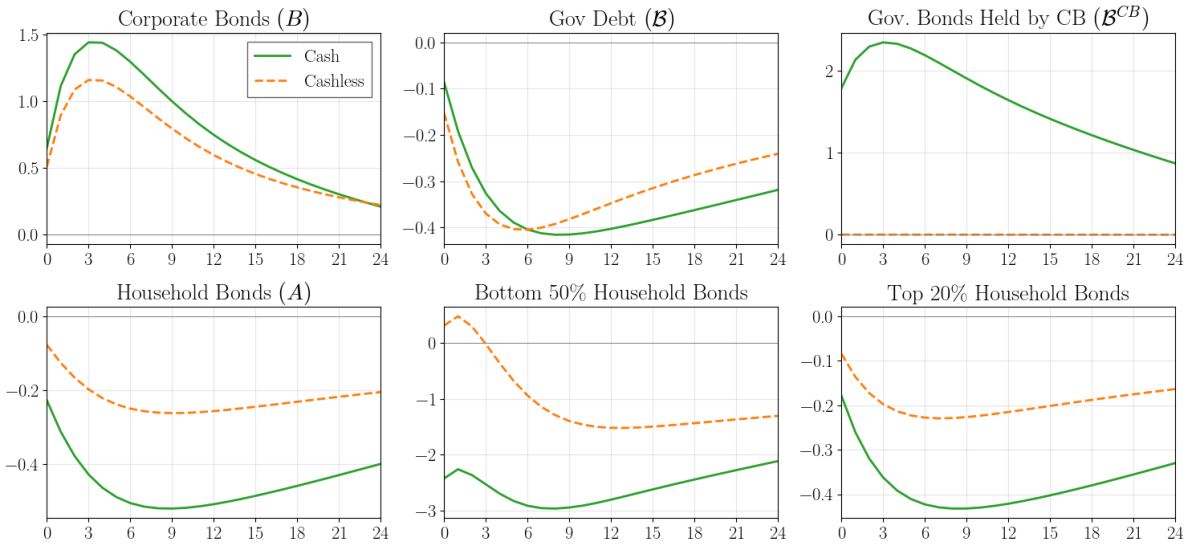
To understand the investment wedge, let χ_t be the multiplier associated with the capital law of motion (12) in the capital firm's problem. Taking the first-order condition with respect to corporate bonds issued, in the cashless economy, implies that $\chi_t = 0$. To understand why the constraint does not bind, notice that, by (14), the firm sells bonds at a price Q_t but discounts future bond payments at the same rate,[23] given that it can finance payments of maturing bonds with income it will earn in the next period. For the cash economy, on the other hand, $\chi_t = \frac{1}{Q_t} - 1$, meaning that, when the interest rate falls, the firm issues more bonds to push the multiplier downwards. As a result, in the absence of frictions that make money necessary, firms use cashless credit to cover bond repayment expenses, meaning that changes in debt service do not affect their decision.

[23]This is a general property if one assumes that the firm discounts the future at the rate at which it finances itself.

Figure 4 plots the IRFs for the financial market variables. As can be seen, households' bond demand falls in both economies with the decrease in the interest rate and the fall in real wages. However, the cash fall is more than two times as strong in the cash economy along the whole transition path. Given the consumption path, this indicates a stronger increase in the marginal propensity to consume (MPC) in the cash economy relative to the cashless one.

As will be shown below more formally with a decomposition, the main reason households' demand for bonds stays lower in the cash economy along the entire transition is the fact that households consume out of earnings from the previous period. This reduces their income, which implies lower savings, especially given the higher MPC relative to the cashless economy. The figure also plots the impulse responses of bond holdings of the households in the bottom 50% and top 20% of the income distribution. The former group displays a much stronger initial fall in bond holdings in the cash economy due to the tightening of the liquidity constraint, whereas the response in the cashless economy is initially positive due to the increase in total earnings.

Figure 4: Impulse response to an expansionary monetary policy shock in the financial market



At the same time, the fall in services generates a budget surplus for the government. In the cash economy, that fully explains the fall of government debt on impact, whereas in the cashless economy, the increase in taxes levied also pushes debt down further. Higher taxation along the transition sustains both a stock of government debt below the steady state value and higher spending. As investment passes its peak and corporate bond supply starts to fall, the lower supply of government bonds leads to persistently low households' bond holdings. In the cash economy, the central bank starts to remove

liquidity, decreasing its bond holdings. Furthermore, since government bonds represent 86% of households' steady-state savings, and government bond supply falls by 0.15% on impact in the cashless economy, while savings fall by less than 0.1%, the amount of corporate debt can expand. In the cash economy, the fall in government debt is not enough to counteract the (over two times as big) fall in savings, meaning that, in the absence of OMOs, investment would *fall*.

This is well illustrated by the decomposition I present below. Although the institution of open-market operations matters for the transmission of the monetary shock, as will be illustrated with an extension, the volume of open-market operations just accommodates the response in the demand for liquidity and bonds to the interest rate shock. This means that OMO volume has no additional informational content, as prior literature has suggested. To see this directly, Figure A9 and Figure A10, Appendix A, plot the part of the IRFs that is explained by OMOs when inflation, output, and capital are controlled for. Aside from a negligible part of government spending and debt coming from higher profits from the central bank and the OMOs path itself, open-market operations explain nothing.

As a result, the marginal contribution of open-market operations to the dynamics presented above does not capture the total effect of OMOs on the response to monetary shocks. Thus, to have a better grasp of the role open-market operations play, I take the OMOs path in Figure 3 and impose it as a shock path, and solve for the transition dynamics. The IRFs to this OMOs shock trajectory are displayed alongside the original cash economy's responses to the monetary shock in Figure 5.

In Figure 5, the dashed dark green lines represent the OMOs path, while the brown dotted line represents the part of the monetary shock IRFs that is not accounted for by OMOs. As stated above, in the absence of open-market operations, the investment response would be negative, which also pushes output into negative territory. Interestingly, although there is a liquidity effect caused by open-market operations, in general equilibrium, the increase in inflation causes the interest rate to be initially *positive* via the Taylor rule's response.

This interest rate path generates a negative consumption response to the OMO shock through intertemporal substitution, despite the increase in real wages. This means that consumption's response to the monetary shock is *moderated* by open-market operations. The initial deficit caused by the increase in the interest rate initially makes government spending slightly negative, which is countered fast by the increase in taxation, cumulatively reducing debt.

For the financial market, displayed in Figure 6, the dynamics for the OMOs shock path, relative to the monetary shock, feature more corporate bond sales and a more

Figure 5: OMOs' contribution to the impulse response to an expansionary monetary policy shock

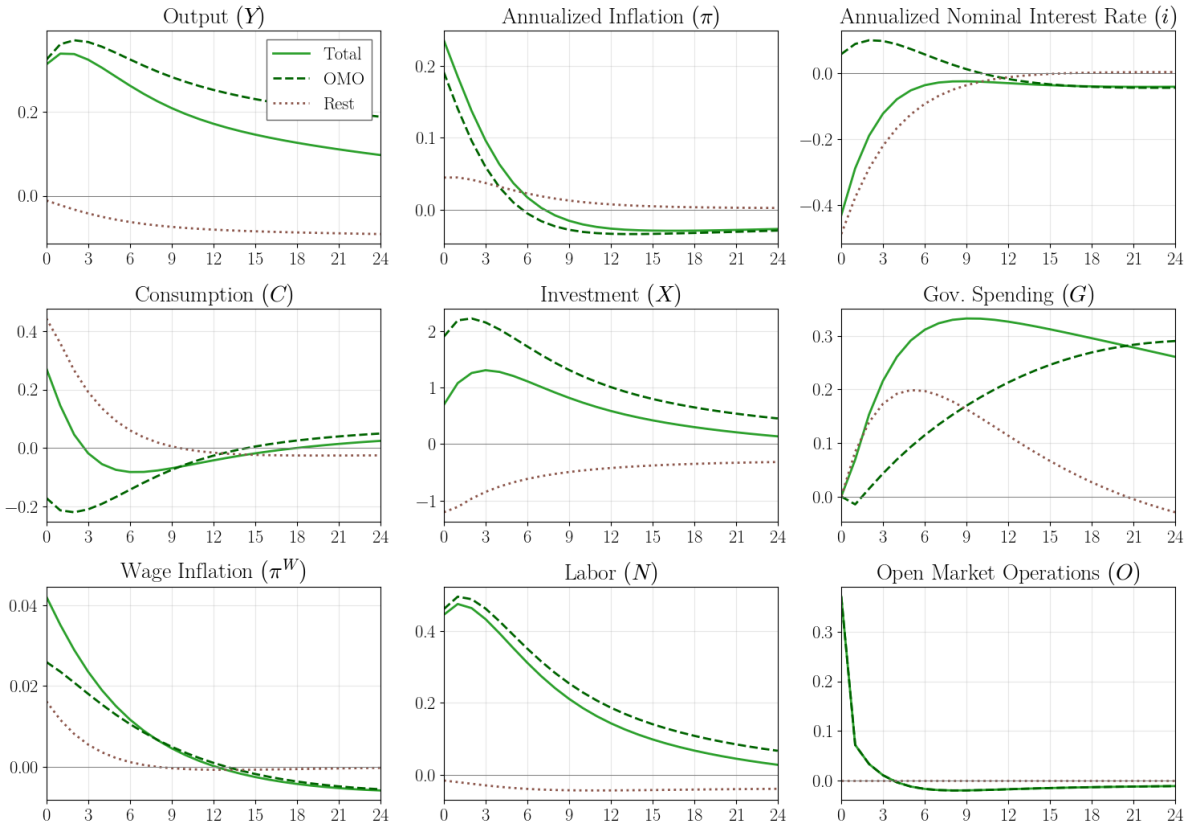
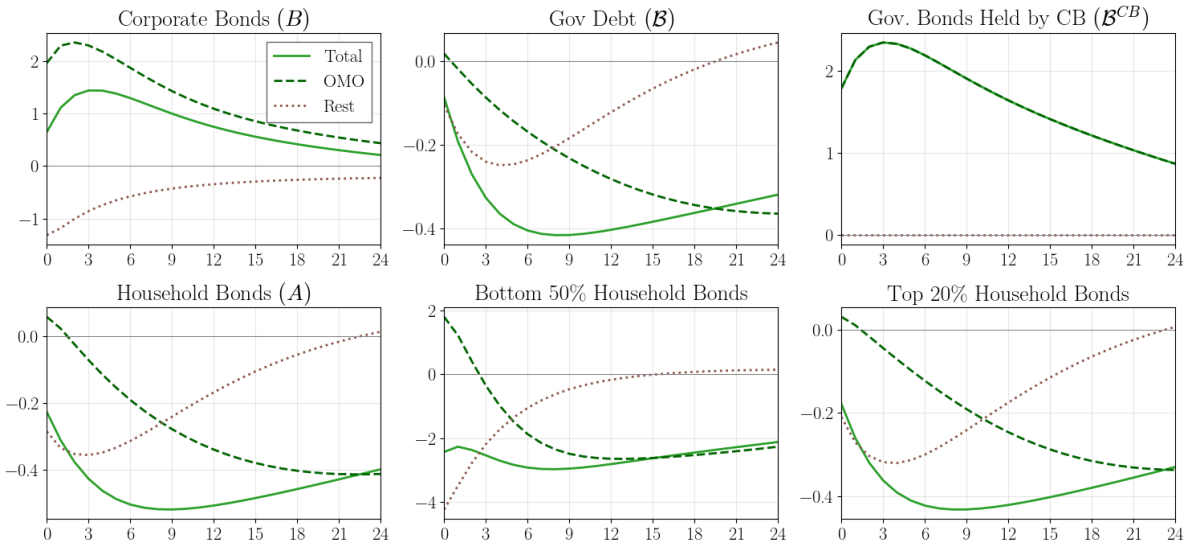


Figure 6: OMOs' contribution to the impulse response to an expansionary monetary policy shock



sluggish fall in government debt and households' security holdings. This more gradual

response is due to the initial increase in the interest rate, which causes households, especially poorer ones, to substitute away from consumption and increase savings on impact.

However, after the investment peak, as the imposed OMOs trajectory dictates that the central bank sells bonds back to the financial sector, and as higher taxation lowers the stock of government debt, households' savings fall. The initial small adjustment around zero in average households' bond holdings creates room for investment to expand more and, through higher capital, generate more persistence. All in all, open-market operations reallocate spending from households to the firm, and via its expansionary effects, eventually to government spending.

Lastly, I study the impact of the lags imposed by the cash-in-advance constraints. To do this, I define the spending wedge $w_t^x = x_{t-1} - x_t$, where x is one of three variables: (i) household's income $(1-\tau)P_t\omega_i n_{it} + \Pi_t$, with both the lag and the current value scaled by the same shock e_{it}; (ii) taxes levied, T_t; and (iii) and expenses with maturing debt, $-\bar{B}_t$.[24] As before, these lags enter as shocks that hit the corresponding variables in the steady state. This exercise captures the part of the response that is caused by the inability to anticipate end-of-period incomes. Figure 7 plots the IRFs in the financial market, whereas the remaining graphs can be found in Appendix A.

Figure 7: Lags' contribution to the impulse response to an expansionary monetary policy shock in the financial market

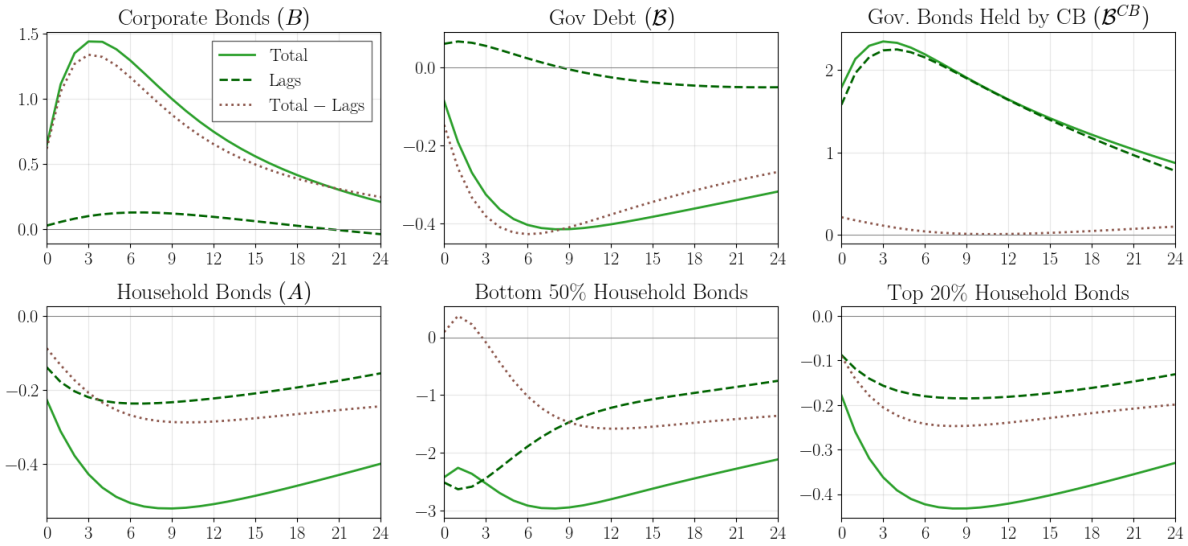


Figure A11, in Appendix A, shows that the wedge caused by lags on most variables is not substantial, except for consumption, where it dampens the initial response by

[24]Notice that, for the case (iii), the wedge also follows the form $w_t^{\bar{B}} = \bar{B}_{t-1} - \bar{B}_t$, but, unlike the other two wedges, the lagged term represents what would have been paid with incomes earned in period t in the absence of the cash-in-advance constraint.

around 30%. This matters because Schmitt-Grohé and Uribe (2007) use a cash-in-advance definition that does not require money to be held *in advance* of transactions. Now, more importantly, Figure 7 shows that nearly the entire path for Treasury bond holdings at the central bank produced by the monetary shock is explained by the existence of lags. This is intuitive, as OMOs relax the cash constraints that would otherwise bind decisions to resources accumulated up to the previous period. The government debt graph confirms that the wedge between cash and cashless economies, including their point of crossing, is accounted for by the presence of lags in the former.

Since corporate debt increases with the monetary policy shock, the need to hold liquidity to meet future debt obligations increases the amount of debt issued by the capital firm. This adds to the service-of-the-debt channel explained above in accounting for the wedge in investment response between cash and cashless economies. More noteworthy is the household bonds' graph. The dynamics not explained by the lags nearly coincide with the cashless path, meaning that the bulk of the wedge between the two economies in the response to the monetary shock is explained by the presence of lags. The impact is highest for the households at the bottom of the earnings distribution, who do not own enough assets to run down on when they face tighter liquidity constraints.

In summary, this section has shown that, although the dynamics of output, inflation and the nominal interest rate do not differ greatly between the cash and cashless economies, the underlying channels are different. The presence of the cash-in-advance constraint causes households, especially poorer ones, to dissave more than the cashless economy would predict after an expansionary shock. The cash-in-advance constraint also causes the capital firm to react more strongly to the interest cut both by lowering the services of the firm's debt and by increasing the firm's demand for money, needed to meet future debt obligations. This wedge is bridged by open-market operations, which is a fundamental piece for enabling, in the cash economy, the usual sign of output and consumption response to the shock, while also accounting to a great extent for its persistence. Now, I consider the policy implications of my framework.

6 Policy Analysis

For this section, I study how the cash and the cashless economies react to different Taylor rule coefficients. I conduct a policy analysis inspired by Schmitt-Grohé and Uribe (2007), where I compare policies involving different Taylor rule coefficients according to a utilitarian welfare function. To compute welfare, I need a second-order approximation, which requires making some changes to the model. For that end, I use the method developed

by Auclert et al. (2026), which allows one to obtain higher-order approximations of the stochastic economy from derivatives of the perfect foresight solution.

6.1 Methodological details and calibration

To implement their method, I first need to assume that idiosyncratic shocks follow the form $e_{i,t}\xi_{i,t}$, where $\log \xi_{i,t} \sim \mathcal{N}(-\sigma_\xi^2/2, \sigma_\xi^2)$, with $\xi_{i,t}$ i.i.d. and satisfying $\mathbb{E}_t[\xi_{i,t}] = 1$. This is a computational device: integrating over $\xi_{i,t}$ within the period lets the distribution of households over assets be computed as a continuous density rather than approximated by a histogram, and it is this computed smoothness that the second-order perturbation of the household block requires (Auclert et al., 2020).

Moreover, to avoid having a utility cost from adjusting wages—which was not consequential for the linear IRFs presented so far but would distort a second-order welfare function approximation,—I assume a Calvo wage-setting friction, with a frequency of adjustment of η_W as in Auclert et al. (2020). Lastly, to a second-order approximation, the real interest rate in the stochastic steady state differs from the one in the deterministic steady state assumed so far, given the stock of bonds and the time preferences calibrated above. Given the Taylor rule and the Fisher equation, the steady state inflation rate will in general differ from the one in the deterministic steady state.

In light of this, two additional assumptions are needed. First, I follow SGU in assuming that the targets in the Taylor rule (19), namely $\overline{r}$, $\overline{\pi}$ and $\overline{Y}$, are inherited from the deterministic steady state. This allows the different rules I will consider to differ only with respect to the inflation and output coefficients, but it means that the economy is off target on average.

Secondly, the baseline steady state bond holdings of the central bank, $\overline{\mathcal{B}}^{CB}$, assumed in the baseline calibration are not compatible with steady state inflation in either of the two economies. To prevent OMOs from being used in the cashless economy to keep real Treasury holdings of the central bank constant, I assume $\overline{\mathcal{B}}^{CB,cashless} = 0$. In the cash economy, in this model $\overline{\mathcal{B}}^{CB,cash} = \frac{Y}{Q} = 1.005$ is the value that is stationary under non-zero trend inflation. In both cases, I adjust total government debt, $\overline{\mathcal{B}}$, accordingly to ensure that households have the same amount of government bonds. It is important to say that these assumptions produce the same deterministic steady state as in Section 5.

I also follow SGU in assuming two shocks: one affecting productivity and the other, government spending, as given by the function (16). Naturally, the government spending shock follows:

$$g_t = \rho_z g_{t-1} + \varepsilon_{g,t},$$

where $\epsilon_{g,t} \sim \mathcal{N}(0, \sigma_g)$. The calibration will follow the procedure in Schmitt-Grohé and Uribe (2006): I use their estimated persistence of the government shock process, $\rho_g = 0.87$, and its standard deviation, $\sigma_g = 0.016$. The parameters of the TFP shock process are calibrated to match business cycle moments. For the calibration of the cash economy, I follow a similar procedure to the one in Section 5.

Table A1 summarizes the changed parameters. The standard deviation of the transitory idiosyncratic shock is set at the same level as in Auclert et al. (2026), $\sigma_\xi = 0.0964$, which still remains close to model moments Floden and Lindé (2001). The baseline values for the Calvo probability of adjusting prices in the goods market and the wage-Phillips curve slope produced too much stickiness and little amplification in the stochastic steady state in my diagnostic simulations. I then set them at the flexible end of the intervals reported in Nakamura and Steinsson (2008) and Barattieri et al. (2014). Relative to the baseline, investment adjustment costs are more than three times larger, and the TFP shock process is more persistent and has a lower standard deviation. As before, I impose the parameters on the cashless economy.

I report the conditional welfare measure similar to the one defined in SGU, adapted to the HANK setting. This measure assumes that the economy starts at a deterministic steady state. In their case, they assume that it starts at the Ramsey steady state. Since the debate on how to define the Ramsey policy in the context of HANK models is ongoing, I assume that each economy is, at time zero, in its deterministic steady state. Moreover, I adopt a utilitarian welfare criterion, which gives the conditional welfare:

$$V_0(\boldsymbol{\theta}) = \mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t \int_0^1 \left[u(c_{i,t}) - v(n_{i,t}) \right] di \;\middle|\; \boldsymbol{\theta} \right\}, \tag{26}$$

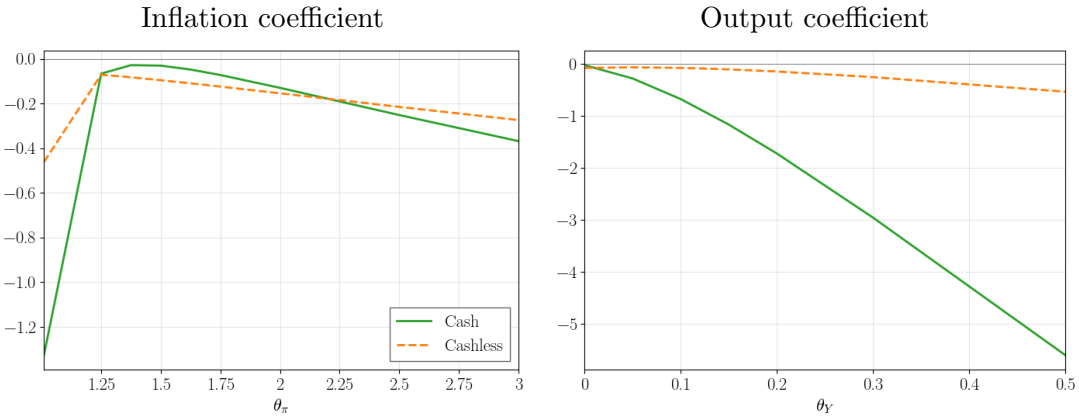
where $\boldsymbol{\theta} = [\theta_\pi, \theta_Y]$ stands for the Taylor rule policy vector. I use the deterministic steady state, which differs between cash and cashless economies, as the benchmark to compute the consumption equivalent. I constrain my attention to $\theta_\pi \in [1.01, 3]$ and $\theta_Y \in [0, 0.5]$. Results are presented below.

6.2 Fixed Taylor rule targets

To begin, I consider the case where the targets $\overline{\pi}$ and $\overline{r}$ are set as in Table 1 and $\overline{Y}$ is the deterministic steady-state output. In this case, the optimal policy in the cash economy is to set the inflation coefficient at $\theta_\pi = 1.375$ and the output coefficient at $\theta_Y = 0$, which gives a consumption equivalent of -0.028% relative to the deterministic steady state. In the cashless economy, the optimal is to set $\theta_\pi = 1.375$ and $\theta_Y = 0.05$, which produces a consumption equivalent of -0.07%. The first thing to notice is that the optimal policies

are very close between the two economies. I now turn to the welfare costs of not following the optimal policy. For the sake of readability, I plot two-dimensional graphs, but the three-dimensional graphs are included in Appendix A.

Figure 8: Consumption equivalent for fixed Taylor rule targets



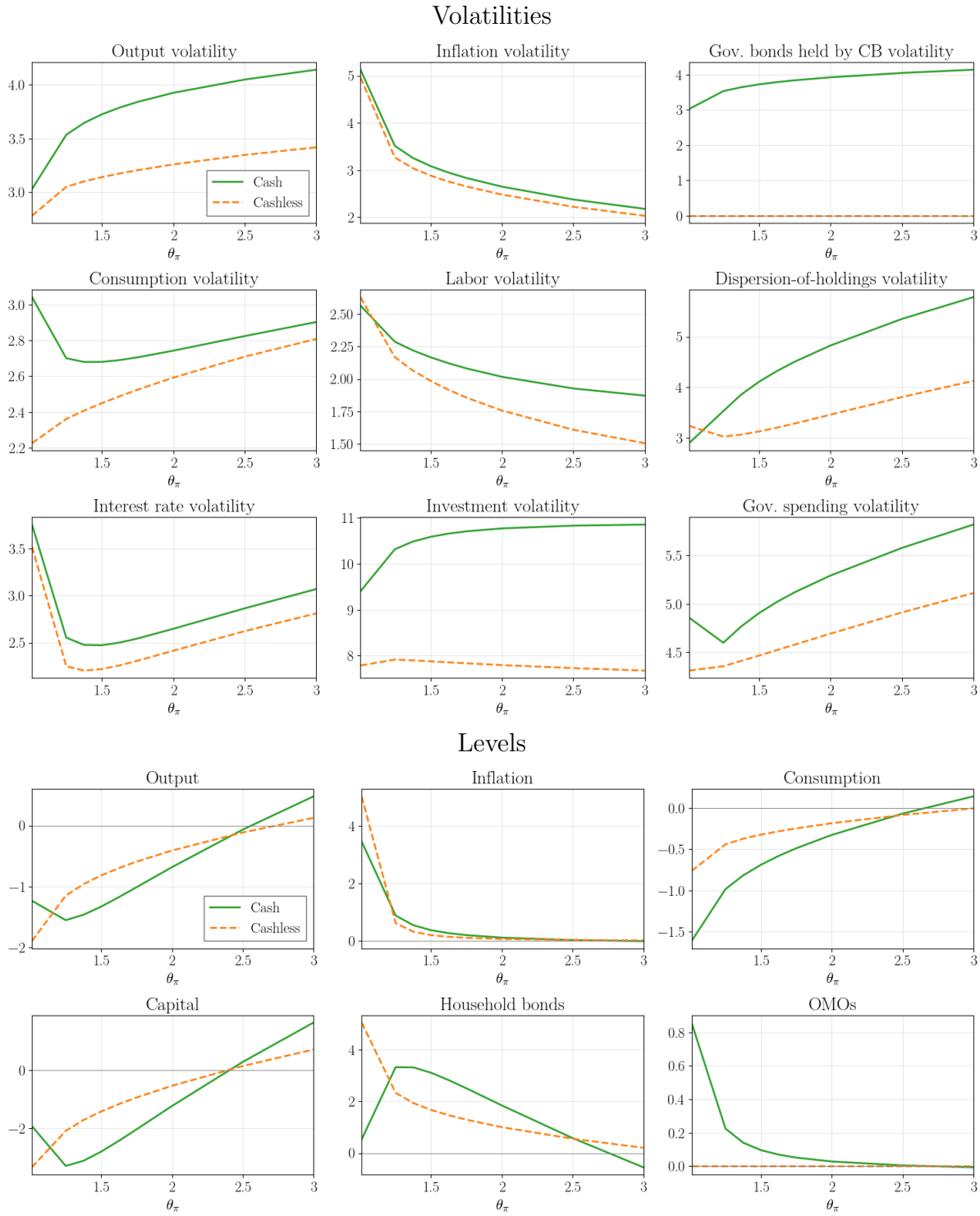
Notes: The first graph fixes $\theta_Y = 0$. The second fixes $\theta_\pi = 1.375$.

Figure 8 plots the consumption equivalent for varying Taylor rule coefficients. In the first panel, I fix the output coefficient at $\theta_Y = 0$, while in the second I fix the inflation coefficient at $\theta_\pi = 1.375$. The graphs show that welfare in the cashless economy is much flatter than in the cash one. As $\theta_\pi \downarrow 1$, the welfare losses get much stronger in the cash economy relative to the cashless one. For values above the optimal point, the measures evolve closely in the two economies, but with a slightly steeper slope in the cash economy. For the output coefficient, the situation differs: welfare losses in the cash economy increase much faster than in the cashless economy as θ_Y increases, whereas any coefficient between 0 and 0.1 is approximately optimal in the cashless model.

Figure 9 displays both how the volatilities change with the inflation coefficient and the steady-state values of some key variables. First, notice that inflation is positive on average for $\theta_\pi < 2.5$ in both economies due to an insufficient response to its deviations (relative to $\overline{\pi} = 0$). Given the Taylor rule and the Fisher identity, the real interest rate is higher than in the deterministic steady state, which depresses investment, the capital stock and, as a result, output and consumption.

Steady-state inflation also requires positive levels of OMOs to increase the monetary base and maintain the Treasury holdings at the central bank stationary. For $\theta_\pi = 1.01$, where inflation peaks in both economies, OMO volume is the highest, which redistributes resources from households to the capital firm. This means that, in the cash economy, at this coefficient, households' demand for bonds is lower and capital is higher than in the cashless economy. This, in turn, implies a lower rate of return on capital, a lower real interest rate and, therefore, a lower inflation rate in the cash economy.

Figure 9: Impact of the inflation coefficient over volatility and steady state levels of key variables for fixed Taylor rule targets



Notes: The graphs fix $\theta_Y = 0$.

With respect to volatilities, first notice that volatility is higher in the cash economy for all variables across almost all values of θ_π. Inflation volatility reacts equally and at similar levels in both economies to the level of the inflation coefficient. However, the high

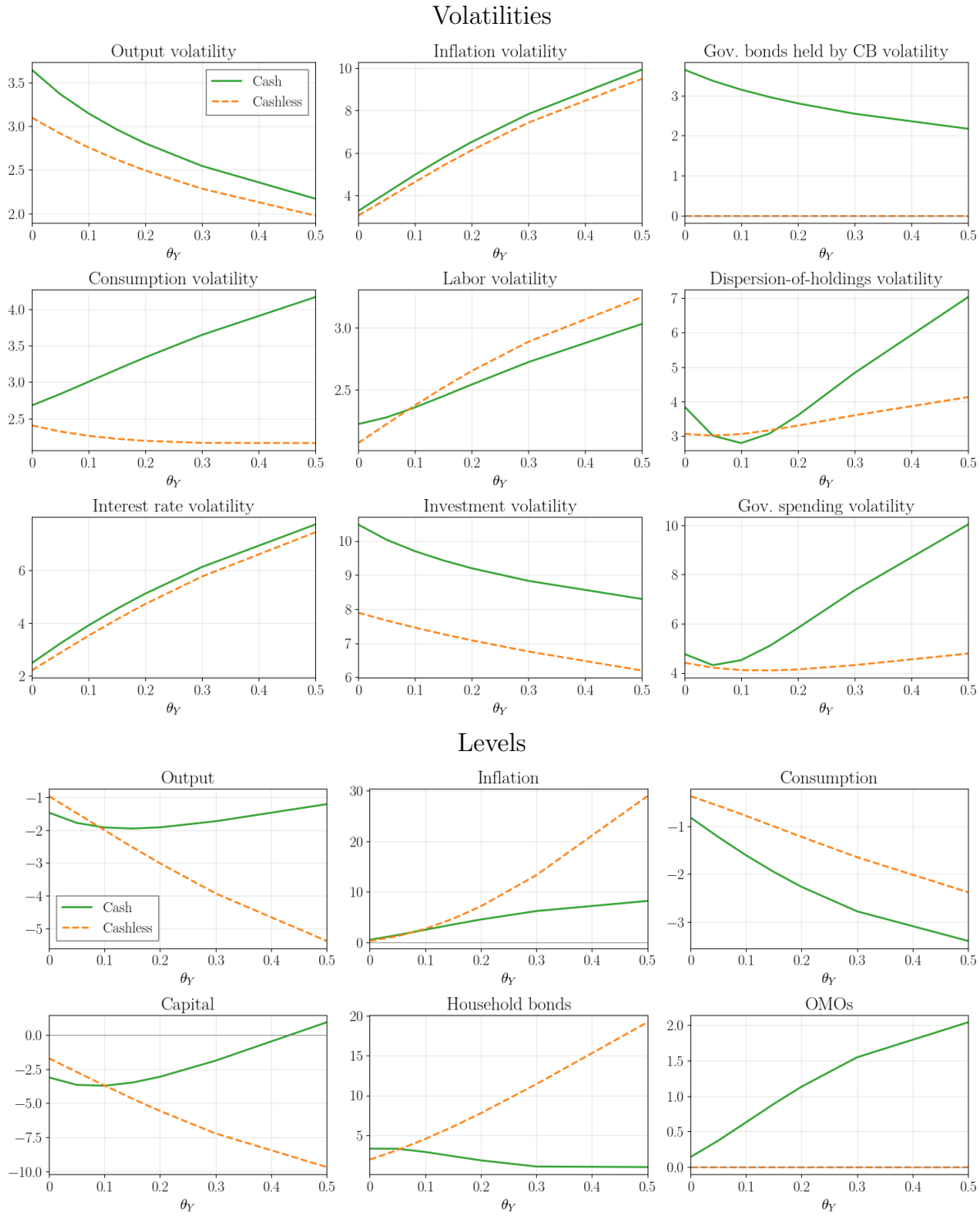
inflation level and volatility at $\theta_\pi = 1.01$ generate higher consumption volatility through the inflation tax on carrying money with lags. This accounts for the strong welfare drop in the cash economy near the lower bound for the inflation coefficient. The fall in inflation volatility, as the coefficient increases from $\theta_\pi = 1.01$, maps into the fall in interest rate volatility. This, in turn, and together with the initial fall in labor volatility, contributes to making government spending volatility fall as well.

Past the optimum, volatility varies with the inflation coefficient at a similar pace for most variables. Still, labor volatility is slightly flatter in the cash economy due to the precautionary behavior of unions in the face of cash-in-advance distortion, while volatility in the dispersion of bond holdings (the standard deviation of the cross-sectional distribution, which serves as a wealth inequality measure) is steeper, possibly due to interest rate volatility, which varies the cost of precautionary savings. While OMO volume decreases with θ_π as inflation approaches its target $\overline{\pi} = 0$, the volatility in real government bond holdings by the central bank (which are here divided by the price level) captures the business cycle fluctuations in OMO volume, which increases with the inflation coefficient. Investment volatility tracks OMO volatility.

Figure 10 plots volatilities and steady state levels for different output coefficients, with $\theta_\pi = 1.375$. The increase in inflation level that is observed in the cashless economy as θ_Y increases is very substantial, reaching almost an annualized 30% rate at $\theta_Y = 0.5$. In the cash economy, inflation increases more slowly, being three times as low at the upper bound of the output coefficient range. Since higher inflation, in the presence of the Taylor rule with fixed targets, implies a higher real interest rate, household bond holdings increase, but the capital stock falls to levels almost 10% below the deterministic steady state level in the cashless economy for $\theta_Y = 0.5$, which also means lower output. In the cash economy, the capital stock is *higher* than at the steady state for a high output coefficient, as inflation is much lower than in the cashless economy and the higher OMO volume in the inflationary scenario favors the capital firm relative to households.

For volatility, the image painted is much different: output inflation and labor volatility display similar slopes in both economies. However, as inflation volatility increases with θ_Y, consumption volatility increases much more strongly in the cash economy via the variations in the value of holding money. Interest rate volatility is similar in the two economies, and investment volatility varies similarly with θ_Y but is higher in the cash economy due to the effect of OMOs. Moreover, for $\theta_Y > 0.1$, volatility in bond holdings dispersion increases significantly more with the output coefficient in the cash economy, possibly reflecting the higher consumption volatility: if consumption is volatile, rich households would like to self-insure, but more households may be pushed back-and-

Figure 10: Impact of the output coefficient over volatility and steady state levels of key variables for fixed Taylor rule targets



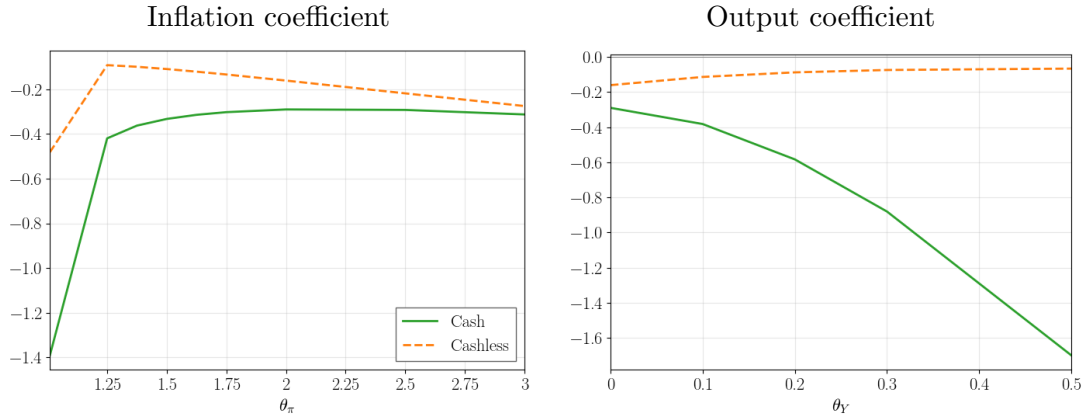
Notes: The graphs fix $\theta_\pi = 1.375$.

forth into a hand-to-mouth position. These two elements account for the rapid welfare deterioration in the cash economy as one moves away from the optimal policy.

6.3 Moving Taylor rule targets

I now consider the case in which the Taylor rule targets, $\overline{r}$, $\overline{\pi}$ and $\overline{Y}$ are solved for to match the corresponding long-run average real interest rate, inflation and output under each policy. Since the behavior of levels and volatility here is similar to the case above, I include the supporting two-dimensional graphs in Appendix A alongside the three-dimensional surfaces. Now, policy differs more starkly between the two economies. The optimal in both economies is an inflation coefficient of $\theta_\pi = 2$, higher than before, because the costs of responding strongly to deviations when the inflation target is set at the actual long-run average are smaller. However, the output coefficient sits on opposite corners for each economy: for the cash economy, the bounded optimal stays at $\theta_Y = 0$, while it is $\theta_Y = 0.5$ for the cashless economy. Figure 11 plots the consumption equivalent slices.

Figure 11: Consumption equivalent for moving Taylor rule targets



Notes: The first graph fixes $\theta_Y = 0$. The second fixes $\theta_\pi = 2$.

Figure 11 shows a similar pattern to what was observed before, but the optimal policy is costlier in the cash economy. While the cashless economy achieves a consumption equivalent of -0.067% relative to its deterministic steady state, a result very close to and slightly better than under the fixed target regime, the cash economy obtains a consumption equivalent of -0.29% of its deterministic steady state consumption, roughly ten times lower than at the fixed regime target. The increase in the optimal output coefficient in the cashless economy seems to be explained by a decrease in government spending volatility, as θ_Y increases, which reduces bond supply volatility and makes bond holdings inequality less volatile, as can be seen in Figure A17. As for the higher welfare losses at the optimal policy in the cash economy, they are due to a level effect: with a higher inflation target, steady-state inflation levels are higher, which is supported by higher OMO volumes. This leads to lower consumption by transferring resources to the capital firm.

6.4 Taking stock

Overall, whether the optimal policy differs substantially between the two economies or not depends on whether the Taylor rule targets reflect long-run conditions or not. Still, the cash economy suffers larger welfare losses from not controlling inflation enough and from targeting output for a series of reasons. First, welfare in the cash economy is more sensitive to inflation volatility, which affects the value of holding money and open-market operation volumes. However, due to the precautionary behavior of unions and this higher sensitivity to inflation, the cash economy moderates strong inflation pressures relative to the cashless economy. Besides, high OMO volatility and long-run levels hurt welfare by producing strong redistribution of resources between households and the capital firm. As a result, despite the overall similarity in optimal policy, the two economies produce starkly different results for suboptimal policies.

7 Extensions

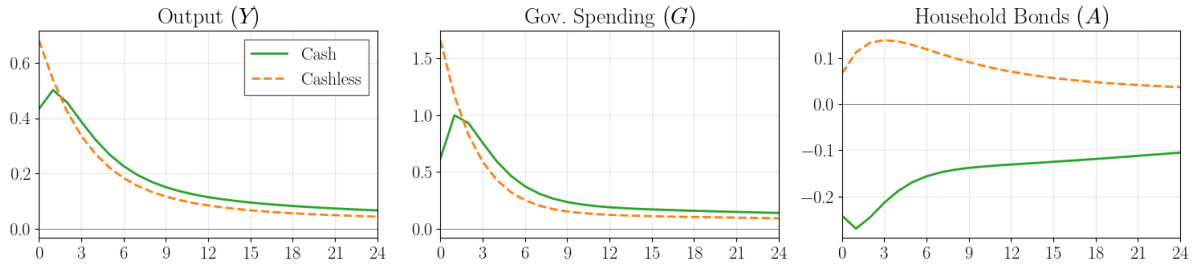
I now consider a brief set of extensions with the purpose of investigating additional implications of the framework presented in this paper. To begin, I discuss an alternative policy rule that forces debt to stay equal to the target. As I will discuss, this will illustrate a feedback mechanism that produces amplification in cashless models. Then, I consider two alternative ways of injecting money into the economy: proportional and lump-sum transfers, corresponding to two alternative definitions of helicopter drops. The goal is to show that, while injection volumes are endogenous, the institutional framework affects transmission. Then, I consider a model where agents have myopia and sticky expectations regarding the interest rate with the purpose of investigating how OMOs volume is affected by an unannounced interest rate shock. Throughout the section, only the most relevant IRFs will be plotted, but the complete set can be found in Appendix A

7.1 Strict debt targeting

So far, I discussed the standard fiscal rule in the literature, where government spending (or, in some papers, taxes), is a function of deviations of government debt from target. The usual calibration indicates that the spending response to the stock of debt is small, meaning that debt should still be strongly autocorrelated. However, there is an important theoretical point to be made regarding an alternative regime where debt targeting is strict, and the fiscal authority enforces constant debt, *i.e.*, $\mathcal{B}_t = \mathcal{B}_{t-1} = \overline{\mathcal{B}}$. Unlike the baseline, where government spending reacts to past developments in the path of debt, and the latter absorbs surpluses and deficits, in this exercise, the opposite occurs: debt stays

constant, and any surplus feeds spending directly. Figure 12 plots the IRFs for the most relevant variables.

Figure 12: Impulse response to an expansionary monetary policy shock for strict debt targeting



As can be seen, the response of government spending on impact is 1.5 times larger in the cashless economy. This is due to a strong government spending multiplier: the surplus from lowering the interest rate generates higher contemporaneous spending, which feeds output, leading to higher taxation and, as a result, higher spending. This feedback mechanism, which produces strong complementarities, seems to be a powerful mechanism whereby the cashless model generates amplification in general. In the baseline specification, however, this is limited, insofar as government spending is concerned, by a backward-looking fiscal rule.

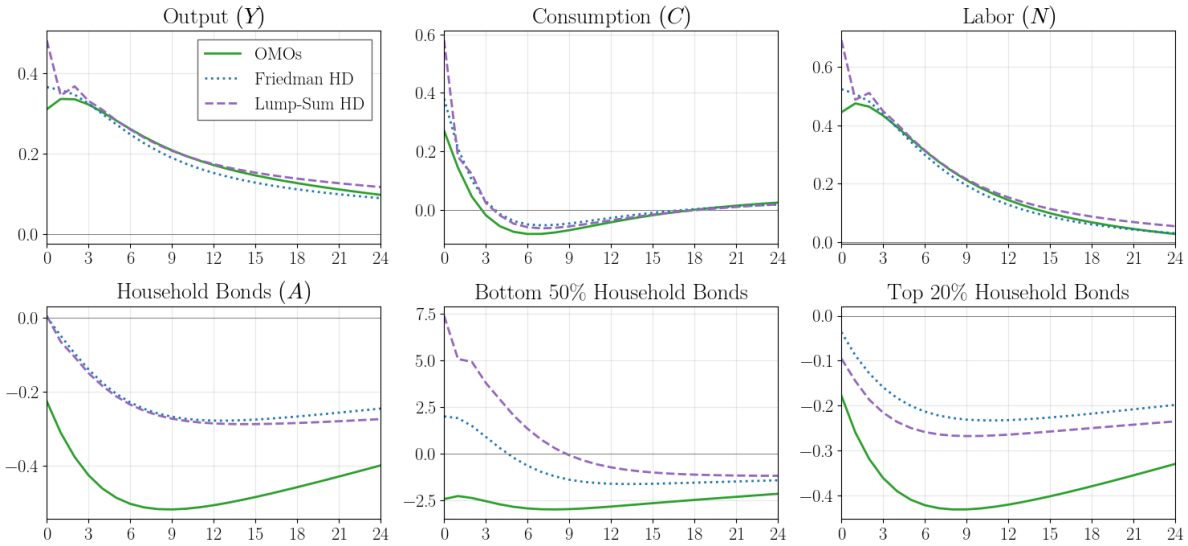
In the cash economy, G_t remains backward-looking since it depends on taxes levied in the past. This suggests that a cashless economy generates amplification via within-quarter feedback mechanisms, whereas the cash economy relies on open-market operations. Without a variation in government debt to enable higher investment and lower savings to coexist, the cashless economy needs households to save *more* after an interest rate cut to finance the higher corporate bond emission. In the cash economy, open-market operations ensure that households' bond demand goes in the expected direction.

7.2 Helicopter Drops

In this subsection I use two alternative definitions of helicopter drops (HD). The first, referred to as lump-sum helicopter drops, consists of lump-sum transfers to households financed with money creation. These transfers enter directly into both the budget and the cash-in-advance constraints faced by households. The second traces back to Friedman (1969), and it consists of transfers that are proportional to households' monetary holdings at the beginning of the period—comprising their past revenues, $e_{i,t}[(1-\tau)P_{t-1}\omega_{t-1}n_{i,t-1}+\Pi_{t-1})]$. The idea behind proportional transfers is that, when households are heterogeneous, lump-sum transfers are distortionary, while proportional transfers do not distort

the distribution of real balances among households. Figure A19 plots the most important IRFs.

Figure 13: Impulse response to an expansionary monetary policy shock for alternative money injection technologies

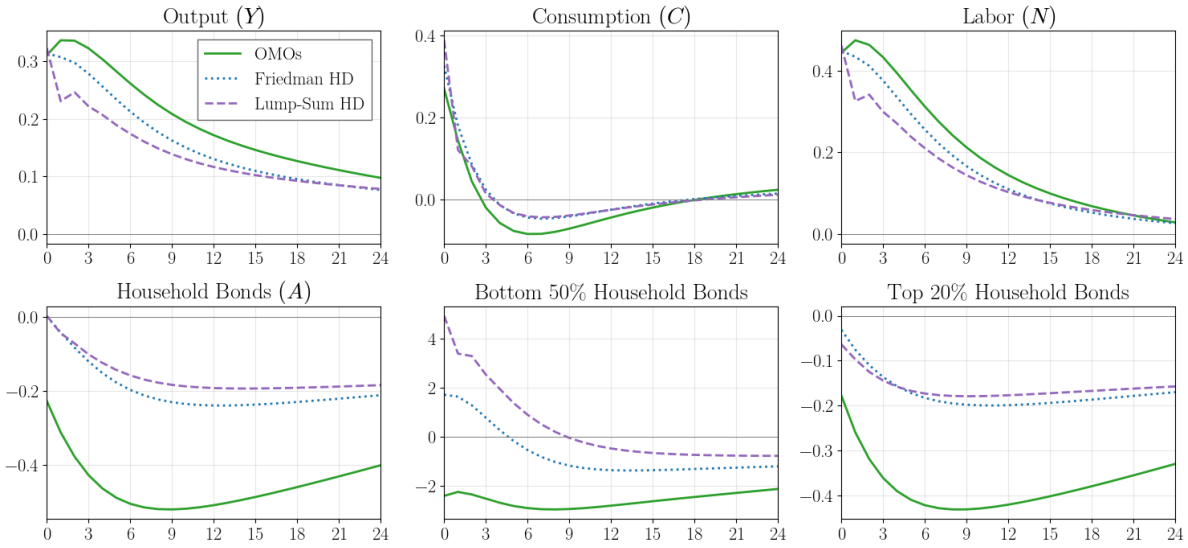


The consumption response for the lump-sum HD economy is between 2–3 times the OMOs economy's response on impact, with Friedman HD (proportional transfers) sitting in between. The consumption response is bigger in the case of lump-sum HD given that such transfers favor poorer households, who have a larger marginal propensity to consume. This also moves output accordingly on impact more on these economies. When no open-market operations occur to finance extra private investment directly, a larger amount of money must be injected to produce similar investment levels.

The aggregate trajectory of households' bond holdings is smaller in both helicopter drop economies. In the case of lump-sum transfers, although the main beneficiaries of the transfers have a lower MPC, the transfers allow them to increase their savings as well as their consumption. In the OMOs economy, dissaving is strongest, given that households benefit less from the money injections, which transfers resources from households to the capital firm and, eventually, the Treasury. None of the three economies match the cashless IRFs closely, and, for the remaining variables, the difference in responses is small (see Figure A19).

Figure A20 plots the case in which the same purely transitory money injection is imposed on the three economies. The amount is equal to the one produced on impact in the baseline economy after the monetary policy shock. While the shock transmits to output roughly to the same amount on impact, the OMOs economy displays more persistence, while the others, and especially the lump-sum HD economy, present faster decay

Figure 14: Impulse response to a monetary base shock for alternative money injection technologies



in activity. This output path also affects total taxes levied along the transition, which, in turn, affects the strength and duration of the government spending response. This comes, again, from the way these shocks are introduced: by boosting investment, OMOs produce a higher capital stock than the others, which makes the effects die out more slowly. This also leads to more persistent government surpluses and, as a result, more amplification and persistence through G_t. The Friedman economy produces intermediate investment levels: by not transferring real balances from richer to poorer agents, it produces more savings and, as a consequence, higher corporate bond purchases.

7.3 Incomplete information on the shock

To capture the period prior to 1994, when the Fed started to announce the federal funds rate target, I adopt an extension with sticky expectations and myopia. Each agent in the economy is assumed to encompass a continuum of members with mass one. These members' role is to acquire information on the interest rate. They keep the information they have about the interest rate with probability λ, and observe the central bank's target for that period with probability $1 - \lambda$. As a result, all agents in the economy will form expectations of the form:

$$Q_t^e = \lambda Q_{t-1}^e + (1 - \lambda) Q_t, \tag{27}$$

where Q_t^e stands for the expected price of bonds. For simplicity, I assume that the credit market clears at the expected rate, meaning that the central bank can at best influence

the closing price, but not fully enforce it. This gets closer to the notion that the central bank decides on a target for the market rate.

With this assumption alone, to a first-order approximation, agents can still perfectly foresee the expected interest rate path everybody else expects, which includes actual information on future interest rates, and the future paths of the remaining variables. To dampen that, I assume myopia along the lines of Gabaix (2020): I assume that, due to inattention, agents discount the actual paths for the expected value of all variables relative to the steady-state path. I assume there is an attention parameter $\bar{m}$ such that:

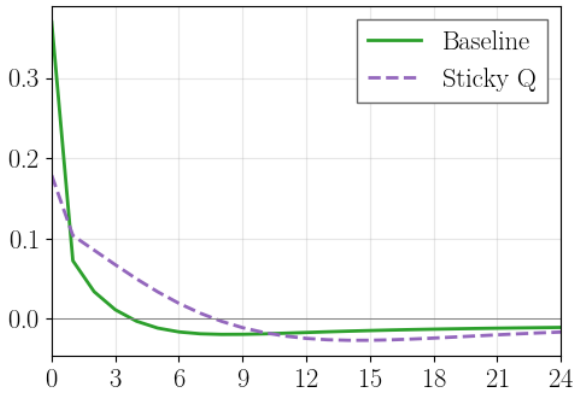
$$\mathbb{E}_t^{BR}[x_{t+k}] = \bar{m}^k \mathbb{E}_t[x_{t+k}] + (1 - \bar{m}^k) x_{ss}, \tag{28}$$

where x is any variable in the system, x_{ss} is its steady state value, $\mathbb{E}_t^{BR}$ is the boundedly rational expectation operator, and $k \in \mathbb{N}$. For the interest rate, this means that:

$$\mathbb{E}_t^{BR}[Q_{t+k}] = \bar{m}^k Q_{t+k}^e + (1 - \bar{m}^k) Q_{ss}.$$

Importantly, when Q_t^e enters forward-looking variables as a stochastic discount factor, it is assumed to also get discounted by $\bar{m}$. This design draws some inspiration from the insight in Angeletos and Huo (2021) that a combination of some form of inattention to the future and some form of sticky expectations can capture informational frictions.

Figure 15: Impulse response of OMOs to a monetary base shock with incomplete information on the shock



I set $\bar{m} = 0.85$ as in Gabaix (2020), which is conservative, and $\lambda = 0.9$ is chosen to produce an approximately right level of OMOs response on impact, and it is close to the value in Auclert et al. (2020). Figure 15 shows the OMOs response. As can be seen, when agents do not know the rate that was announced, the OMO volume is lower on impact, but descends more slowly. Intuitively, when agents do not know the announced rates and stick to a more conservative backward-looking prior that also dampens expected future

deviations from the steady state, investment and household bond demand respond less on impact (as can be seen in Figure A21).

This means that the enforcement wedge that OMOs have to bridge is smaller, causing its impact response to the shock to shrink. The incomplete information model, however, produces a hump shape—similarly to sticky expectations in Auclert et al. (2020),—meaning that most variables peak later than in the full information baseline model. This additional response delays the decay of OMO volume. In summary, if the expected effect of rate announcements is expected to generate faster transmission and stronger initial responses, the finding that the OMO volume responds more strongly on impact after 1994 is compatible with the model.

8 Concluding Remarks

This paper builds on the existing evidence of a nuanced role for money in the economy and studies its importance for monetary transmission and optimal policy design by means of a HANK model with cash-in-advance frictions, corporate debt, and open-market operations. I first provide empirical evidence of an impact response of OMOs to monetary policy shocks, despite the announcement effect within days of monetary policy announcements. On this foundation, I show with the calibrated model that the need to carry money in advance of transactions and the institutional framework in which the central bank commits to use OMOs to enforce its interest rate policy affect monetary policy transmission and optimal policy discussions in a way that cannot be captured by a cashless framework.

This framework is compatible with much of the existing evidence that monetary aggregates have low informational content, as well as with the long-run comovements between prices and money. It can be extended to address many features potentially relevant for the question, such as fractional reserve banking, money velocity, default risk and bond premia. It can also be used to study events in which demand for money apparently broke down (Goldfeld et al., 1976) or the puzzlingly low inflation response to quantitative easing.

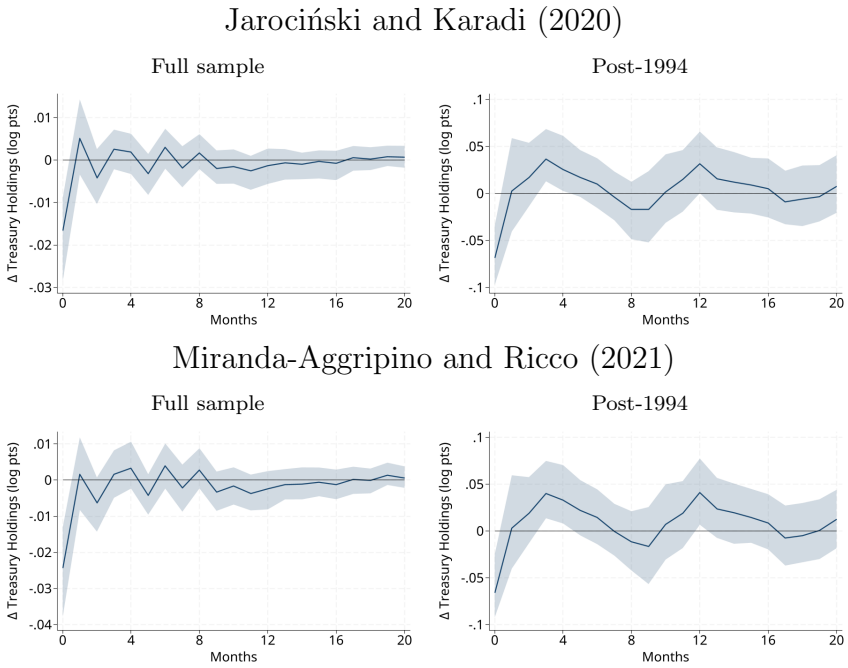
As McCallum (2001) argues, models without money are misspecified, but their adequacy depends on the misspecification error. While previous literature found this error to be small, I show that the opposite result arises in an environment where empirically plausible features, such as idiosyncratic risk, corporate debt, and cash-in-advance frictions, produce a well-defined enforcement wedge of monetary policy. This highlights the importance of a medium of exchange in monetary models, even if the goal is to understand under what conditions the role of money breaks down.

Appendix

A Supplementary Figures and Tables

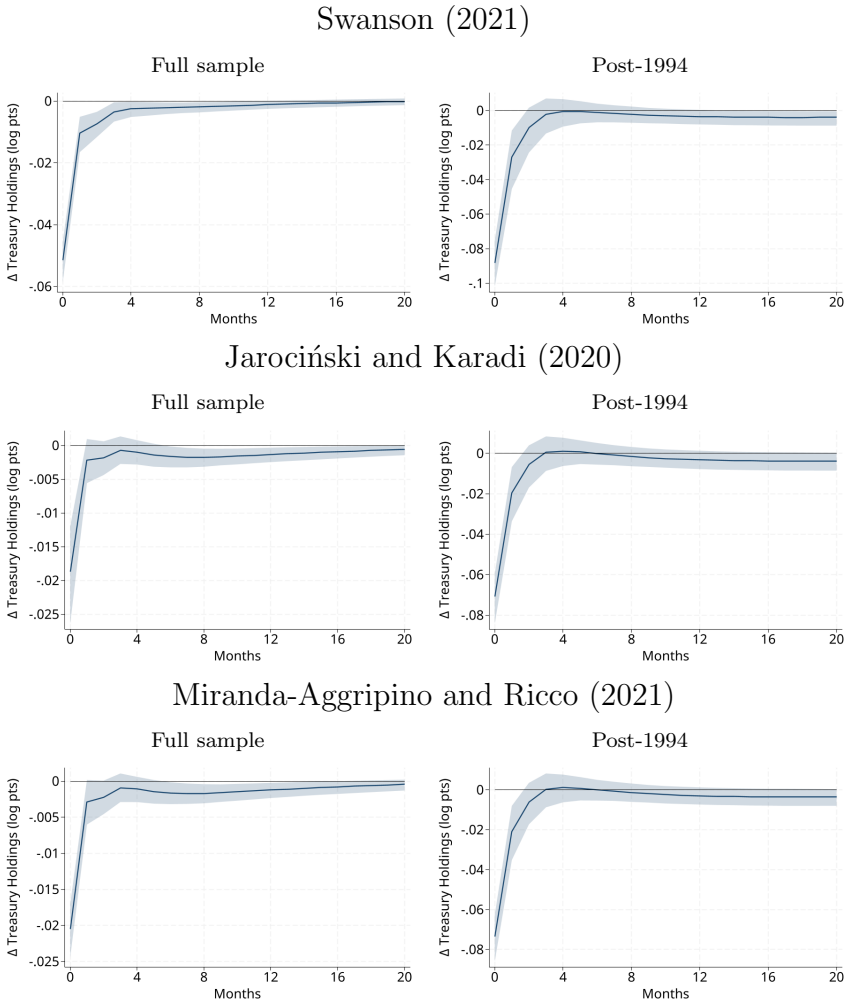
A.1 Additional Empirical Results Tables

Figure A1: Response of Treasury holdings to a contractionary monetary policy shock: frequentist VAR-IV, all shocks



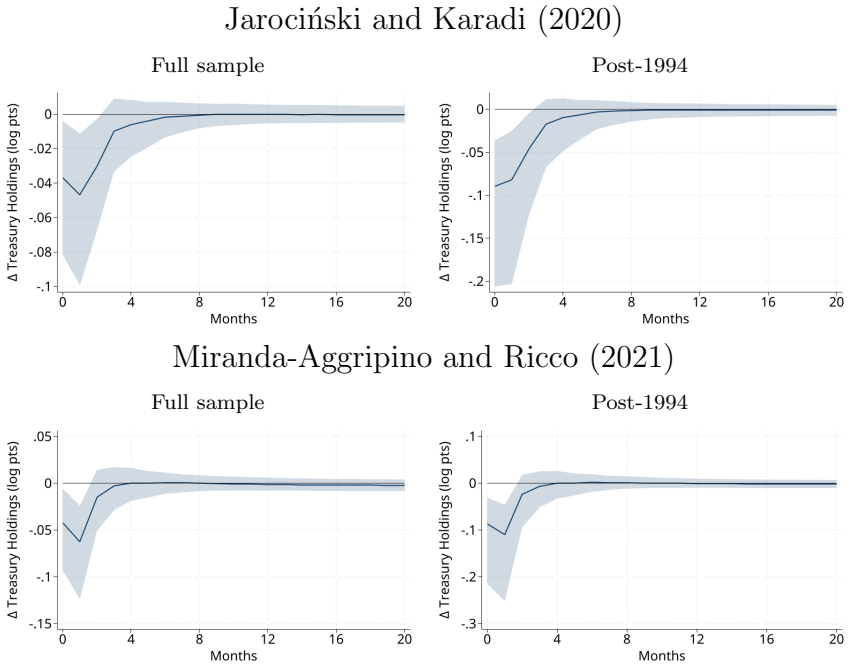
Notes: Jarociński and Karadi (2020), and Miranda-Aggripino and Ricco (2021) shocks. Responses in percentage points of monthly growth of Treasury holdings to a 100 basis points contractionary monetary policy shock. Frequentist VAR-IV; 90% confidence intervals.

Figure A2: Response of Treasury holdings to a contractionary monetary policy shock: Bayesian VAR-IV, all shocks



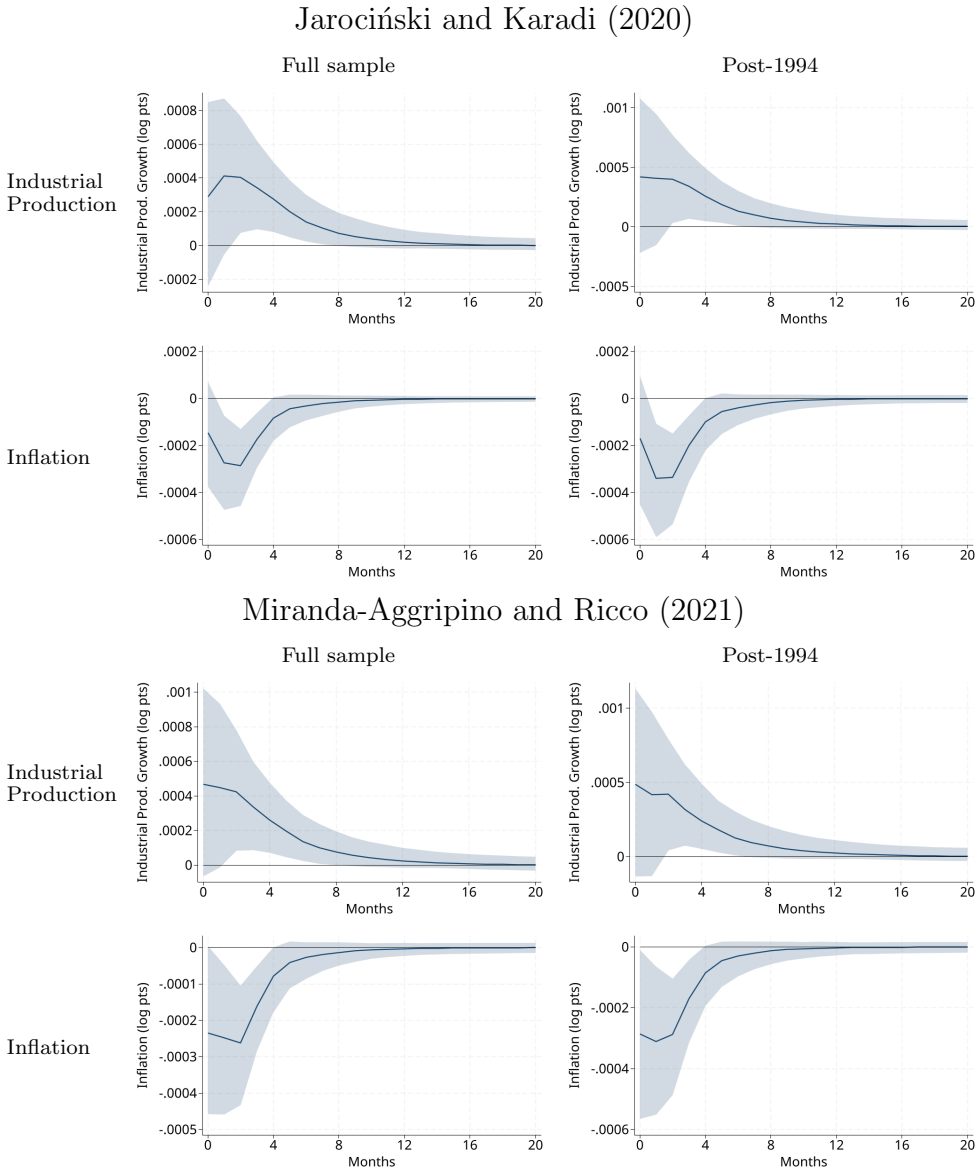
Notes: Swanson (2021), Jarociński and Karadi (2020), and Miranda-Aggripino and Ricco (2021) shocks. Responses in percentage points of monthly growth of Treasury holdings to a 100 basis points contractionary monetary policy shock. Bayesian VAR-IV with Minnesota prior; 90% credible bands.

Figure A3: Response of Treasury holdings to a contractionary monetary policy shock: Bayesian recursive VAR, JK and MAR shocks



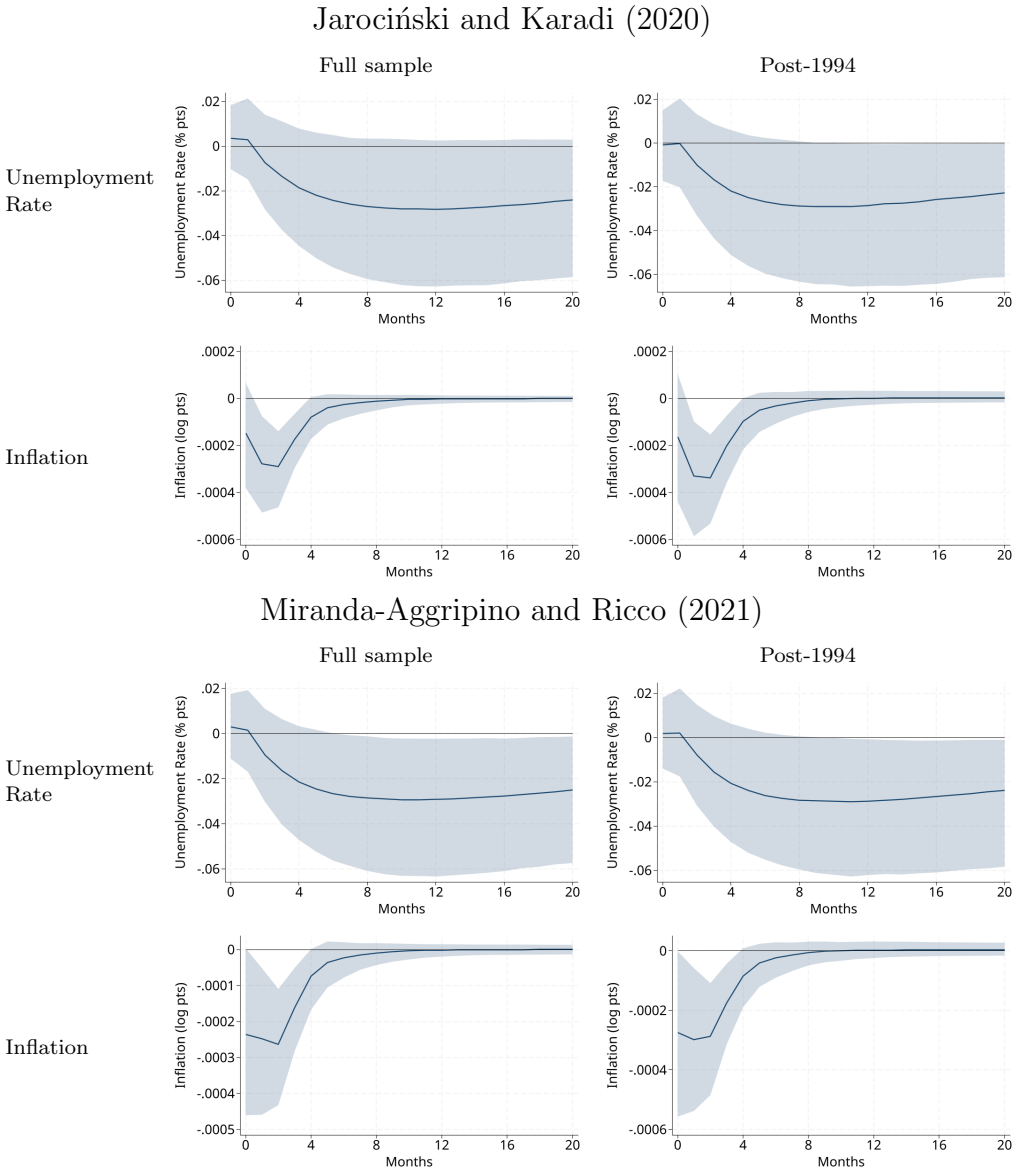
Notes: Jarociński and Karadi (2020) and Miranda-Aggripino and Ricco (2021) shocks. Responses in percentage points of monthly growth of Treasury holdings to a 100 basis points contractionary monetary policy shock. Bayesian recursive VAR with Minnesota prior; 90% credible bands.

Figure A4: Response of industrial production and inflation to open-market Treasury purchases: Bayesian recursive VAR, JK and MAR shocks



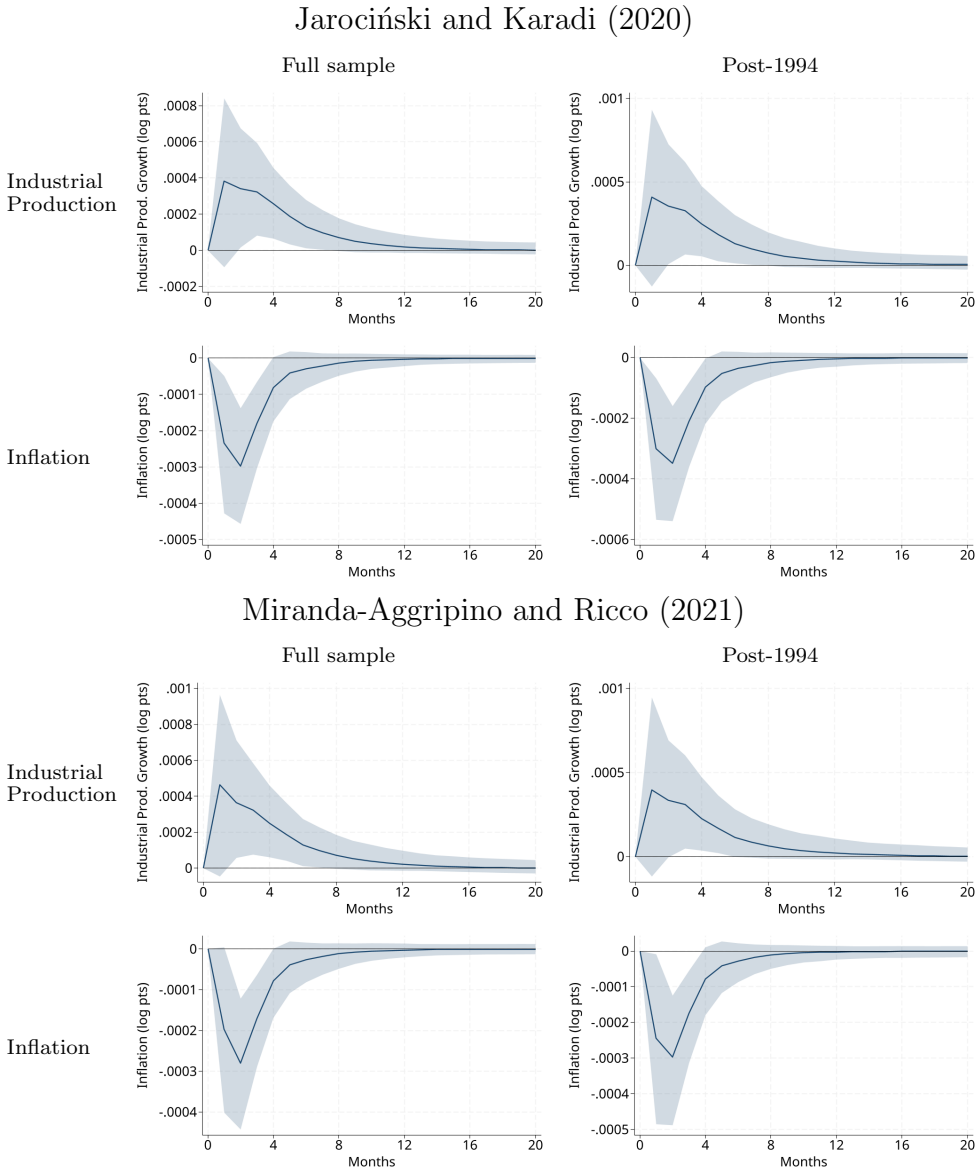
Notes: Jarociński and Karadi (2020) and Miranda-Aggripino and Ricco (2021) shocks. Responses in percentage points of monthly IPI growth and monthly inflation to a one standard deviation OMOs shock. Bayesian recursive VAR with Minnesota prior; 90% credible bands.

Figure A5: Response of unemployment rate and inflation to open-market Treasury purchases: Bayesian recursive VAR, JK and MAR shocks



Notes: Jarociński and Karadi (2020) and Miranda-Aggripino and Ricco (2021) shocks. Responses in percentage points of the unemployment rate and of monthly inflation to a one standard deviation OMOs shock. Bayesian recursive VAR with Minnesota prior; 90% credible bands.

Figure A6: Response of industrial production and inflation to open-market Treasury purchases: Bayesian recursive VAR, JK and MAR shocks, inverted ordering



Notes: Jarociński and Karadi (2020) and Miranda-Aggripino and Ricco (2021) shocks. OMOs variable placed last. Responses in percentage points of monthly IPI growth and monthly inflation to a one standard deviation OMOs shock. Bayesian recursive VAR with Minnesota prior; 90% credible bands.

A.2 Cash Flow Diagrams

Figure A7: Cash Flows in the Goods Market at t

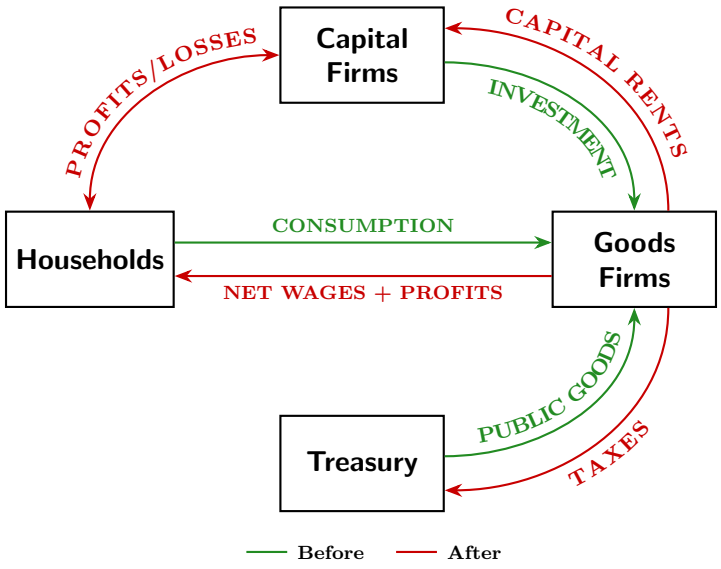
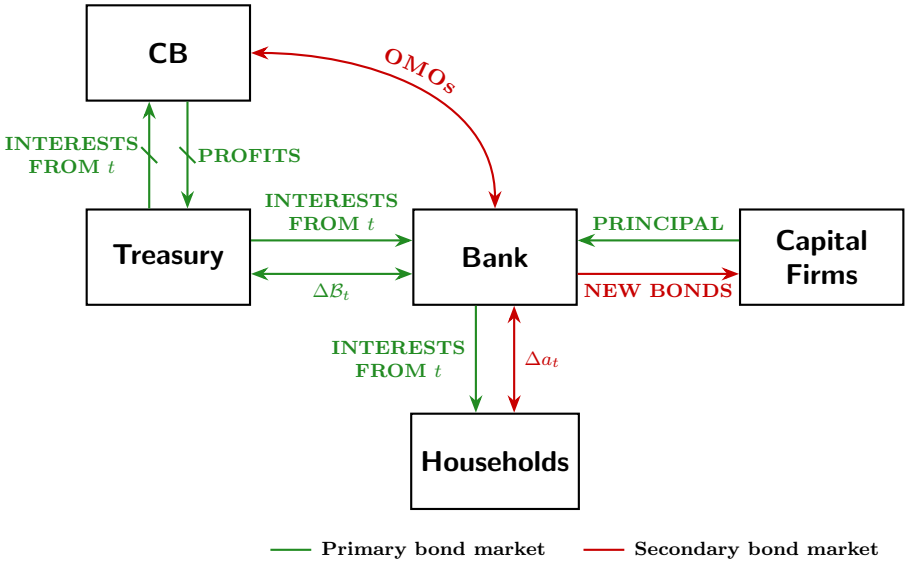


Figure A8: Cash Flows in the Bonds Market at $t+1$



A.3 Quantitative results

Figure A9: OMOs' marginal contribution to the impulse response to an expansionary monetary policy shock

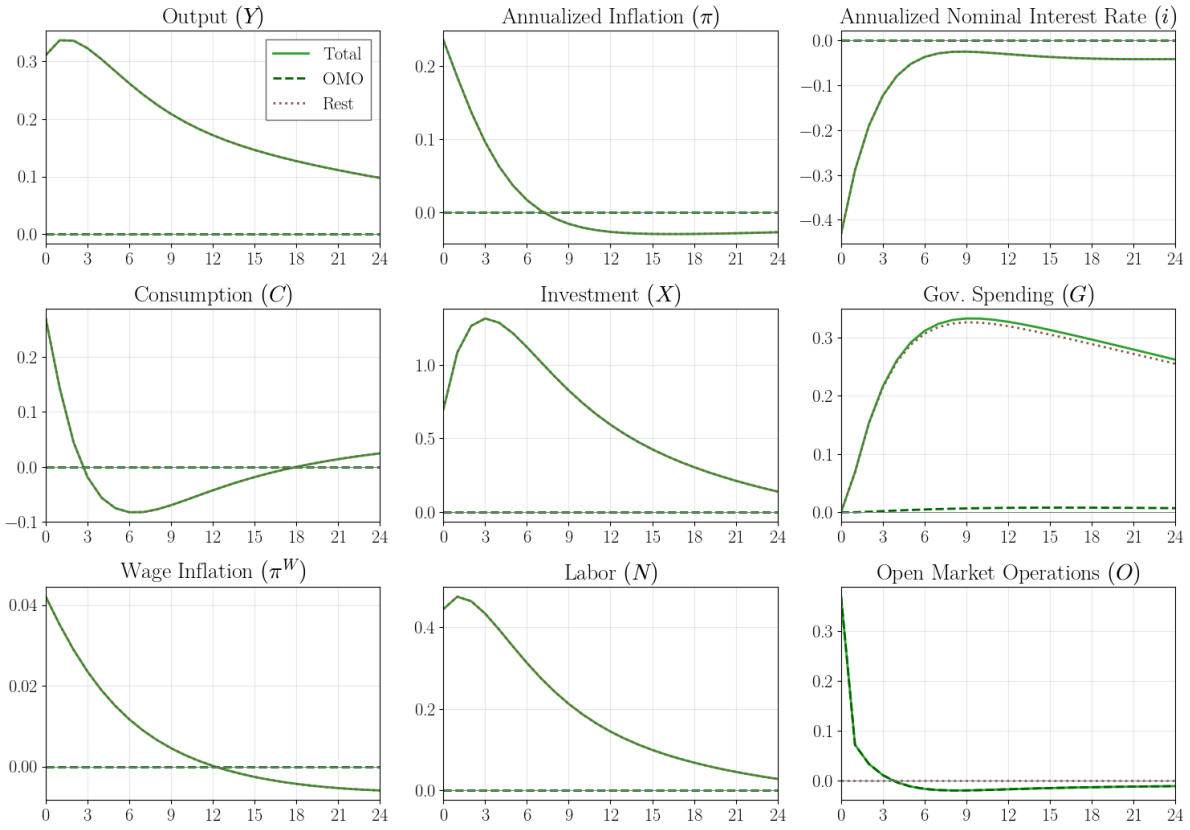


Figure A10: OMOs' marginal contribution to the impulse response to an expansionary monetary policy shock in the financial market

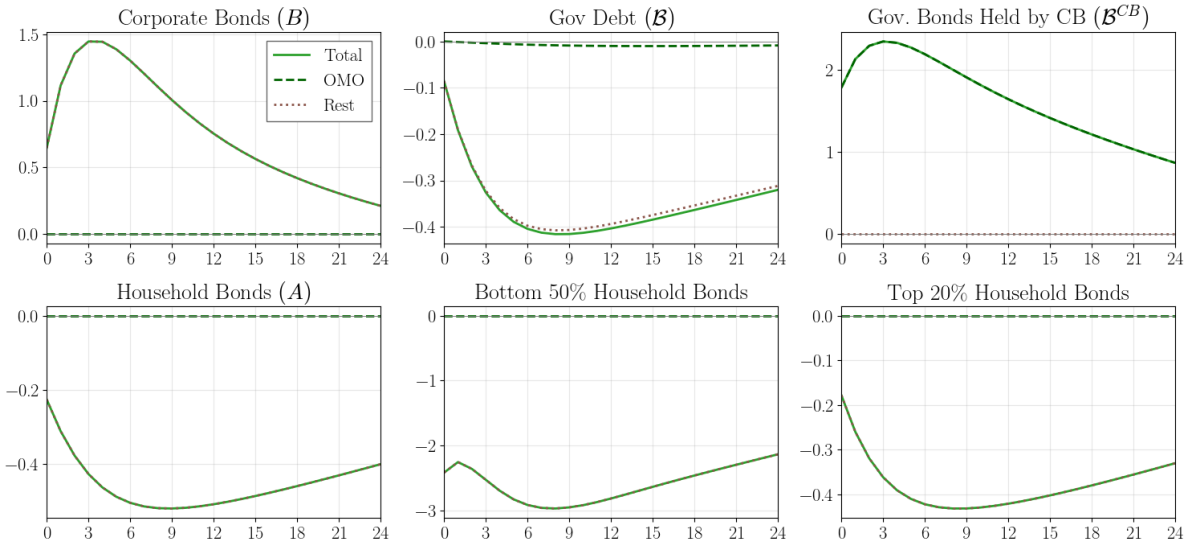
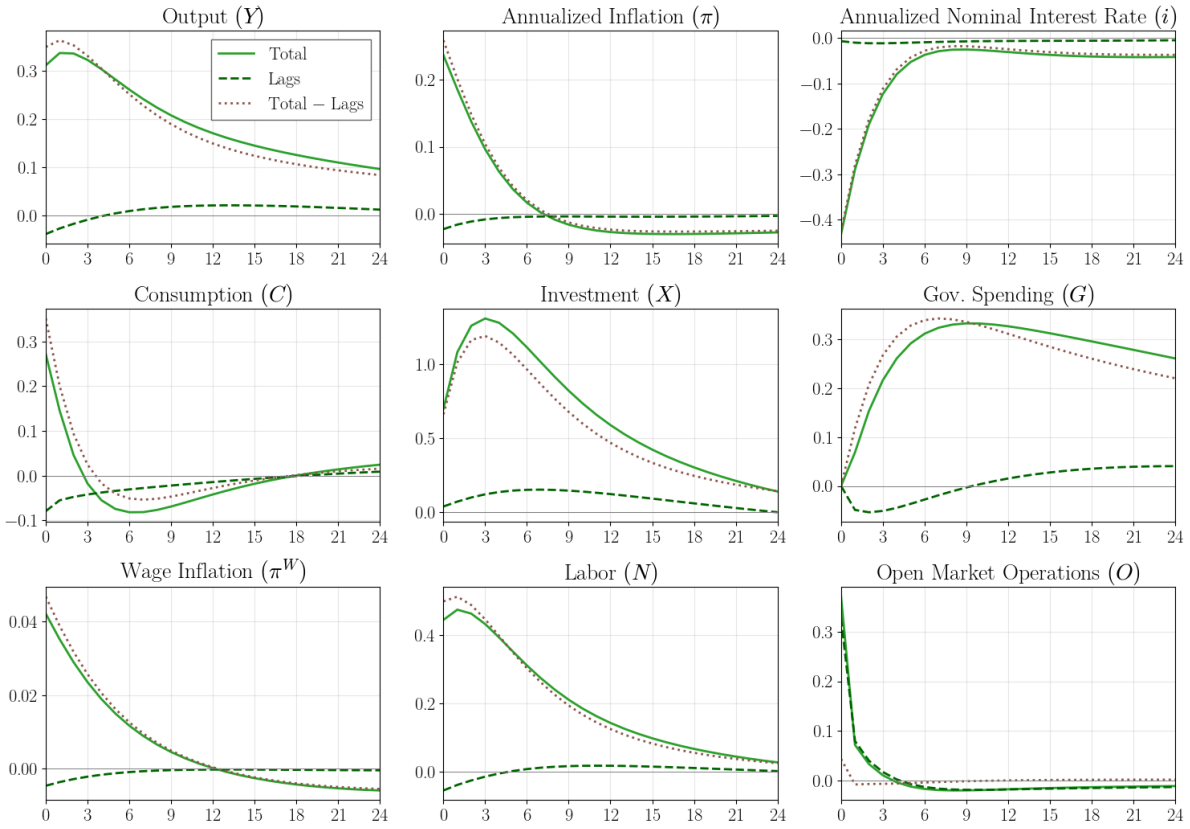


Figure A11: Lags' contribution to the impulse response to an expansionary monetary policy shock



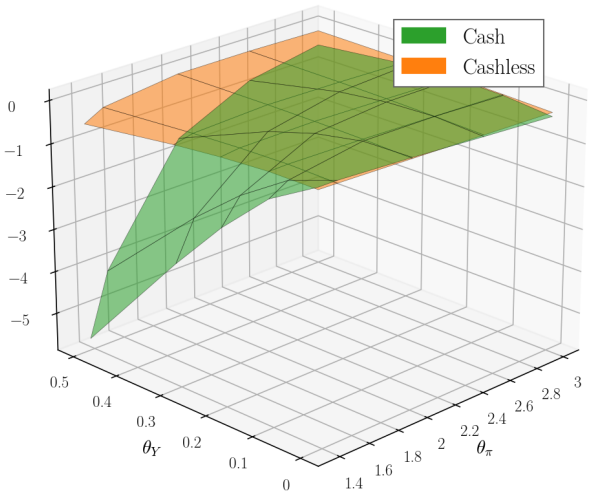
A.4 Policy Analysis

Table A1: Welfare model changed parameters

Parameter		Value	Source / target
Fixed			
Households and firms			
σ_ξ	Std. dev. of the transitory income shock	0.0964	Auclert et al. (2026)
η	Calvo price stickiness	0.684	Nakamura and Steinsson (2008): flexible end
η_W	Calvo wage stickiness	0.734	Barattieri et al. (2014), flexible end
Policy			
$\overline{B}^{cash}$	Debt target (cash economy)	2.397	Adjusted to new B^{CB}

Parameter		Value	Source / target
$\overline{B}^{cashless}$	Debt target (cashless economy)	1.392	Adjusted to new B^{CB}
$B^{CB,cash}$	Bonds held by the CB (cash economy)	1.005	Stationary level with long-run inflation
$B^{CB,cashless}$	Bonds held by the CB (cashless economy)	0	Stationary level with long-run inflation
	Estimated by Schmitt-Grohé and Uribe (2006)		
ρ_g	Std. dev. of government spending shock	0.87	Schmitt-Grohé and Uribe (2006)
σ_g	Persistence of government spending shock	0.016	Schmitt-Grohé and Uribe (2006)
	Calibrated to business cycle moments		
ξ	Investment adjustment cost	6.024	King and Rebelo (1999): $\text{sd}(\log I)/\text{sd}(\log Y) = 2.93$
ρ_Z	Persistence of TFP	0.8185	McKay and Reis (2016): $\text{autocorr}(\log Y) = 0.864$
σ_Z	S.d. of the TFP innovation	0.0169	McKay and Reis (2016): $\text{sd}(\log Y) = 0.015$

Figure A12: Consumption equivalent surface for fixed Taylor rule targets



A.5 Extensions

Figure A13: Impact of the policy over volatility and steady state level surfaces of key variables for fixed Taylor rule targets

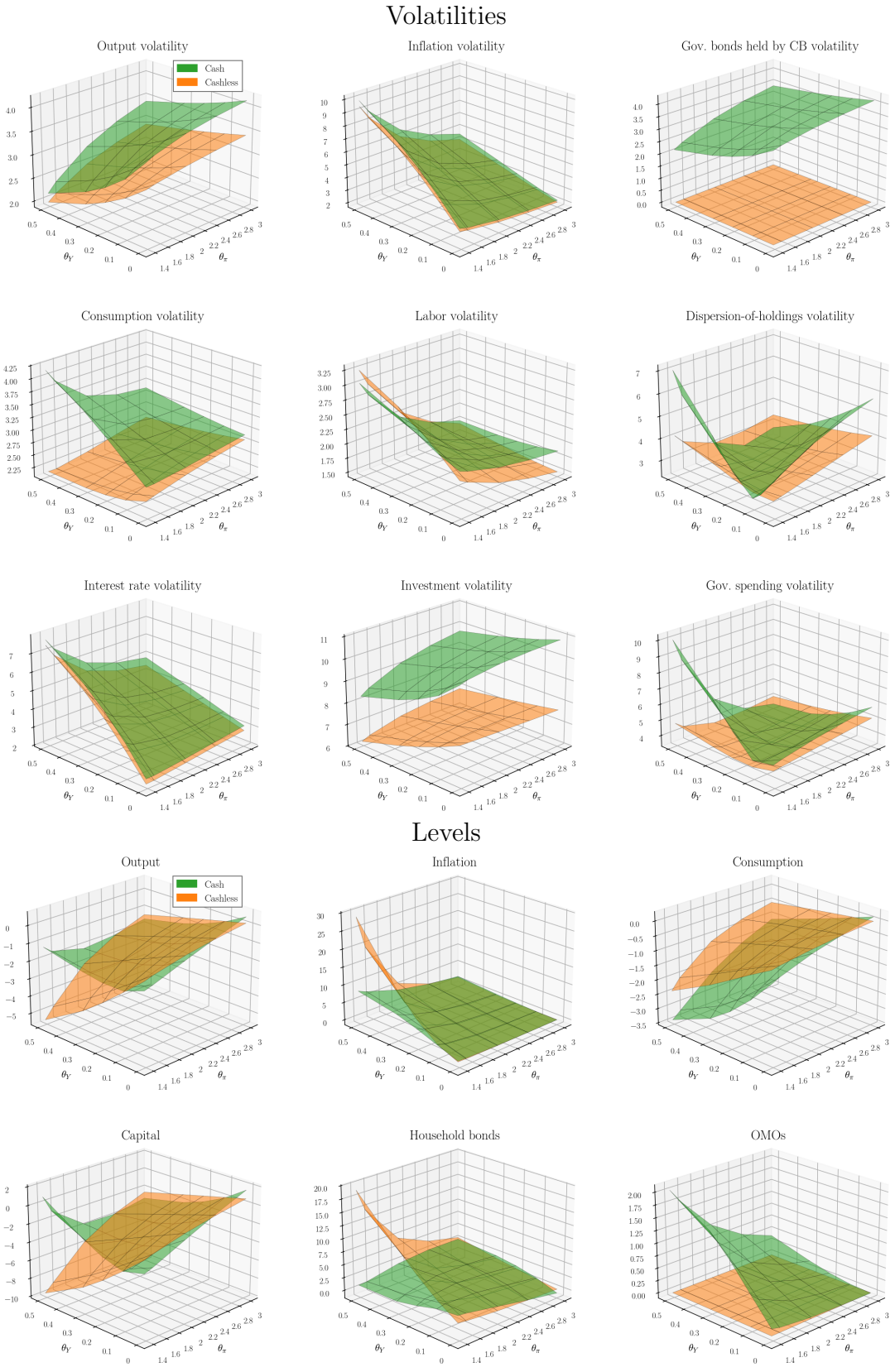


Figure A14: Consumption equivalent surface for moving Taylor rule targets

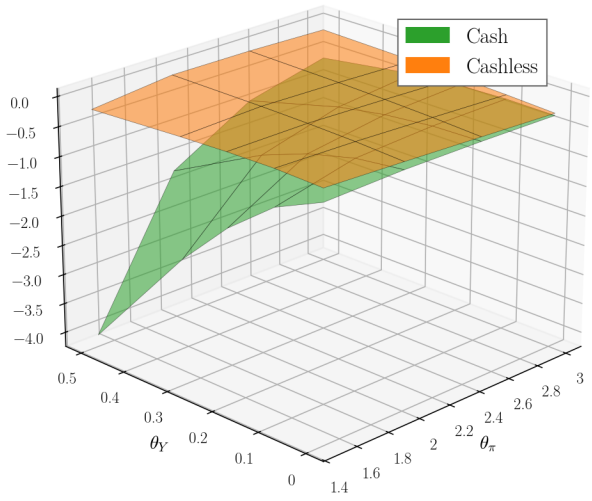


Figure A15: Impact of the policy over volatility and steady state level surfaces of key variables for moving Taylor rule targets

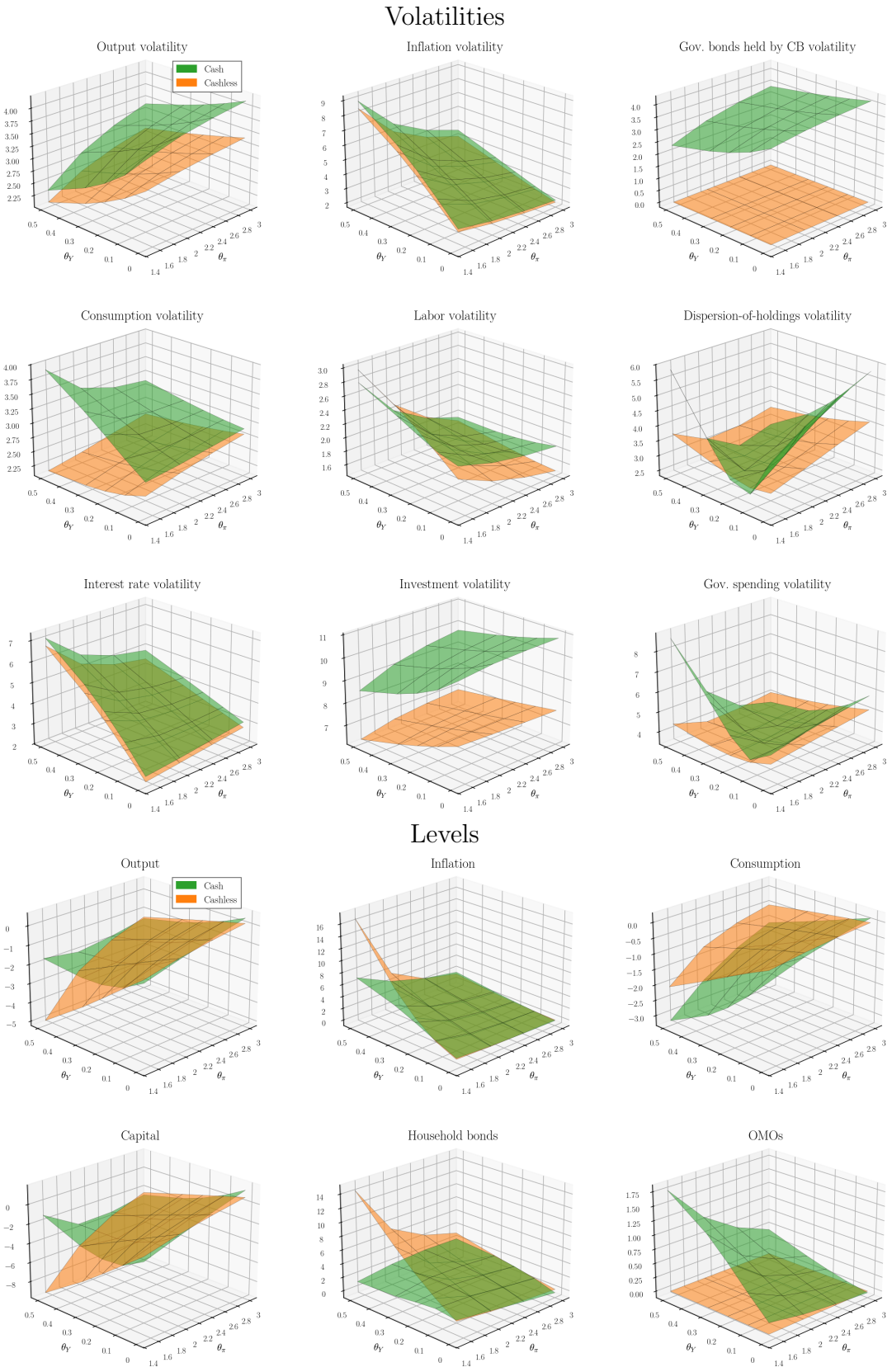
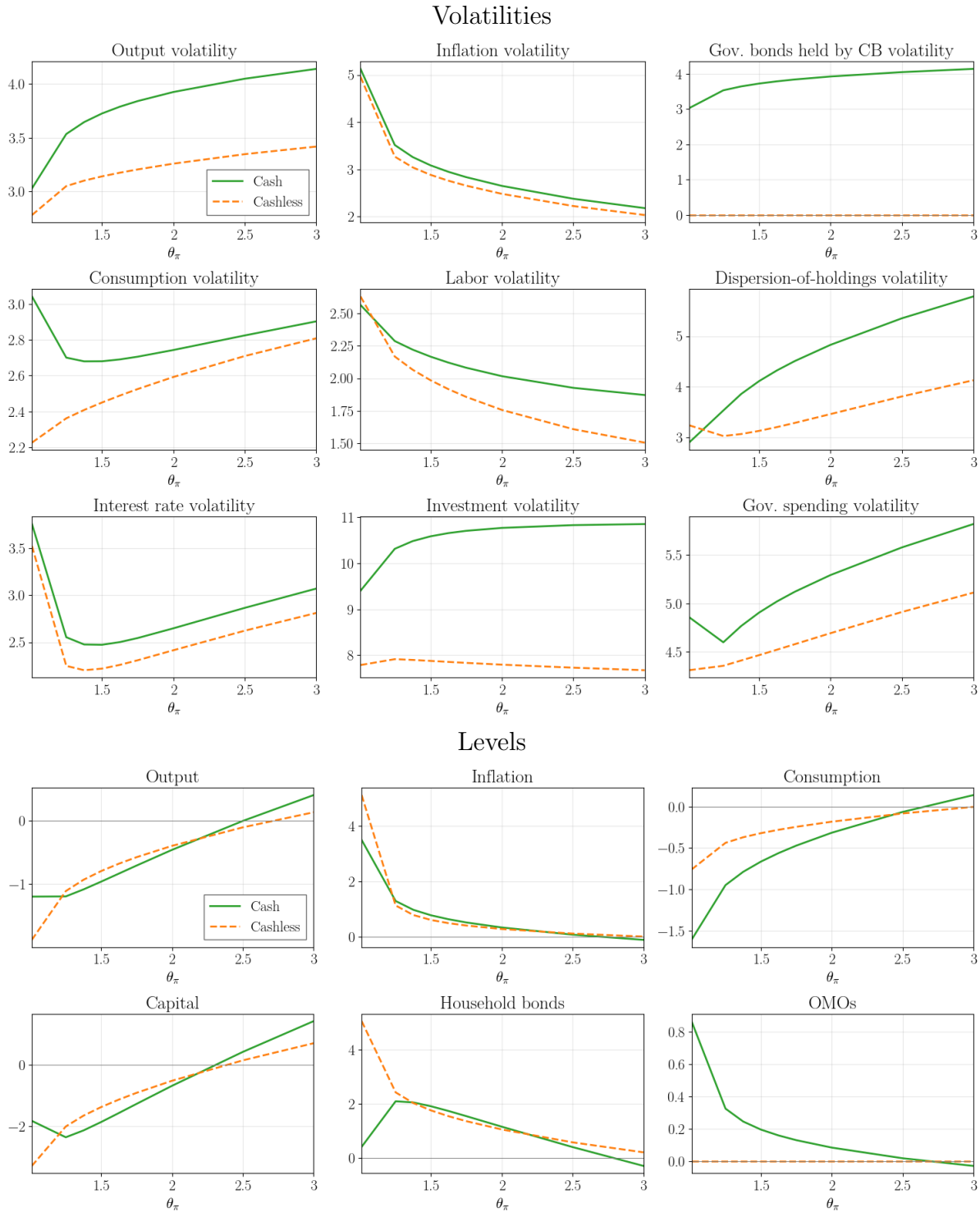
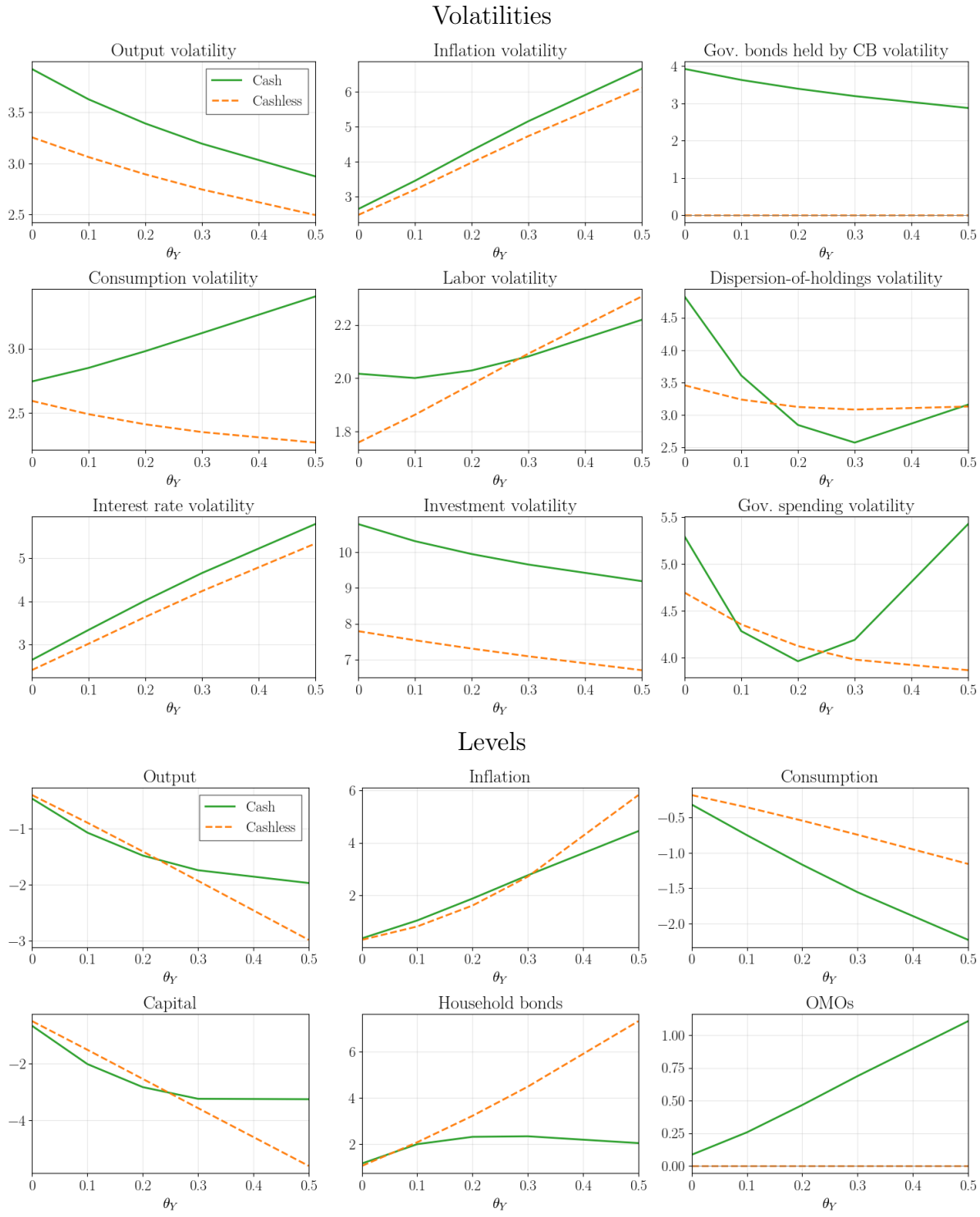


Figure A16: Impact of the inflation coefficient over volatility and steady state levels of key variables for moving Taylor rule targets



Notes: The graphs fix $\theta_Y = 0$.

Figure A17: Impact of the output coefficient over volatility and steady state levels of key variables for moving Taylor rule targets



Notes: The graphs fix $\theta_\pi = 2$.

Figure A18: Complete set of impulse responses to an expansionary monetary policy shock for strict debt targeting

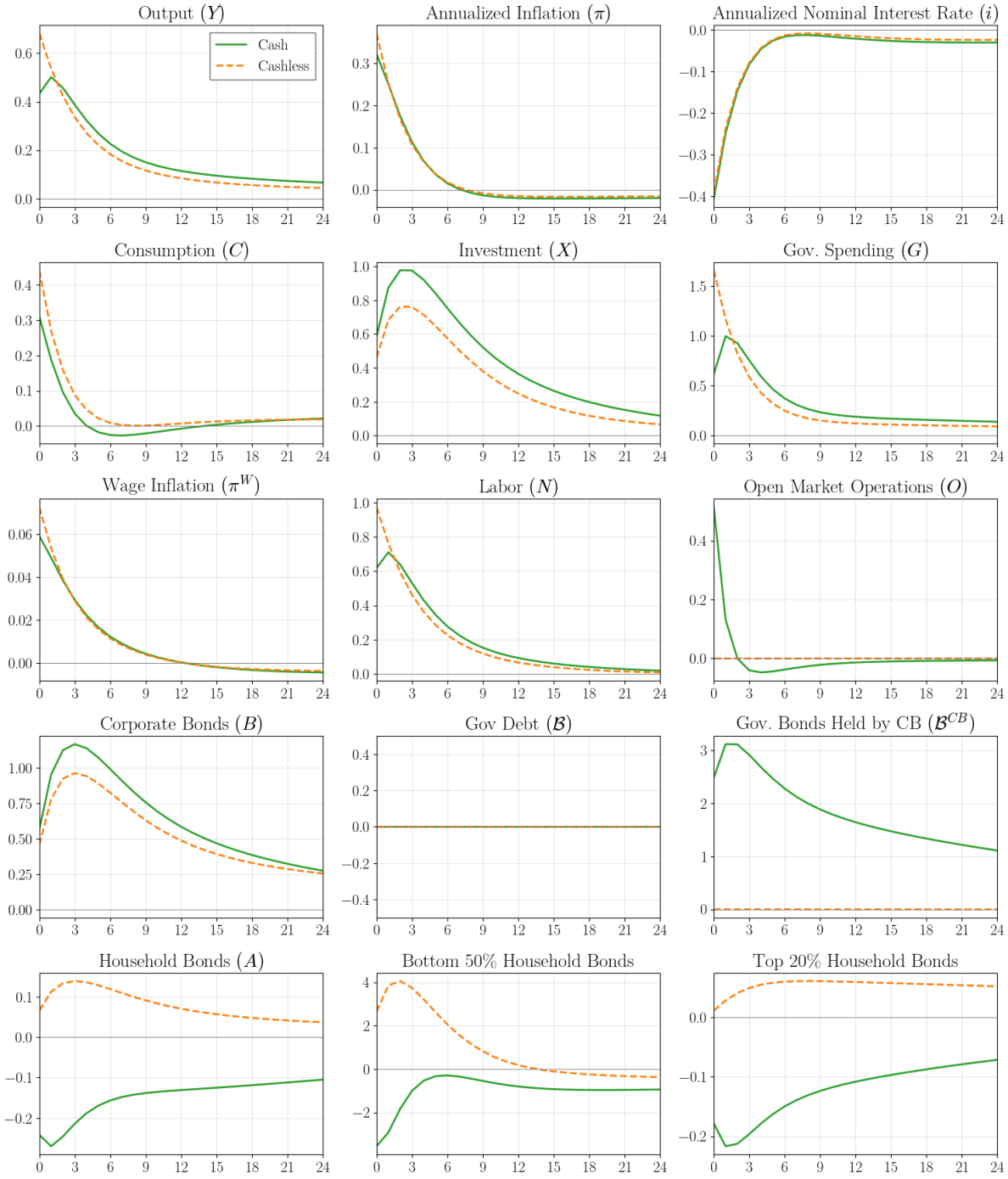


Figure A19: Complete set of impulse responses to an expansionary monetary policy shock for alternative money injection technologies

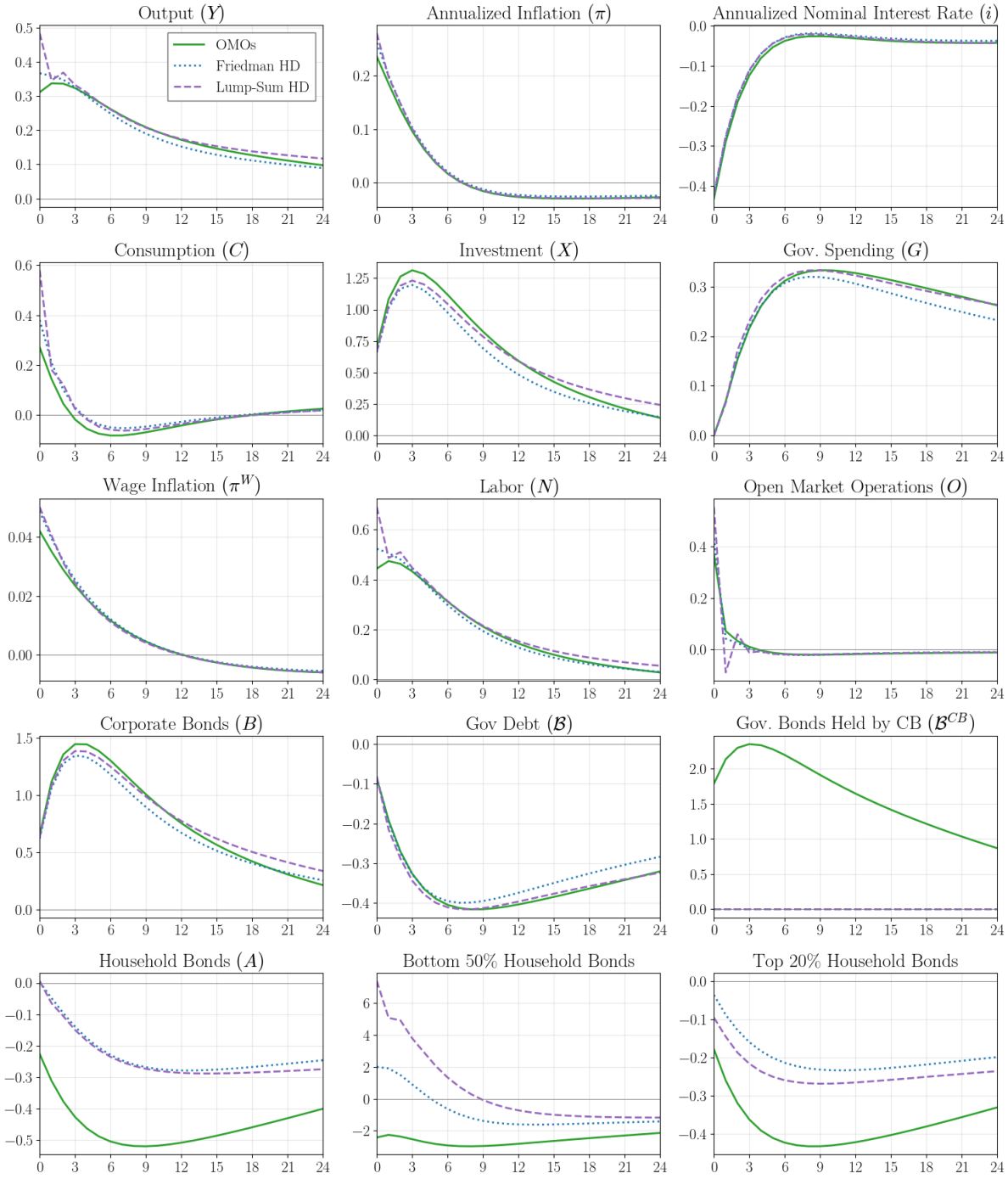


Figure A20: Complete set of impulse responses to a monetary base shock for alternative money injection technologies

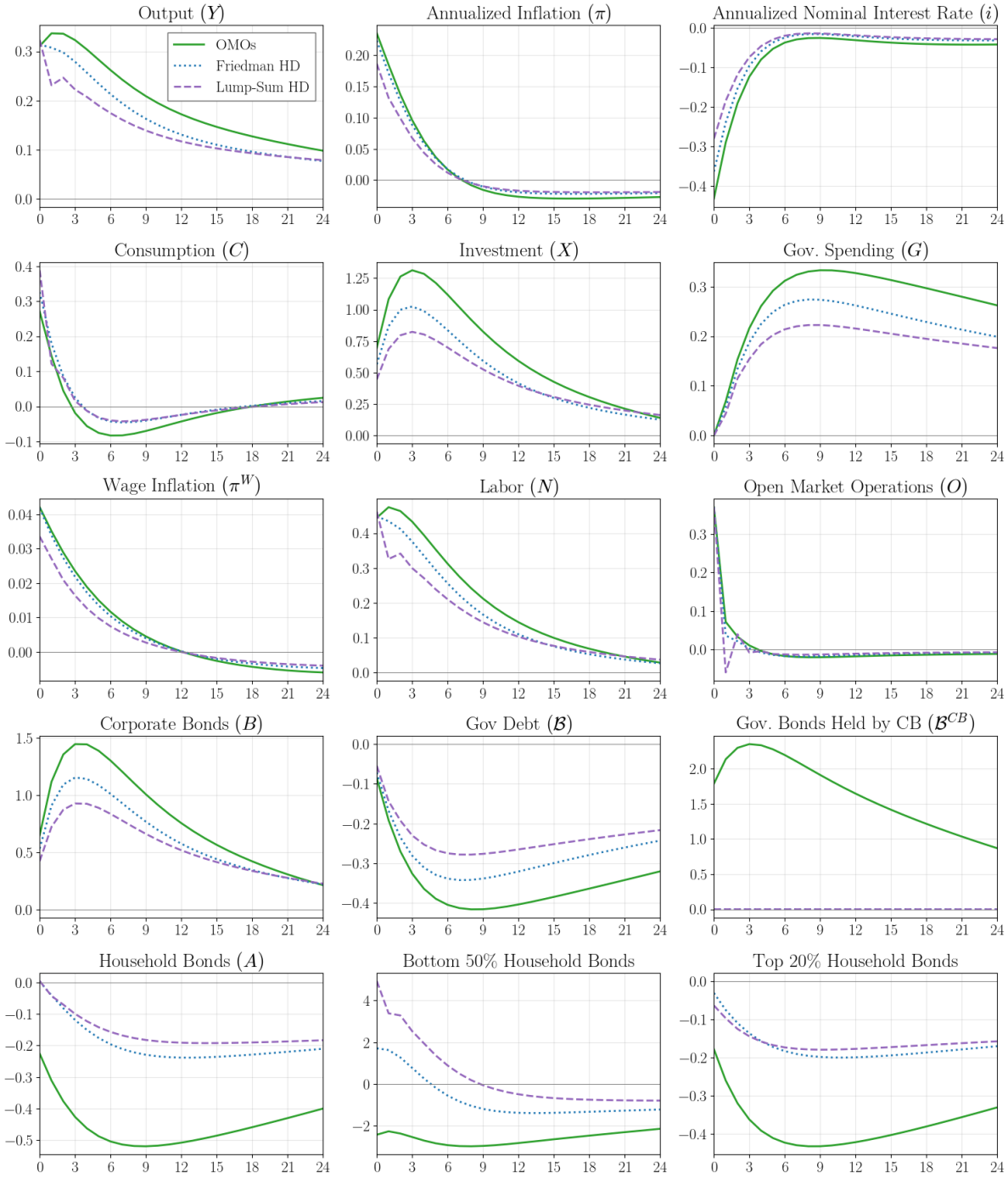
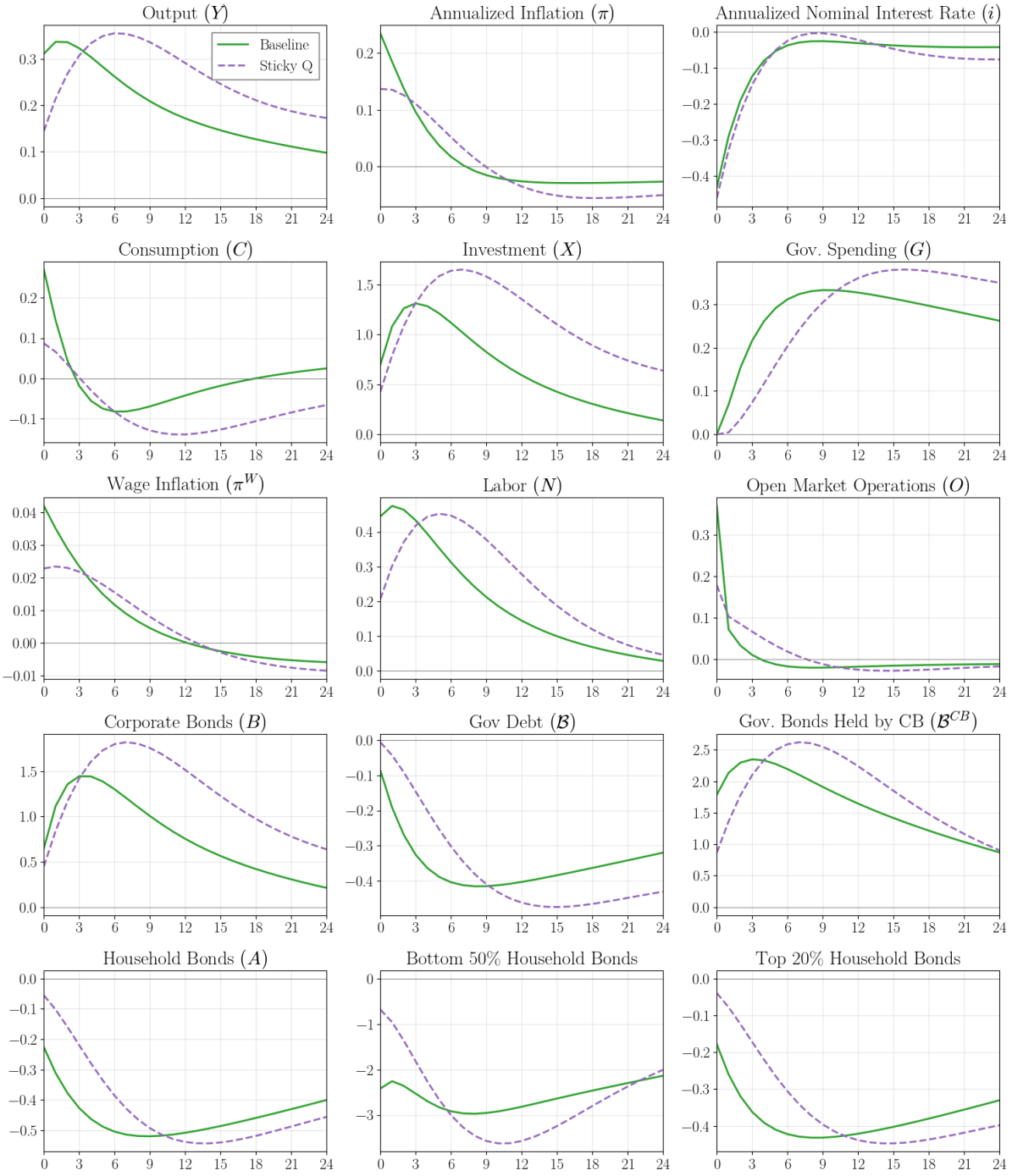


Figure A21: Complete set of impulse responses to a monetary base shock with incomplete information on the shock



B Supplementary Text

B.1 Bayesian Recursive VAR Specification

For estimating the impact of OMOs on output and inflation, I cannot use the VAR-IV method employed in Section 3, because without further restrictions, I cannot estimate the IRFs of industrial production and CPI with respect to an OMO shock. I then estimate (1) by imposing short-run restrictions through a Cholesky decomposition. I follow Plagborg-Møller and Wolf (2021) in ordering the shocks first in the VAR. This leads to the following ordering for the variables $\boldsymbol{Y}_t = \left(m_t^{FF},\ FFrate_t,\ OMO_t,\ \log IP_t,\ \log CPI_t \right)'$. The ordering between the federal funds rate, the industrial production index and the CPI are standard, and the only judgment call relative to the literature is where to place the OMOs variable.

The underlying assumption for this ordering is that, taking the case of an interest rate cut as an example, OMOs can be used to inject the liquidity needed to expand the credit base for additional private spending. However, OMOs could react endogenously to a higher desired investment and consumption spending caused by the usual monetary transmission channels. Therefore, I also present results for regressions where OMOs are placed last as a robustness test. Another robustness exercise I run is to replace industrial production with the unemployment rate. Although the IPI is the most common proxy for GDP, industrial participation in value added decreased over the last decades. So, the unemployment rate could work as an alternative and, arguably, better proxy.

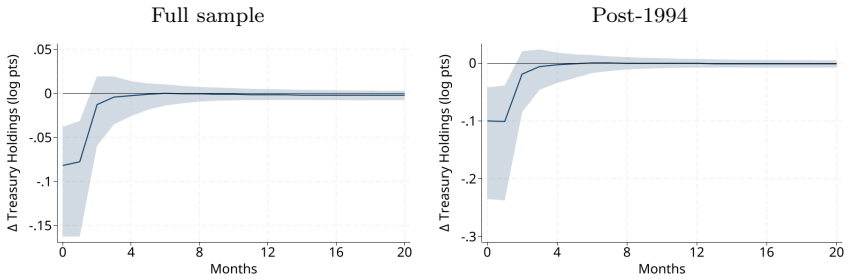
For this recursive VAR specification, one cannot expand the sample beyond the availability of the instrument for the reduced form regression. Besides, the number of coefficients to be estimated is 61. Given that I have 206 observations for the whole sample with the instrument available, and only 175 for the post-1994 sample, I run a Bayesian recursive VAR with a Minnesota prior as a baseline. This allows me to have a narrower credible interval in spite of the low number of observations.

B.1.1 Results

Figure B1 show the IRFs of Treasury holdings to a 100 basis points contractionary monetary policy Swanson (2021) shock in the Bayesian recursive VAR specification for BS shocks. Figure A3 show the corresponding IRFs for JK and MAR shocks. As in Section 3, Treasury purchases by the central bank significantly fall on impact after the shock in both samples, but more strongly after 1994.

Figure B2 shows the responses of industrial production growth (the first difference of the logarithm of the industrial production index) and inflation to one standard-deviation

Figure B1: Response of Treasury holdings to a contractionary monetary policy shock: Bayesian recursive VAR, BS shocks



Notes: Swanson (2021) shocks, orthogonalized with the method by Bauer and Swanson (2023). Responses in percentage points of monthly growth of Treasury holdings to a 100 basis points contractionary monetary policy shock. Bayesian recursive VAR with Minnesota prior; 90% credible bands.

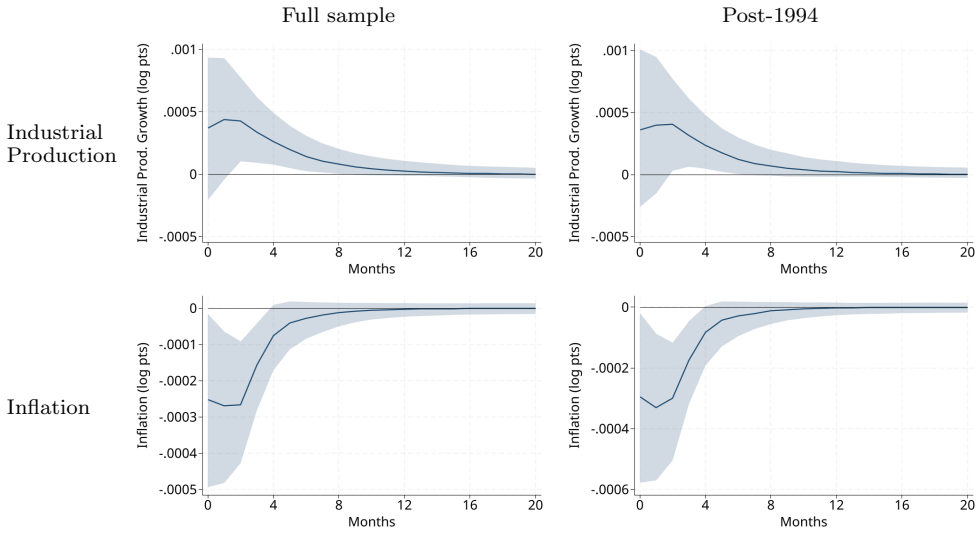
Treasury purchases by the central bank. This corresponds to just over a 1% increase in the Fed's Treasury holdings. The Bayesian specification shows a significant increase in industrial production caused by the shock, which remains significant for six to eight months, depending on the sample length (full sample or post-1994 only). While the magnitude is very modest, it's important to point out that an increase in bond holdings of the central bank of this size is small, as this should roughly correspond to a 0.3% increase in M1.

For inflation, the effect is also significant but goes in the opposite direction of what one would expect. This inversion in the expected sign of the inflation response on impact, the price puzzle, is not an uncommon result and has been associated with shocks that are not fully orthogonal (Sims, 1992; Ramey, 2016). These results seem to indicate another dimension of the price puzzle, associated with open-market operation shocks.

B.1.2 Robustness

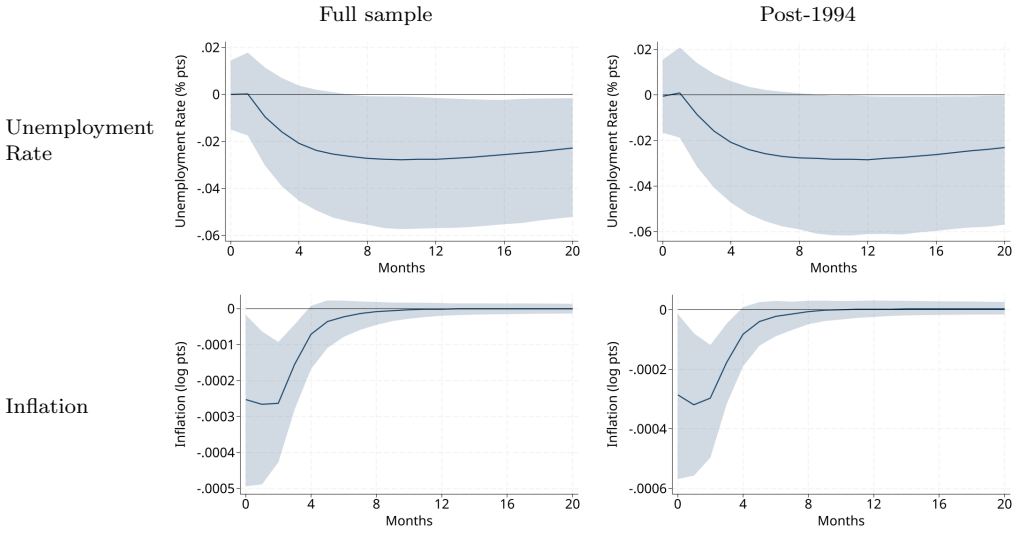
I now perform two robustness checks. First, I replace the IPI with the unemployment ratio. This can be seen in Figure B3 for the baseline BS shocks, Figure A5 for JK and MAR shocks. Then, I show results for an order inversion in the recursive VAR, where I place the OMOs variable last in the Cholesky decomposition. The results are shown in Figure B4 for the baseline shocks, Figure A6 for the remaining JK and MAR shocks. The unemployment responses are much more persistent than the industrial production ones and slightly significant over long horizons, indicating that the labor market takes longer to adjust. Only for JK shocks over the full sample, the unemployment response is never significant. Moreover, the alternative ordering does not change the overall IRF patterns nor significance, and changes in magnitudes are mild relative to the baseline specification. Across all specifications, the price puzzle remains.

Figure B2: Response of industrial production and inflation to open-market Treasury purchases: Bayesian recursive VAR, BS shocks



Notes: Swanson (2021) shocks, orthogonalized with the method by Bauer and Swanson (2023). Responses in percentage points of monthly IPI growth and monthly inflation to a one standard deviation OMO shock. Bayesian recursive VAR with Minnesota prior; 90% credible bands.

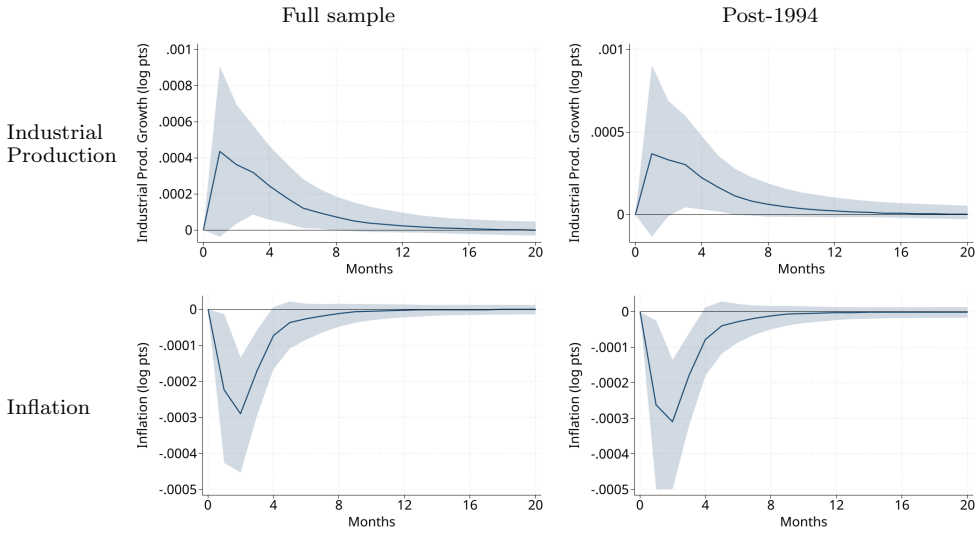
Figure B3: Response of unemployment rate and inflation to open-market Treasury purchases: Bayesian recursive VAR, BS shocks



Notes: Swanson (2021) shocks, orthogonalized with the method by Bauer and Swanson (2023). Responses in percentage points of the unemployment rate and of monthly inflation to a one standard deviation OMOs shock. Bayesian recursive VAR with Minnesota prior; 90% credible bands.

Importantly, the identification of open-market operation shocks does not take a stance on whether it precedes or follows responses in other variables. However, the results shown are not sensitive to the timing assumption, so the ordering choice is not a threat to identification of OMO shocks. Moreover, for the model that follows, no assumption

Figure B4: Response of industrial production and inflation to open-market Treasury purchases: Bayesian recursive VAR, BS shocks, inverted ordering



Notes: Swanson (2021) shocks, orthogonalized with the method by Bauer and Swanson (2023). OMOs variable placed last. Responses in percentage points of monthly IPI growth and monthly inflation to a one-standard-deviation OMO shock. Bayesian recursive VAR with Minnesota prior; 90% credible bands.

needs to be made on the proper causal chain, since money demand, output and prices are jointly determined in general equilibrium.

B.2 Remaining Optimization Programs

Following Campos et al. (2024), I assume that each household supplies a continuum of labor tasks, $n_{i,k,t}$. There is a union for each task, that aggregates $N_{k,t} = \int_0^1 z_{i,t} n_{i,k,t} di$. A competitive labor packer aggregates these tasks into the labor supply:

$$\overline{N}_t = \left(\int_0^1 N_{k,t}^{\frac{\epsilon_\omega - 1}{\epsilon_\omega}} dk \right)^{\frac{\epsilon_\omega}{\epsilon_\omega - 1}}$$

Let $W_{k,t} \coloneqq P_t \omega_{kt}$ be the nominal wage for task $k \in [0,1]$ and $\pi^{\omega}_{k,t} \coloneqq \frac{W_{k,t}}{W_{k,t-1}}$ be the wage inflation for this task. Also, assume the functional forms (23), adopted in the calibration.

Then, the union for the task $k \in [0,1]$ solves:

$$\max_{\{\omega_{k,t},N_{k,t}\}_{t=0}^{\infty}} \mathbb{E}_t\left\{\sum_{t=0}^{\infty}\beta^{t-1}\left[\int_0^1\left(\frac{c_{i,t}^{1-\sigma}-1}{1-\sigma}-\varphi\frac{n_{i,t}^{1+\nu}}{1+\nu}\right)di-\frac{\psi}{2}\left(\log\left(\frac{W_{k,t}}{W_{k,t-1}(1+\overline{\pi})}\right)\right)^2\right]\right\} \tag{B1}$$

$$\text{subject to} \qquad N_{k,t} = \left(\frac{\omega_{k,t}}{\omega_t}\right)^{-\epsilon_\omega} N_t \tag{B2}$$

$$\int_0^1 [m_{i,t}+P_t c_{i,t}+Q_t a_{i,t}]\,di \leq \int_0^1 [m_{i,t-1}+a_{i,t-1}+(1-\tau)P_t\omega_t\hat{z}_{i,t}n_{i,t}]\,di+\Pi_t \tag{B3}$$

$$\int_0^1 [P_t c_{i,t}+Q_t a_{i,t}]\,di \leq \int_0^1 [m_{i,t-1}+a_{i,t-1}]\,di \tag{B4}$$

$$c_{i,t}, a_{i,t} \geq 0 \quad \forall i \in [0,1], \tag{B5}$$

where (B2) is the labor packer's demand for labor on task $k \in [0,1]$. This problem means that the union maximizes the average utility of all equally weighted workers subject to a quadratic utility cost of adjusting the nominal wage relative to the inflation target, $\overline{\pi}$, which is the same for the CB. In the cash economy, given that unions are homogeneous, this yields the Wage-Phillips Curve:

$$\log\left(\frac{1+\pi_t^\omega}{1+\overline{\pi}}\right) = \kappa_\omega\left\{-\left(\frac{\epsilon-1}{\epsilon}\right)(1-\tau^D)\omega_t\beta\mathbb{E}_t\left[\frac{1}{1+\pi_{t+1}}\int_0^1 c_{i,t+1}^{-\sigma}di\right]+\varphi N_t^\nu\right\}N_t + \beta\mathbb{E}_t\left\{log\left(\frac{1+\pi_{t+1}^\omega}{1+\overline{\pi}}\right)\right\}, \tag{B6}$$

where π_t^ω is the average wage inflation and $\kappa_\omega = \frac{\epsilon_\omega}{\psi}$. In the cashless economy, we have:

$$\log\left(\frac{1+\pi_t^\omega}{1+\overline{\pi}}\right) = \kappa_\omega\left\{-\left(\frac{\epsilon-1}{\epsilon}\right)(1-\tau^D)\omega_t\int_0^1 c_{i,t}^{-\sigma}di+\varphi N_t^\nu\right\}N_t+\beta\mathbb{E}_t\left\{log\left(\frac{1+\pi_{t+1}^\omega}{1+\overline{\pi}}\right)\right\}.$$

The representative final goods firm operates on a competitive sector, producing with intermediate goods following the production function:

$$Y_t = \left(\int_0^1 Y_{j,t}^{\frac{\epsilon_I-1}{\epsilon_I}}dj\right)^{\frac{\epsilon_I}{\epsilon_I-1}},$$

where $Y_{j,t}$ corresponds to demand for intermediate good $j \in [0,1]$. The intermediate goods firms hire labor and capital, in a monopolistically competitive market, to solve:

$$\max_{\{P_{j,t},N_{j,t},K_{j,t},\overline{Y}_{j,t}\}_{t=0}^{\infty}} \mathbb{E}_t \left[\sum_{s=t}^{\infty} Q_{t,s} \Pi_{js}^I \right] \tag{B7}$$

$$\text{subject to} \qquad \overline{Y}_{js} = K_{js}^{\alpha} (e^{\zeta_t} N_{js})^{1-\alpha} \geq \left(\frac{P_{js}}{P_s} \right)^{-\epsilon_I} Y_s \tag{B8}$$

$$\Pi_{js}^I = P_{js} \overline{Y}_{js} - P_s \omega_s N_{js} - P_s r_s^k K_{js}, \tag{B9}$$

where $\overline{Y}_s$ corresponds to output supplied by the j^{th} company, and Π_{js}^I is its profit. Average profits for intermediate goods firms is given by $\Pi_t^I := \int_0^1 \Pi_{jt}^I dj$. In every period, the company can adjust its price with probability $1-\eta$. This yields the standard Phillips Curve:

$$\left(\frac{P_{j,t}^*}{P_t} \right)^{\frac{1-\alpha+\alpha\epsilon_I}{1-\alpha}} = \left(\frac{\epsilon_I}{\epsilon_I - 1} \right) \left\{ \frac{\mathbb{E}_t \left[\sum_{s=t}^{\infty} \eta^{s-t} Q_{t,s} (1+i_s) \pi_{t,s}^{\frac{1-\alpha-\epsilon_I}{1-\alpha}} mc_s Y_{j,s} \right]}{\mathbb{E}_t \left[\sum_{s=t}^{\infty} \eta^{s-t} Q_{t,s} \pi_{t,s}^{\epsilon_I} Y_{j,s} \right]} \right\}, \tag{B10}$$

where $P_{j,t}^*$ is the optimal price for firms that can re-set at period t, $Q_{t,s}$ and $\pi_{t,s}$ are nominal discount and inflation between periods t and s, and mc_s is the average real marginal cost.[25] Naturally, all firms who re-set their price make the same choice, that is, there is an optimal price satisfying $P_t^* = P_{j,t}^*$ for all $j \in [0,1]$. Given the solution of the final good firm's problem, we have:

$$P_t^{1-\epsilon_I} = \eta P_{t-1}^{1-\epsilon_I} + (1-\eta) P_t^{*1-\epsilon_I}. \tag{B11}$$

Given the timing assumptions, intermediate goods firms hire labor and capital and only need to pay them at the end of the period, after earning sales revenues. Likewise, final good firms can pay for the intermediate goods after selling its output. As a consequence, no cash-in-advance constraint needs to be enforced in their problems.

B.3 Solution to the capital firm's problem

First, let μ_t be the multiplier of the capital law of motion, and plug the borrowing constraint (11) into the budget constraint (15), for the cash economy, and (14), for the cashless one, to replace bonds. Taking the first order condition with respect to $\bar{K}_{t+1}$

[25] As pointed out by Schmitt-Grohé and Uribe (2007), the fact that all firms share the same constant returns-to-scale technology and face the same prices implies that they face the same marginal cost.

yields:

$$\mu_t = \mathbb{E}_t \left[Q_t P_{t+1} r^K_{t+1} + (1-\delta)\mu_{t+1} \right] \tag{B12}$$

in both economies. Given the Cobb-Douglas production function assumed below

In the cash economy, the first-order condition with respect to X_t is given by:

$$\mu_t = \frac{P_t}{Q_t}\left[1 + s\left(\frac{X_t}{X_{t-1}}\right) + s'\left(\frac{X_t}{X_{t-1}}\right)\frac{X_t}{X_{t-1}}\right] - Q_t \mathbb{E}_t \left[\frac{P_{t+1}}{Q_{t+1}} s'\left(\frac{X_{t+1}}{X_t}\right)\frac{X^2_{t+1}}{X^2_{t+1}}\right] \tag{B13}$$

In the cashless economy, we have:

$$\mu_t = P_t\left[1 + s\left(\frac{X_t}{X_{t-1}}\right) + s'\left(\frac{X_t}{X_{t-1}}\right)\frac{X_t}{X_{t-1}}\right] - Q_t \mathbb{E}_t \left[P_{t+1} s'\left(\frac{X_{t+1}}{X_t}\right)\frac{X^2_{t+1}}{X^2_{t+1}}\right], \tag{B14}$$

which differs from the cash counterpart for not having the bond prices in the denominator of both right-hand-side terms. These terms capture the cost of setting money aside to service the debt in the next period. Since, in the cashless economy, services are paid with future, discounted income, the term drops away, yielding the same first-order conditions as in a model without the borrowing constraint (11).

B.4 A note on empirical fit

For this subsection, I follow the same procedures described above in both the cash economy (the baseline values in Table 1) and the cashless economy. A series of targeted and untargeted business cycle moments can be found in Table B1. The first three targeted moments were exactly matched by the calibration procedure. The last target was capped by the flatness of the moment in the relevant interval for κ_ω. Still, the moment is not far away from the data counterpart.

Turning to untargeted moments, the autocorrelation of the nominal interest rate is very close. The largest AR(3) root (LAR) of inflation, defined in Pivetta and Reis (2007), is off the mark and corresponds in the model to just above half of the empirical value. According to the authors, in distant horizons after a shock, the inflation path is dominated by the largest root, meaning that the model will understate the persistence of inflation after shocks. The other two moments are reasonably close to their data counterparts. The cash economy matches all moments slightly better than the cashless one, though the difference is not substantial.

Now, I will consider how well the calibrated model fits empirical responses to monetary policy shocks, which, by the calibration procedure described above, is entirely untargeted. To achieve this goal, I run frequentist VAR-IV regressions similar to the ones presented in Section 3, with 12 lags for every variable and the same Swanson (2021) shock series

Table B1: Business cycle moments

Moment	Cashless	Cash	Data
Targeted			
Std. dev. of log output	0.015	0.015	0.015[a]
Autocorrelation of log output	0.864	0.864	0.864[a]
Ratio of investment-output std. dev.	2.93	2.93	2.93[b]
Std. dev. of log real wage	0.0078	0.0076	0.0068[b]
Untargeted			
Autocorrelation of real wage	0.8660	0.8529	0.66[b]
Autocorrelation of nominal interest rate	0.8063	0.7921	0.785[c]
Std. dev. of log inflation	0.0045	0.0046	0.00638[a]
Largest AR(3) root of inflation	0.4765	0.4980	0.85[a]

[a] McKay and Reis (2016).
[b] King and Rebelo (1999).
[c] Board of Governors of the Federal Reserve System, 1979–2008.

used as baseline.[26] Beyond the federal funds rate, the industrial production index, and the CPI, I add monthly variables for investment, nominal wages, and commodity prices. I use, respectively, industrial production of business equipment, average production and nonsupervisory hourly earnings, and the CRB spot index.

Commodity prices are included to prevent the appearance of the price puzzle (Christiano et al., 1996), although they have no model counterpart. I specify two VARs: in the first, henceforth *cash VAR*, I include the OMOs variable, whereas in the second, henceforth *cashless VAR*, I do not. Monthly IRFs are converted to monthly by taking their average value, except for the OMOs variable, which is computed as a sum to properly account for the total volume of operations within each quarter.

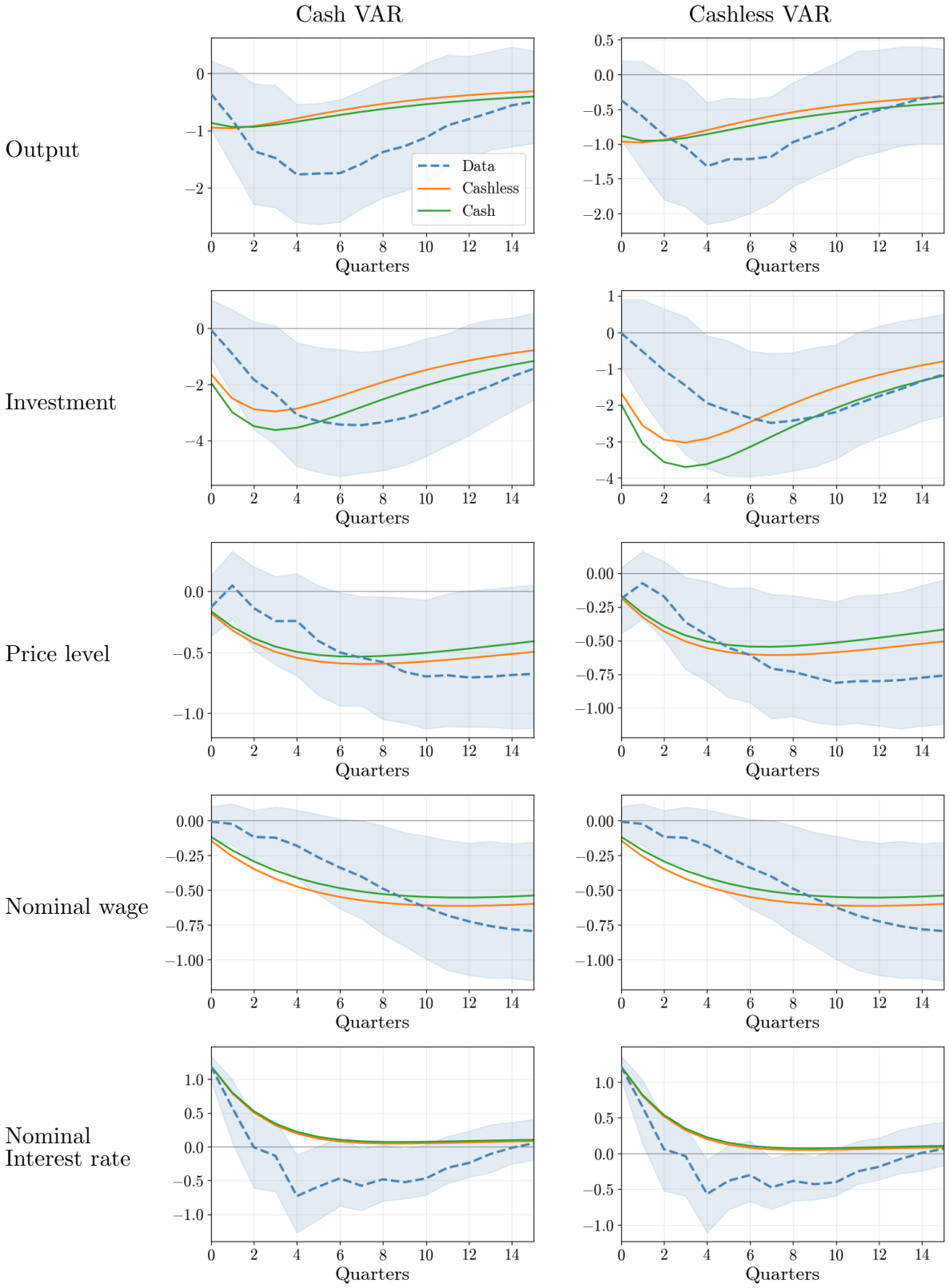
To measure fit, I use the objective used for IRF-matching proposed by Christiano et al. (2005). Let $\boldsymbol{\gamma}$ be the vector of parameters in the model, $\boldsymbol{\Psi}(\boldsymbol{\gamma})$, the IRFs produced by the model for the N variables included in the regressions, and let $\hat{\boldsymbol{\Psi}}$ be the empirically estimated IRFs. Moreover, let the number of horizons be H. Then, the vectors $\boldsymbol{\Psi}(\boldsymbol{\gamma})$ and $\hat{\boldsymbol{\Psi}}$ and $NH \times 1$, giving a total of NH moment conditions. The objective is given by:

$$J = \left[\hat{\boldsymbol{\Psi}} - \boldsymbol{\Psi}(\boldsymbol{\gamma})\right]' \boldsymbol{V}^{-1} \left[\hat{\boldsymbol{\Psi}} - \boldsymbol{\Psi}(\boldsymbol{\gamma})\right], \tag{B15}$$

where $\boldsymbol{V}$ is a diagonal matrix with the sample variance for each of the NH moments. The IRF-matching procedure consists in minimizing (B15). As a result, in what follows, a lower statistic indicates a better fit.

[26] I use Mertens-Ravn wild bootstrap for the standard errors.

Figure B5: Untargeted fit to the empirical impulse responses

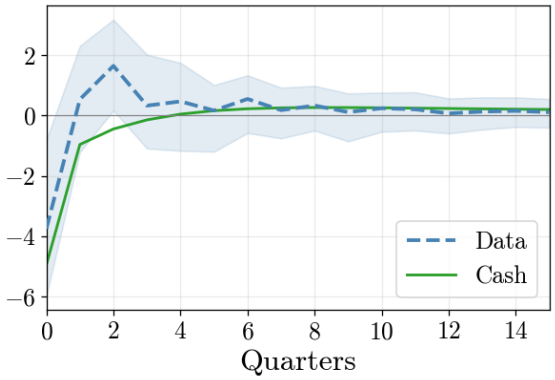


Notes: Swanson (2021) shocks. Responses in percentage points to a 100 basis points contractionary monetary policy shock. Mertens-Ravn wild bootstrap; 90% confidence bands.

Figure B5 plots the fit both for the cash and cashless VAR specifications. While the model cannot replicate the empirical hump shape in the output path nor the reversal in the interest rate path without additional assumptions, the magnitudes are roughly right and within the confidence intervals for most of the transition. The cash VAR produces stronger output and investment responses, which the model struggles to match, leading to a weaker fit.

Now, I report the values for the statistic (B15). For the cash IRFs, the cash economy obtains a value of 116.3, while the cashless economy obtains 125.2. For the cashless IRFs, the values are, respectively, 116.6 and 112.7. This means that the cash economy produces a statistic 7% lower relative to the IRFs produced by the cash VAR specification, while the statistic is 3.5% higher relative to the cashless VAR specification. Therefore, the cash model fits the cash IRFs better, but the cashless ones a bit worse.

Figure B6: Untargeted fit to the OMOs impulse response



Lastly, Figure 2 presents the fit of the cash economy to the IRF of the monetary shock on open market operations volume.[27] To keep them comparable, the model counterpart of the OMOs variable is computed in the same way. While the rebound in the early quarters is not captured by the model in this particular parameter combination,[28] the 4% drop in bond holdings by the central bank is matched very closely by the model. This is meaningful, because OMO volume, in my framework, is a function of the enforcement wedge. The existence of the mismatch is what generates the need for open-market operations as an enforcement measure, reinforcing a likely enforcement need as accounting for the empirical OMOs response to monetary shocks. Furthermore, this is the only significant rebound observed in all regressions I conducted (see **??** and Appendix A), and most estimated OMO IRFs behave as the one produced by the model.

[27]The fit for this variable is left out of the fit computations reported in the previous paragraph.

[28]The return to the steady state requires that expansionary OMOs get partially undone over the consecutive quarters to push real balances back to the steady state level. However, whether a strong initial rebound or a gradual one takes place depends on the persistence of the effects generated by the shock.

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