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Nominal Contracting With Positive Trend Inflation: Which Way to Go?

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La Chaire en macroéconomie et prévisions est fière de s'appuyer sur un partenariat avec les organisations suivantes:

Nominal Contracting With Positive Trend Inflation: Which Way to Go?

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Abstract

We offer evidence questioning the wide use of Calvo contracts in the DSGE literature since the mid-1990s. We contrast the cyclical and welfare implications of Taylor (1980) and Calvo (1983) nominal contracts in medium-scale DSGE models with positive trend inflation. Taylor contracts better match comovements between inflation, nominal interest rate and real variables. They also generate persistent and hump-shaped responses of inflation to monetary policy and investment shocks, while Calvo contracts do not. Calvo contracts can imply very strong monopolistic distortions. Also, steady state wage dispersion and consumer-equivalent welfare losses generated by trend inflation are highly sensitive to plausible variations in the average age of wage contracts, the degree of substitutability among labor skills, economic growth, and the Frisch elasticity of labor supply. Distortions are weaker, and wage dispersion and inflation costs are much smaller under Taylor contracts. We nonetheless estimate that with Taylor contracts the welfare benefits of going from 7% trend inflation as in the pre-1980s to 3% after the early 1980s may have reached 7%. The Fed being held accountable for the decline in trend inflation, this suggests the welfare benefits from bringing inflation down were potentially important.

JEL classification: E31, E32, E37.

Keywords: Trend Inflation; Taylor and Calvo Contracts; Wage Dispersion; Welfare Costs; Inflation Dynamics.

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1 INTRODUCTION

Nominal wage and price contracts have been key ingredients of macroeconomic models with rational expectations for more than forty years, the two most popular modeling approaches to nominal rigidities being those of Taylor (1980) and Calvo (1983).[1] For years, nominal contract models have formally assumed that long-run (or steady state) inflation is zero, perhaps due to perceptions that low levels of trend inflation like those experienced since the early 1980s should have fairly small cyclical and welfare implications.

Following the works of Yun (1996), King and Watson (1996), Rotemberg and Woodford (1997), Galí (1999), and Erceg, Henderson, and Levin (2000), Calvo contracts have been the type most widely used in Dynamic Stochastic General Equilibrium (DSGE) models. Therefore, comparisons between Calvo and Taylor contracting frameworks have not been numerous. Given the key role played by nominal contracts in recent DSGE models of business cycle fluctuations and policy analysis, we argue that a systematic comparison of the cyclical and welfare implications of both contracting frameworks is needed. This is what our paper does.

The initial focus with Calvo and Taylor contracting models was on their ability to generate persistent output fluctuations. An influential paper by Chari, Kehoe, and McGrattan (2000) questioned whether Taylor's staggered price contracts can generate persistent output responses to monetary shocks once imposing the rigor and discipline of general equilibrium on these models. They show that Taylor price contracts fail to produce a large "contract multiplier for output" when micro-foundations are explicitly laid out.[2] By contrast, Christiano, Eichenbaum, and Evans (2005) were able to obtain persistent and hump-shaped responses of output and inflation to a monetary shock after combining Calvo's wage and price contracts with a subset of real adjustment frictions and the complete indexation of non-reset nominal wages and prices to past inflation.

While it is certainly useful to look at the responses of output and inflation following a monetary policy shock in order to discriminate between alternative models, we argue this test is only of secondary importance relative one that compares their cyclical and welfare implications when long-run inflation is positive.

A burgeoing literature on positive trend inflation has built on variants of the canonical New Keynesian (NK) model with sticky prices and flexible nominal wages. Therefore, early comparisons

[1]Early rational expectations models with nominal rigidities include those of Gray (1976, 1978), Fischer (1977) and Phelps and Taylor (1977).

[2]Huang and Liu (2002) show that Taylor staggered wage contracts can induce a larger contract multiplier for output than staggered price contracts, but without generating a hump-shaped response of output. Huang, Liu, and Phaneuf (2004) propose a DSGE model with Taylor wage and price contrats, and examine questions related to monetary nonneutrality and the cyclicality of real wages. Our work differs from Huang et al. in that it assumes positive trend inflation and draws the comparison between Taylor contracts and Calvo contracts.

of Calvo and Taylor contracting frameworks with positive trend inflation have been based on fairly standard sticky-price models. For example, Ascari (2004) compared the steady-state output losses resulting from non-zero trend inflation under both types of contracts. Amano, Ambler, and Rebei (2007) looked at the impact of trend inflation on the stochastic means of key macro variables in both sticky-price models. Coibion and Gorodnichenko (2011) compared how trend inflation affects the prospect of indeterminacy when assuming Calvo or Taylor price contracts, and Coibion, Gorodnichenko, and Wieland (2012), how both types of contracts affect the optimal rate of inflation.

In price-setting models, trend inflation drives inflation costs and the prospect of indeterminacy through inefficient price dispersion. However, some recent evidence based on US disaggregated price data by Nakamura et al. (2018) suggests there is no perceptible relation in the data between higher trend inflation and increased price dispersion even when average inflation reaches a high level as in the 1970s and early 1980s.

A more recent literature has focused on the relation between positive trend inflation and inefficient wage dispersion, and this assuming Calvo's wage contracts and not only price contracts. For example, Ascari, Phaneuf, and Sims (2018) demonstrate that the key relation driving inflation costs at moderate levels of inflation involves sticky wages, trend inflation, economic growth and wage dispersion. Phaneuf and Victor (2019) find that a Calvo model with both nominal wage and price contracts is not inconsistent with evidence of a weak relation between higher trend inflation and increased price dispersion even when the annualized rate of inflation reaches 10%. Khan, Phaneuf, and Victor (2019) explore how Calvo wage and price contracts affect the prospect of indeterminacy at low levels of trend inflation.

Our paper first assesses the empirical relevance of Calvo and Taylor contracting frameworks by looking at their ability to match some standard business cycle moments. We find that both frameworks account relatively well for the basic comovements between output growth, consumption growth, investment growth and change in hours. In particular, both generate a positive correlation between consumption growth and investment growth and are not prone to the comovement problem of a negative correlation between consumption and investment.

But both models differ in their ability to match the correlations between nominal variables, namely inflation and the nominal interest rate, and real variables like output growth, consumption growth, investment growth and change in hours. Whereas these correlations are found to be mildly negative in the data, Calvo contracts imply correlations which have the wrong sign or are significantly off the mark. By comparison, Taylor contracts match these correlations quite successfully. We show that this is true whether TFP shocks or investment shocks are most important in driving business cycle fluctuations.

Both models also differ with respect to their inflation responses to a monetary policy shock and an investment shock. Conditioned on either type of shock, we find that Taylor contracts generate a response of inflation which is persistent and hump-shaped, and this without requiring the indexation of wages and prices to past inflation. Calvo contracts do not.[3]

An outmost difference between Taylor and Calvo contracts pertains to their welfare implications under positive trend inflation. Here, we assess the severity of monopolistic distortions and provide a quantitative evaluation of the consumer-equivalent welfare losses implied by non-zero steady state inflation in the two models. For an equal average age of nominal wage and price contracts, we find significant differences in the impact of positive trend inflation on wage dispersion and welfare costs.

Trend inflation exacerbates wage dispersion much more with Calvo contracts. For instance, with an annualized rate of trend inflation of 4% relative to 0%, steady state wage dispersion increases by 33% with Calvo contracts. By comparison, it increases by only 4% with Taylor contracts. With a trend inflation of 7%, which is roughly the average rate in the mid-1960s and 1970s, steady state wage dispersion rises by 530% with Calvo contracts! By comparison, it increases by 8.5% with Taylor contracts. Consistent with our findings regarding wage dispersion, the steady state consumer-equivalent welfare loss of 4% trend inflation is 12% with Calvo contracts compared to 1.7% with Taylor contracts. With 7% trend inflation, the loss is extreme at 55% with Calvo contracts.

We show that steady state wage dispersion and consumer-equivalent welfare losses are highly sensitive to variations in the following four factors under Calvo contracts: the average age of nominal wage contracts, the degree of substitutability between differentiated labor skills, real capita output growth, and the inverse Frisch elasticity of labor supply. The high sensitivity of results to these factors with Calvo contracts casts serious doubts about the plausibility of Calvo's contracting framework. By comparison, wage dispersion and welfare losses are quite stable to changes in these factors with Taylor contracts.

Our paper addresses one final question with important consequences for monetary policy: What were the potential consumer-equivalent welfare gains of reducing trend inflation from 7%, as in the mid-1960s and 1970s, to 3% after the early 1980s?[4] To provide a conservative answer to this question, we turn to Taylor contracts. We find estimates of the steady-state welfare gains of such a

[3] In Christiano, Eichenbaum, and Evans (2005), the response of inflation to a monetary policy shock is both persistent and hump-shaped due to full indexation of non-reset wages and prices to past inflation.

[4] Clarida, Galí, and Gertler (2000) have studied how the Fed's adoption of a less accommodative monetary policy has affected the volatility of output and inflation. Using a standard sticky-price model with zero trend inflation, they have shown that better monetary policy after 1983 may have led to the Great Moderation. Coibion and Gorodnichenko (2011) have shown that the combination of a less accommodative policy stance and a lower level of trend inflation have increased the prospect of determinacy after the early 1980s.

reduction in trend inflation that lie between 3% and 7%. Since the Fed is generally held accountable for lower inflation after the early 1980s, our findings suggest the welfare gains accompanying the Fed's efforts to bring inflation down were potentially important.

The rest of the paper is organized as follows. Section 2 presents a medium-scale NK model with Taylor nominal contracts. Section 3 discusses issues related to calibration and model fit. Section 4 looks at some long-run issues with both types of nominal contracts. Section 5 examines their cyclical implications. Section 6 contains concluding remarks.

2 A Medium-Scale DSGE Model With Taylor Contracts

Our baseline model includes monopolistically competitive markets for intermediate goods and labor, Taylor nominal wage and price contracts, positive trend inflation, trend output growth, roundabout production and real adjustment frictions. Following Greenwood, Hercowitz, and Krusell (1997) and Fisher (2006), we assume that technical change stems from trend growth in neutral and investment-specific technological progress. Monetary policy is based on a Taylor rule.

Trend inflation can play a non-trivial role in the Taylor and Calvo models since we omit indexation (e.g. see Ascari, Phaneuf, and Sims, 2018). Following Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2007), indexation has been included in several medium-scale NK models. It more or less neutralizes the effects of positive trend inflation on equilibrium dynamics up to a first-order approximation.[5] However this assumption has been questioned by Woodford (2007), Cogley and Sbordone (2008) and Chari, Kehoe, and McGrattan (2009) since it implies that all nominal wages and prices in the economy change every three months, something which is inconsistent with evidence from micro data on U.S. price and nominal wage adjustments.[6]

When looking at the business cycle properties of Taylor and Calvo models, we assume that aggregate fluctuations are driven by shocks to total factor productivity, investment and monetary policy. Unlike Fisher (2006) and Smets and Wouters (2007) who model investment shocks as a kind of disturbance identified through trend reductions in the relative price of investment goods to consumption goods, we take investment shocks to be those affecting the transformation of savings

[5]That is, non-reset nominal wages and prices are partially indexed to the previous quarter rate of inflation and to steady state inflation with indexing parameters summing to 1. From a steady state perspective, both reset and non-reset wages and prices adjust to trend inflation, offsetting most of the effects it would have otherwise on wage and price dispersion, inflation costs and indeterminacy.

[6]Ascari, Phaneuf, and Sims (2018) offer survey evidence that the quarterly indexation of nominal wages is not supported by U.S. and European data. Indexation has recently been abandoned in the medium-size DSGE models of Christiano (2015), Christiano, Eichenbaum, and Trabandt (2015, 2016).

into future capital input while being orthogonal to the relative price of investment as in Justiniano, Primiceri, and Tambalotti (2011).[7]

The full set of equilibrium conditions is presented in Appendix A. We keep the set of equilibrium conditions of the Calvo model for Appendix B.

2.1 Good and Labor Composites

There are a continuum of firms, indexed by $j \in [0, 1]$, producing differentiated goods with the use of a composite labor input. The composite labor input is aggregated from differentiated labor supplied by a continuum of households, indexed by $i \in [0, 1]$. The differentiated goods are bundled into a gross output good, X_t, by a competitive final good firm. Some of this gross output good is used as a factor of production by firms. Net output, Y_t, is gross output less intermediates. Households can either consume or invest the final net output good. Differentiated labor input is bundled into a final labor input by a competitive labor packer. The composite gross output and labor input are respectively:

$$X_t = \left(\int_0^1 X_{jt}{}^{\frac{\theta-1}{\theta}} dj \right)^{\frac{\theta}{\theta-1}}, \tag{1}$$

$$L_t = \left(\int_0^1 L_{it}{}^{\frac{\sigma-1}{\sigma}} di \right)^{\frac{\sigma}{\sigma-1}}. \tag{2}$$

The parameters $\theta > 1$ and $\sigma > 1$ are the elasticities of substitution between goods and labor, respectively. Profit maximization yields the following conventional downward-sloping demand curves for varieties of intermediate goods and labor:

$$X_{jt} = \left(\frac{P_{jt}}{P_t} \right)^{-\sigma} X_t, \tag{3}$$

$$L_{it} = \left(\frac{W_{it}}{W_t} \right)^{-\sigma} L_t. \tag{4}$$

2.2 Households and Wage Setting

Households supply differentiated labor input, facing a downward-sloping demand for their variety of labor. Nominal wages are set in a staggered fashion following Taylor (1980). The duration of each wage contract is fixed for N_w periods, with a fraction $1/N_w$ of nominal wages being reset

[7] Evidence in Schmitt-Grohé and Uribe (2004) shows that investment shocks identified through the relative price of investment explain very little of output fluctuations. By contrast, shocks to the marginal efficiency of investment are found to explain between 50% and 60% of output fluctuations in (Justiniano, Primiceri, and Tambalotti, 2011; Khan and Tsoukalas, 2012; Phaneuf and Victor, 2017).

each period. As in Erceg, Henderson, and Levin (2000), utility is separable in consumption and labor. State-contingent securities insure households against idiosyncratic wage risk arising from staggered wage-setting. With this setup, households are identical along all dimensions other than labor supply and wages.

Households own physical capital. In each period, they choose consumption C_t, labor L_{it}, investment I_t, savings in the form of nominal bonds B_t, and physical capital K_t. They also choose the capital utilization rate, u_t. Both capital services and labor are rented to firms at the rental rate R_t^k and the nominal wage W_{it}, respectively.

The problem of a typical household, omitting dependence on i except for these two dimensions, is:

$$\max_{C_t, L_{it}, K_{t+1}, B_{t+1}, I_t, u_t} \quad E_0 \sum_{t=0}^{\infty} \beta^t \left(\ln\left(C_t - bC_{t-1}\right) - \eta \frac{{L_{it}}^{1+\chi}}{1+\chi} \right), \tag{5}$$

subject to the following budget constraint,

$$P_t C_t + I_t + \left(\frac{a(u_t) K_t}{\varepsilon_t^{I,\tau}} \right) + \frac{B_{t+1}}{1+i_t} \leq W_{it} L_{it} + R_t^k u_t K_t + \Pi_t + B_t + T_t, \tag{6}$$

the physical capital accumulation process,

$$K_{t+1} = \vartheta_t \varepsilon_t^{I,\tau} \left(1 - \frac{\kappa}{2} \left(\frac{I_t}{I_{t-1}} - g_I \right)^2 \right) I_t + (1-\delta) K_t, \tag{7}$$

and the downward-sloping demand for labor (4).

P_t is the nominal price of goods, C_t is consumption, and I_t is investment measured in units of consumption. Capital services are the product of utilization and the stock of physical capital $u_t K_t$.[8] Π_t denotes distributed dividends from firms. B_t is a stock of nominal bonds with which a household enters a period. T_t is a lump-sum transfer from the government to households. $a(u_t)$ is the cost of capital utilization which satisfies $a(1) = 0$, $a'(1) = 0$, $a''(1) > 0$. This cost is determined by:

$$a(u_t) = \gamma_1 \left(u_t - 1\right) + \frac{\gamma_2}{2} \left(u_t - 1\right)^2, \tag{8}$$

where γ_1 and $\gamma_2 \geq 0$ are parameters. Utilization equals one in the steady state ($u_t = 1$). κ is a parameter governing a cost to adjusting investment, $g_{\varepsilon^I} \geq 1$ is the long-run growth of investment, and i_t is the nominal interest rate. $0 < \beta < 1$ is a discount factor, $0 < \delta < 1$ is a depreciation rate, and $0 \leq b < 1$ is a parameter for internal habit formation. χ is the inverse Frisch labor supply

[8] The relative price of investment goods to consumption goods is $1/\varepsilon_t^{I,\tau}$. Hence, if $\widehat{I}_t$ is physical units of investment, then $\varepsilon_t^{I,\tau} I_t = \widehat{I}_t$. Writing the accumulation equation in terms of investment measured in consumption units yields (7).

elasticity. The dollar cost of capital utilization per unit of physical capital is $\frac{P_t a(u_t)}{\varepsilon_t^{I,\tau}}$. $\varepsilon_t^{I,\tau}$, which enters the capital accumulation equation by multiplying investment and the budget constraint in terms of the resource cost of capital utilization, measures the level of IST. We assume that it follows a deterministic trend with no stochastic component:

$$\varepsilon_t^{I,\tau} = g_{\varepsilon^I} \varepsilon_{t-1}^{I,\tau}. \tag{9}$$

The deterministic trend is necessary to match the observed downward trend in the relative price of investment goods in the data. The exogenous variable ϑ_t is an investment shock orthogonal to the relative price investment. It follows a stationary AR(1) process, with innovation drawn from a mean zero normal distribution with standard deviation σ_I:

$$\vartheta_t = (\vartheta_{t-1})^{\rho_I} \exp(\sigma_I \varepsilon_t^I), \quad 0 \leq \rho_I < 1. \tag{10}$$

There are N_w equally sized household cohorts having N_w-period wage contracts. Households setting a new contract will choose the same nominal wage rate W_{it}^* maximizing the present discounted sum of expected utility (5) subject to the labor demand schedule (4). The optimal wage decision rule derived from the first-order conditions of the household's problem is:

$$w_t^{*1+\sigma\chi} = \mu_w E_t \frac{\sum_{h=0}^{N_w-1} \beta^h \eta \pi_{t+1,t+h}^{\sigma(1+\chi)} w_{t+h}^{\sigma(1+\chi)} L_{t+h}^{1+\chi}}{\sum_{h=0}^{N_w-1} \beta^h \pi_{t+1,t+h}^{\sigma-1} w_{t+h}^{\sigma} \lambda_{t+h}^r L_{t+h}}, \tag{11}$$

where w_{it}^* is the real optimal reset wage, and μ_w is the steady-state wage markup, λ_t^r is the marginal utility of an additional unit of real income received by the household, and $\pi_{t+1,t+h}$ is cumulative inflation between t and $t+h-1$. Given our assumption about preferences and wage setting, all updating households have the same optimal reset wage denoted by $w_t^* = w_{it}^*$.

2.3 Intermediate Goods Producers

The production function for a typical producer j is:

$$X_{jt} = A_t {\Gamma_{jt}}^{\phi} \left({\widehat{K}_{jt}}^{\alpha} {L_{jt}}^{1-\alpha} \right)^{1-\phi} - \Upsilon_t F, \tag{12}$$

where A_t denotes an exogenous neutral technological progress. Neutral productivity obeys a process with both a trending and stationary component. A_t^τ is the deterministic trend component, where g_A is the gross growth rate:

$$A_t = A_t^\tau \widetilde{A}_t, \tag{13}$$

$$A_t^\tau = g_A A_{t-1}^\tau. \tag{14}$$

The initial level in period 0 is normalized to 1: $A_0^\tau = 1$. The stationary component of neutral productivity follows an AR(1) process in the log, with the non-stochastic mean level normalized to unity, and innovation, σ_t^A, drawn from a mean zero normal distribution with known variance equal to σ^A:

$$\widetilde{A}_t = \left(\widetilde{A}_{t-1}\right)^{\rho_A} \exp\left(\sigma_t^A \varepsilon_t^A\right), \quad 0 \leq \rho_A < 1, \tag{15}$$

where g_A is the steady-state growth rate of neutral technology, and ε_t^A is an i.i.d. $N(0, \sigma_A^2)$ neutral technology shock. F is a fixed cost, and production is required to be non-negative. Υ_t is a growth factor, to be discussed later. Given Υ_t, F is chosen to keep profits zero along a balanced growth path, so the entry and exit of firms can be ignored. Γ_{jt} is the amount of intermediate input, and $\phi \in (0,1)$ is the intermediate input share. Intermediate inputs come from aggregate gross output, X_t. $\widehat{K}_{jt}$ is capital services (the product of utilization and physical capital), while L_{jt} is labor input.

The firm gets to choose its price, P_{jt}, as well as quantities of intermediates, capital services, and labor input. Each period there is a fraction $1/N_p$ of firms resetting their price for N_p periods. Regardless of whether a firm is given the opportunity to adjust its price, it will choose inputs to minimize total cost, subject to the constraint of producing enough to meet demand. The cost minimization problem of a typical firm is:

$$\min_{\Gamma_t, \widehat{K}_t, L_t} \quad P_t \Gamma_t + R_t^k \widehat{K}_t + W_t L_t \tag{16}$$

s.t.

$$A_t \Gamma_t^\phi \left(\widehat{K}_t^\alpha L_t^{1-\alpha}\right)^{1-\phi} - \Upsilon_t F \geq \left(\frac{P_{jt}}{P_t}\right)^{-\theta} X_t.$$

Since capital is perfectly mobile across firms, capital services and labor will be hired in the same ratios by all firms. Under these conditions, all intermediate goods firms will have the same real marginal cost.

There are N_p equally sized firm cohorts having N_p-period price contracts. Firms setting a new price contract will choose the same price P_{jt}^* maximizing the present discounted value of future profits, subject to (3) and cost minimization. This yields the following optimal price:

$$p_t^* = \mu_p \frac{E_t \sum_{h=0}^{N_p-1} \beta^h \lambda_{t+h}^r mc_{jt+h} \pi_{t+1,t+h}^\theta X_{t+h}}{E_t \sum_{h=0}^{N_p-1} \beta^h \lambda_{t+h}^r \pi_{t+1,t+h}^{\theta-1} X_{t+h}}, \tag{17}$$

with $p^*_{jt} \equiv \frac{P^*_{jt}}{P_t}$ denoting the relative optimal price, μ_p is the steady-state price markup and mc_{jt} is the real marginal cost. Since all updating firms have the same markup and the same marginal cost, they will fix the same optimal price $p^*_t = p^*_{jt}$.

2.4 Average Age of Taylor and Calvo Contracts

Our basis of comparison for the length of Taylor and Calvo contracts is their *average age* as suggested by Dixon and Kara (2006). To produce the same average contract ages as those implied by the Calvo parameters ξ_p and ξ_w, the Taylor-contract length needs to be $\frac{1+\xi_p}{1-\xi_p}$ periods for prices and $\frac{1+\xi_w}{1-\xi_w}$ periods for nominal wages.

Specifically, let the average age of a Taylor nominal wage or price contract in the cross-section be,

$$A^T_x = \frac{N_x + 1}{2}, \; x = w, p.$$

Let $1 - \xi_x$ be the probability of reoptimization of nominal wages or prices x ($x = w, p$) in the Calvo model. The average age of contracts in the Calvo model is given by the reciprocal of the reset probability of x,

$$A^C_x = \frac{1}{1 - \xi_x}, \; x = w, p.$$

We choose a pair $\{1 - \xi_x, N_x\}$, $x = w, p$, so that the average ages in the two models are the same: $A^T_x = A^C_x$, $x = w, p$. The relationship between $\{1 - \xi_x, N_x\}$, $x = w, p$, is then given by

$$1 - \xi_x = \frac{2}{N_x + 1} \Leftrightarrow N_x = \frac{(1 + \xi_x)}{1 - \xi_x}, \; x = w, p.$$

For example, $\xi_x = 2/3$ implies $N_x = 5$, and $\xi_x = 3/4$, $N_x = 7$.

2.5 Monetary Policy

Monetary policy follows a Taylor rule:

$$\frac{1 + i_t}{1 + i} = \left(\frac{1 + i_{t-1}}{1 + i}\right)^{\rho_i} \left[\left(\frac{\pi_t}{\pi}\right)^{\alpha_\pi} \left(\frac{Y_t}{Y_{t-1}} g_Y^{-1}\right)^{\alpha_y}\right]^{1-\rho_i} \varepsilon^r_t. \tag{18}$$

In setting the nominal interest rate, the monetary authority reacts to deviations of inflation from an exogenous steady-state inflation target, π, and to deviations of output growth from steady state output growth, g_Y. The parameter ρ_i governs the smoothing effect on nominal interest rates, α_π and α_y are control parameters, and ε^r_t is an exogenous policy shock assumed to be drawn from a mean zero normal distribution with known standard deviation σ_r.

The rule does not include a response of nominal interest rates to the level of the output gap. Khan, Phaneuf, and Victor (2019) show that, with Calvo wage and price contracts and no or mild indexation, achieving determinacy when the Taylor rule includes the level of the output gap calls for responses to inflation that largely exceed the original Taylor Principle ($\alpha_\pi \geq 1$) and estimates generally found in the empirical literature. This is true even for low levels of trend inflation such as 2% and 3%. By contrast, a rule reacting to output growth widens the set of responses to inflation consistent with determinacy.

2.6 Growth

The trend growth factor is deterministic and given by:

$$\Upsilon_t = (A_t^\tau)^{\frac{1}{(1-\phi)(1-\alpha)}} \left(\varepsilon_t^{I,\tau}\right)^{\frac{\alpha}{1-\alpha}}. \tag{19}$$

This expression shows that for a given level of trend growth in neutral productivity, the economy will grow faster the larger the share of intermediates in production. Without intermediate inputs $\phi = 0$, the expression for trend growth reverts to the conventional trend growth factor $\Upsilon_t = (A_t^\tau)^{\frac{1}{(1-\alpha)}} \left(\varepsilon_t^{I,\tau}\right)^{\frac{\alpha}{1-\alpha}}$. A higher ϕ amplifies the effects of trend growth in neutral productivity on output and its components.

3 Parametrization and Model Fit

This section describes the parameterization of our models and assesses their empirical fit by focusing on some business cycle moments.

3.1 Non-Shock Parameters

Baseline parameter values are summarized in Panel A of Table 1. We set the discount factor $\beta = 0.99$, which implies that the annual real rate of interest is 4 percent in the steady state. The parameter h determining consumer habit formation is 0.8, in line with the literature. The weight on the disutility of labor is $\eta = 6$, implying that steady-state labor hours is 1/3. The inverse Frisch labor supply elasticity χ is 1. The rate of depreciation of capital is $\delta = 0.025$, so that the annual rate of depreciation is 10%. The share of capital services α is 1/3. The investment adjustment cost parameter is $\kappa = 3$, consistent with the estimate in Christiano, Eichenbaum, and Evans (2005). The parameter γ_1 is set so that steady state utilization is 1, and that γ_2 is five times γ_1, consistent with the estimates provided in Justiniano, Primiceri, and Tambalotti (2010, 2011).

The elasticity of substitution between differentiated goods θ is set at 4, following Nakamura et al. (2018) who base their calibration on estimates of the elasticity of demand for individual products found in the industrial organization and international trade literatures. The elasticity of substitution between labor skills σ is set at 6, following Huang and Liu (2002) and Liu and Phaneuf (2007). The share of intermediate inputs into gross output is set at 0.5.

The average ages of nominal contracts in the Taylor and Calvo models are linked by $N_x = \frac{1+\xi_x}{1-\xi_x}$, $x = w, p$, N_x being the number of contract-periods of x, and $1 - \xi_x$ the Calvo probability of reoptimization of x. Christiano, Eichenbaum, and Evans (2005) report that $\xi_w = 0.64$ and $\xi_p = 0.6$ using a procedure that minimizes the distance between the impulse responses of key variables to a monetary policy shock from an estimated structural vector-autoregression (SVAR) and those from their estimated DSGE model. Smets and Wouters (2007) report an estimate of ξ_w of 0.73 and of ξ_p of 0.65. Justiniano, Primiceri, and Tambalotti (2011) report that $\xi_w = 0.76$ and $\xi_p = 0.778$.

Yet, another source of information is the evidence based on micro data on nominal wage and price adjustments. Using data on nominal wage adjustment, Barattieri, Basu, and Gottschalk (2014) report that the probability of a quarterly wage change according to their U.S. dataset lies roughly between 0.2 and 0.25. Evidence from microeconomic price data presented Bils and Klenow (2004) and Nakamura and Steinsson (2008) suggests a wider range for the average waiting time between price adjustments, between 5.5 and 11 months, whether evidence is based only on regular price changes or price changes that include sales.

Therefore in light of the evidence, it appears reasonable to set $\xi_w = 3/4$ and $\xi_p = 2/3$ as our baseline Calvo probabilities, so that the baseline basis of comparison with Taylor contracting in terms of average age of nominal contracts is $N_w = 7$ and $N_p = 5$.

The Taylor rule parameters are chosen as follows: the interest rate smoothing parameter is set at 0.8, the parameter governing the response of the nominal interest rate to deviations of inflation from target (or trend inflation) is set at 1.5, and the parameter determining the response to deviations of output growth from steady state is set at 0.2. These values are quite standard in the literature.

3.2 Trend Growth, Trend Inflation and Shock Parameters

The values assigned to trend growth, trend inflation and the shock parameters are summarized in Panel B of Table 1.[9] The trend growth rate of investment-specific technology, g_{ε^I}, equals the negative of the average growth rate of the relative price of investment goods to the price of consumption goods. It is is obtained by mapping the model to the data. Investment is the sum of expenditures on new durables and private fixed investment, while consumption represents the sum of consumer

[9] Detailed information about how the dataset was produced can be found in Ascari, Phaneuf, and Sims (2018).

expenditures on nondurables and services. These series are borrowed from the BEA for the period 1960Q1-2007Q3.

The average growth rate of the relative price of investment goods for our sample is -0.00472, which implies $g_{\varepsilon^I} = 1.00472$. Aggregate output (or real GDP) is the sum of non-durable consumption, services consumption, expenditure on durables, and fixed investment. Real per capita GDP is computed by subtracting from the log-level the log civilian non-institutionalized population. The average growth rate of the resulting output per capita series for our sample period is 0.005712, implying $g_Y = 1.005712$ or 2.28% a year. The standard deviation of output growth over the same period is 0.0078. Given that the growth rate of IST is $g_{\varepsilon^I} = 1.00472$, we pick g_A to generate the appropriate average growth rate of output. This implies $g_A = 1.0022$ or a measured TFP growing at about 1% per year.

The corresponding price deflator is the ratio of the nominal and to real GDP series. The average growth rate of the price index for our sample period is 0.0088, implying an average rate of inflation (or trend inflation) $\pi^* = 1.0088$ or an average annual rate of inflation of 3.52%.

Whereas shocks do not matter for assessing the non-stochastic steady-state monopolistic distortions (wage and price dispersion) and inflation costs, they are relevant for their assessment conditioned on stochastic means and for generating business cycle moments. Aggregate fluctuations are driven by shocks to neutral technology, investment and monetary policy. Their standard deviations are σ_A, σ_I, and σ_r. To ease the comparison between Taylor and Calvo contracting, the two models are put on an equal footing by imposing that each matches the volatility of output growth in the postwar data, for an inflation trend equal to the actual average annualized rate of inflation. The size of shocks is then determined by assigning to each a percentage contribution to the unconditional variance decomposition of output.

To make our case as general as possible, we consider two different scenarios. The first scenario assumes the investment shock is the main source of output fluctuations. The second scenario assumes the TFP shock is the key driver.[10] This will enable us to assess whether our main findings are sensitive to which type of shock is assumed to be the most important source of output fluctuations. The first scenario assigns 50% of the variance of output growth to the investment shock, 35% to the TFP shock, and 15% to the monetary policy shock. The second scenario assigns 50% of the variance of output growth to the TFP shock, 35% to the investment shock, and 15% to the monetary policy shock. These splits will have no effect on the non-stochastic steady-state distortions

[10]See also Ascari, Phaneuf, and Sims (2018) and Phaneuf and Victor (2019) for a similar procedure. We cannot resort to Bayesian estimation due to our parsimonious choice of shocks. We cannot use either a procedure that would require matching the impulse-responses estimated from a SVARs since they are no known identifying restrictions for investment shocks that are not based on the relative price of investment goods to consumption goods.

and inflation costs. The autoregressive parameter of the neutral productivity shock is set at 0.95 and that of the investment shock at 0.8, which is consistent with evidence in the literature.

3.3 Model Fit

To provide some idea of the empirical relevance of the Taylor and Calvo models, we compare some theoretical business cycle moments predicted by the two models with those in the data.[11] The moments are summarized in Table 2. The reported volatility and correlation statistics are for variables measured in growth rates.

The volatility of output growth in the two models matches the actual volatility in the data by construction. Both models predict that investment growth is significantly more volatile than consumption growth, and that consumption growth is less volatile than output growth and first-differenced hours. The Calvo model provides a better match of the volatility of consumption growth than Taylor. At the same time, the Taylor model does better than Calvo matching the volatilities of investment growth, first-differenced hours, inflation and interest rates.

The Taylor model somewhat underestimates the correlation between the growth rates of consumption and output (0.6 vs 0.75), while the Calvo model overestimates this correlation (0.81 vs 0.75). Both models accurately predict that the correlation between investment growth and output growth is high and that first-differenced labor hours are procyclical.

The Taylor and Calvo models correctly predict that the correlation between consumption growth and investment growth is positive. While this correlation is 0.44 in the data, the Calvo model overestimates it at 0.66, while the Taylor model matches this correlation almost perfectly at 0.43. It is well known that NK models with standard preferences are unable to generate a positive correlation between consumption growth and investment growth (e.g. see Khan and Tsoukalas, 2011; Furlanetto and Seneca, 2014). This anomaly results from a negative response of consumption to a positive investment shock for about 5 or 6 quarters after the shock. By contrast, Figure 1 shows that both our Taylor and Calvo models imply a positive response of consumption following an investment shock. Using a Calvo wage and price setting model with standard preferences, Ascari, Phaneuf, and Sims (2019) have shown that the interaction between real per capita output growth and roundabout production generates a response of consumption which is non-negative on impact of a positive investment shock and positive after.

However, we find significant differences between the Calvo and Taylor models in explaining the correlations between nominal and real variables. As Table 2 shows, these correlations are negative in the data. While inflation is mildly countercyclical in the data at -0.37, the Calvo model predicts

[11] The model is solved via second order perturbation about the non-stochastic steady state.

it is weakly procyclical at 0.07. By contrast, the Taylor model predicts the correlation between output growth and inflation is negative at -0.2. The actual correlation between inflation and consumption growth is -0.42. The Calvo model predicts this correlation is -0.15, and the Taylor model that it is -0.37. While in the data the correlation between inflation and investment growth is -0.26, the Calvo model predicts it is positive at 0.19, and the Taylor model that it is negative at -0.03. The actual correlation between inflation and first-differenced hours is negative at -0.13. Both the Calvo and Taylor models imply this correlation is positive, the Taylor model predicting it is nearly 0 and the Calvo model predicting that it is mildly positive at 0.4.

The actual correlation between output growth and the interest rate is also negative at -0.33. Both models correctly predict that this correlation is negative. However, the Taylor model does better than Calvo matching this correlation. The Taylor model generates a correlation of -0.28, while the Calvo model implies a correlation of -0.07. Interest rates and consumption growth are also negatively correlated in the data at -0.3. The Taylor model implies -0.41 and the Calvo model -0.02. Interest rates and investment growth are also negatively correlated in the data at -0.28. This correlation is -0.18 with Taylor contracting and -0.01 with Calvo contracting. The actual correlation between the interest rate and the change in hours is -0.2. The Taylor model predicts it is -0.23 while the Calvo model predicts it is -0.05.

While the actual autocorrelations of output growth are respectively 0.36 and 0.34 at a one- and two-quarter lag, they are 0.68 and 0.42 in the Taylor model and 0.72 and 0.49 in the Calvo model. Cogley and Nason (1995) argue these particular moments offer a useful test of the potency of endogenous propagation mechanisms included in a model.

The actual autocorrelations of inflation at a one-quarter lag and a two-quarter lag are very high at 0.91 and 0.86. The Taylor predicts they are 0.88 and 0.73, while the Calvo model predicts they are 0.84 and 0.71. Therefore, both models predict inflation is highly persistent despite there is no indexation. The autocorrelations of the nominal interest rate are 0.95 and 0.89 in the data. The Taylor model predicts they are 0.85 and 0.71, and the Calvo model that they are 0.89 and 0.8.

4 Welfare Properties of Taylor and Calvo Contracting Models

This section analyzes some normative aspects of positive trend inflation under Taylor and Calvo contracting. We offer quantitative measures of dispersion and welfare costs generated by positive trend inflation in the two models.

4.1 Monopolistic Distortions and the Welfare Costs of Inflation

Define aggregate welfare as a function of the realization of the vector of state variables, S_t:

$$V(S_t) = \ln(C_t - bC_{t-1}) - \eta v_t^w \frac{L_t^{1+\chi}}{1+\chi} + \beta E_t V(S_{t+1}), \tag{20}$$

where v_t^w measures wage dispersion, which results from aggregating differentiated labor inputs across households. As in Schmitt-Grohé and Uribe (2004), this recursive measure of welfare can be included as an equilibrium condition in a second order solution.[12] The model is solved for different levels of trend inflation.

Let the subscript B denote a "base" scenario (for example, 0% trend inflation) and A be an "alternative" scenario (for example, 4% trend inflation). The level of trend inflation affects both the policy functions, $V(\cdot)$, and the realizations of the state vector, S_t. There are several ways to compare welfare across different levels of trend inflation. One is to compute consumption-equivalent differences conditioned on steady-state welfare. Let λ denote the fraction of consumption that would need to be sacrificed in each period in the base case to yield the same welfare as in the alternative case. Conditioned on non-stochastic steady states, it is given by:

$$\lambda_{ss} = 1 - \exp\left[(1-\beta)\left(V_A(S_A^*) - V_B(S_B^*)\right]\right. \tag{21}$$

An alternative welfare comparison can be conditioned on stochastic means. An advantage of this measure is that it incorporates information on how the level of trend inflation interacts with stochastic disturbances. It is given by:[13]

$$\lambda_m = 1 - \exp\left[(1-\beta)\left(E\left[V_A(S_{A,t})\right] - E\left[V_B(S_{B,t})\right]\right)\right]. \tag{22}$$

We first compare steady-state and mean welfare costs corresponding to levels of trend inflation of 0%, 2%, 4% and 7%.[14] The results obtained with our baseline calibration are presented in

[12] Note that we take a second order approximation to all equilibrium conditions. This means that we need not make dubious assumptions such as the existence of a subsidy to undo steady state distortions associated with monopoly power to derive a closed form welfare cost measure.

[13] The consumption equivalent metrics defined in (21)-(22) do not account for transition dynamics. If an economy were to transition from a world with 0% trend inflation (B) to a world with 4% inflation (A), either of the above metrics might overstate the welfare cost because it takes time for the state variables to transition to the higher inflation regime.

[14] We assume that the average age of nominal wage and price contracts is invariant to the level of trend inflation. One could wonder whether this is appropriate for years of higher inflation like the 1970s. While it may be theoretically appealing to entertain the idea that the average age of contracts should decrease with a higher level of trend inflation, this conjecture is not supported by evidence in Golosov and Lucas (2007) and Alvarez et al. (2018) (see also Christiano, 2015) suggesting that the length of nominal contracts is not affected by trend inflation ranging from 0 to 8%, so that endogenous contract length can be safely disregarded.

Table 3. Panel A reports wage and price dispersion indicators with Calvo contracts, and Panel B dispersion indicators with Taylor contracts.

The two models predict that price dispersion is weakly correlated with trend inflation, and this even for a level of inflation reaching 7%. These findings are consistent with evidence in Nakamura et al. (2018) showing that there is no indication of an increase in price dispersion while inflation got higher during the 1970s.

By contrast, wage dispersion is a lot more sensitive to trend inflation than price dispersion. With Calvo contracts, a rise from 0% to 2% trend inflation generates increases in steady-state wage dispersion of 10% and mean dispersion of 11%. For an inflation trend of 4%, these figures are 33% and 36%, respectively. With an inflation trend of 7% relative to one of 0%, steady-state wage dispersion increases by 530% and mean dispersion by 824%. By comparison, with Taylor contracts steady-state wage dispersion increases by 1.9% with an inflation trend of 2% and mean wage dispersion by 2.1%. With a 4% trend inflation, steady-state wage dispersion increases by 4% and mean dispersion by 4.2%. With a 7% trend inflation, the increases in steady-state and mean wage dispersion are 8.5% and 8.7%, respectively.

We view the high sensitivity of monopolistic distortions to trend inflation with Calvo contracts as an unattractive feature of this model. It went largely unnoticed until now due to a particular emphasis in the literature on trend inflation on sticky-price models. The less severe distortions under Taylor contracts ensures this model is more reliable to assess the long-run properties of the NK model with positive trend inflation.

These findings raise three questions. A first question is: Why is wage dispersion is a lot more sensitive to trend inflation than price dispersion? In answering the first question, let us consider the following steady-state expressions for price and wage dispersion under Taylor contracting:

$$\nu_{ss}^{p} = \frac{\left(\sum_{h=0}^{N_p-1} \pi^{h(\theta-1)}\right)^{\theta} \sum_{h=0}^{N_p-1} \pi^{h\theta}}{N_p^{1+\theta}}, \tag{23}$$

and

$$\nu_{ss}^{w} = \frac{\left(\sum_{h=0}^{N_w-1} (g_\Upsilon \pi)^{h(\sigma-1)}\right)^{\frac{\sigma(1+\chi)}{1-\sigma}} \sum_{h=0}^{N_w-1} (g_\Upsilon \pi)^{h\sigma(1+\chi)}}{N_w^{\frac{(1+\chi)}{1-\sigma}}}. \tag{24}$$

These expressions show that wage dispersion and price dispersion depend on different structural factors, except for trend inflation which is common to both dispersion measures. Price dispersion is a function only of the level of trend inflation, π, the number of periods of price contracts, N_p, and the degree of substitutability between differentiated goods, θ. Wage dispersion is a function of more factors, that is, trend inflation, the number of periods of wage contracts, N_w, the degree of substitutability between differentiated skills, σ, the inverse Frisch elasticity of labor supply, χ, and the steady-state real per capita output growth, g_Y.

A second question is: How does trend inflation exacerbate wage dispersion in our models? To put things into perspective, let's consider the standard medium-scale NK model of Christiano, Eichenbaum, and Evans (2005). In this model, trend inflation is zero and there is no technical change. The wage distribution is characterized by nominal wages which are identical in the steady state. Therefore, steady-state wage dispersion is zero. With positive trend inflation but no technical change, not all wages are identical in the steady state, newly reset wages being high relative to old non reset wages. Trend inflation hence generates inefficient wage dispersion. With a convex disutility of labor, total labor disutility rises non linearly with higher wage dispersion, making inflation more costly as trend inflation rises. Adding technical change to sticky wages with zero trend inflation generates some wage dispersion compared to the no growth case. Adding technical change on top of positive trend inflation and sticky wages amplifies wage dispersion and makes inflation even more costly.[15]

A third question is: Why is wage dispersion much more sensitive to trend inflation with Calvo contracts? In a Calvo wage and price setting framework, wage setting households face an exogenous probability of changing nominal wages each period. There is always a fraction of households with very outdated nominal wages. With positive trend inflation, households allowed to reset their nominal wage will put weight on possible outcomes far in the future in which their relative wage are very non competitive. Therefore the gap between newly reset wages and outdated nominal wages may be large, inducing costly wage dispersion. By contrast, the staggered contracting approach of Taylor (1980) holds that nominal wages are set for a pre-determined period, imposing zero weight on expected future utilities beyond those of the contract length in the household's reset wage optimization. Therefore the gap between newly reset wages and outdated wages is smaller with Taylor contracts. Calvo contracting hence comes along with stronger monopolistic distortions than Taylor contracting.

To obtain a better idea of how different factors affect wage dispersion in the Taylor and Calvo models, we perform a number of exercises assessing the sensitivity of wage dispersion to key parameters of the model. Except for the one parameter that we focus on, other parameters remain at their baseline values.

[15] See Amano et al. (2009) for a similar reasoning in a simpler NK model with sticky wages and TFP growth.

Panel A of Figure 2 assesses the sensitivity of steady-state wage dispersion to variations in structural parameters with Calvo contracts. Panel B conveys the same information with Taylor contracts. The first line of Panel A looks at how varying the probability of wage non-reoptimization affects wage dispersion, while the first line of Panel B looks at the effect of varying the number of periods of Taylor wage contracts. We compare steady-state wage dispersion for $\xi_w = 0, 2/3$ and $3/4$ with Calvo contracts. The corresponding number of periods of wage contracts with Taylor contracting is $N_w = 1, 5$ and 7.

Varying ξ_w between 0 and 3/4 with Calvo contracts has a very large impact on steady-state wage dispersion. With flexible nominal wages ($\xi_w = 0$), wage dispersion is zero (i.e. wage dispersion indicator equal to 1). There is a very large increase in wage dispersion when ξ_w increases from 2/3 to 3/4 and trend inflation reaches 6%. With 7% trend inflation, the dispersion indicator reaches 5.3, meaning that wage dispersion increases by 530%. By contrast, with Taylor wage contracts and a trend inflation of 7%, wage dispersion increases by 5% with $N_w = 5$ and 8.5% with $N_w =$ 7. Therefore, while the length of wage contracts is a key factor affecting wage dispersion in both models, the effect is much stronger with Calvo contracts.

The second line of Panels A and B examines the sensitivity of wage dispersion to the degree of substitutability between differentiated labor skills, σ. For this exercise, we assume $\sigma = 4, 6$ and 8. With Calvo contracts, the effect of increasing σ from 6 to 8 becomes extremely large when trend inflation reaches 6% or more. With Taylor contracts, the impact is much smaller, but still the increase in wage dispersion at 6% trend inflation is about twice as large with $\sigma = 8$ than with $\sigma = 6$. These findings suggest that wage dispersion is very sensitive to variations σ, especially with Calvo contracts.

The third line of Panels A and B compares steady-state wage dispersion with and without economic growth. The impact of economic growth on wage dispersion is also very significant. With Calvo contracts and a level of trend inflation of 7%, the increase in wage dispersion with economic growth is about 4 times larger than without economic growth. Economic growth also has a significant impact on wage dispersion with Taylor contracts. The impact is perhaps not of the same order of magnitude, but it is nonetheless sizeable.

The fourth line of Panel A and B assesses the effect of the Frisch labor supply elasticity on wage dispersion. The inverse Frisch elasticity is given by the parameter χ. We set $\chi = 0, 1$ and 2. $\chi = 0$ corresponds to the case of infinite Frisch elasticity, and is isomorphic to the indivisible labor model of Rogerson (1988) and Hansen (1985). With $\chi = 0$, wage dispersion responds much less to trend inflation. The intuition for the effect of χ on wage dispersion is straightforward. Trend inflation distorts the relative allocation of labor across households, inducing wage dispersion. With curvature in preferences over labor, this misallocation can be quite significant. But if this curvature is absent, as is the case with $\chi = 0$, misallocated labor and wage dispersion are much smaller. Of course, the reverse if true if $\chi = 2$, so that labor supply is less elastic than in our baseline.

Consistent with our findings on wage dispersion, we find that Calvo contracts imply much higher inflation costs than Taylor contracts. The results are reported in Table 4**,** Panel A summarizing inflation costs computed from steady states and means with Calvo contracts and Panel B, inflation costs with Taylor contracts.

With Calvo contracts, going from an inflation trend of 0% to 4% induces a steady-state welfare cost of 12.2% and a mean cost of 13.3%. These are high estimates. With 7% trend inflation, these figures rise to 56.2% and 66.1%, respectively. While it is well known that inflation and unemployment have reached simultaneously high levels in the 1970s, welfare costs of this magnitude can be received with some skepticism. By comparison, inflation costs are also much smaller with Taylor contracts. Increasing trend inflation from 0% to 4% generates a steady-state inflation cost of 1.71% and a mean cost of 1.73%. With a 7% trend inflation, these costs are 3.94% and 3.96%, respectively.

We look at two other scenarios of interest in Table 4. A first scenario considers how costly it would be to raise trend inflation from 2% to 4%. In the wake of the Great Recession and the Zero Lower Bound on the nominal interest rate, economists like Blanchard, Dell'Ariccia, and Mauro (2010), Ball (2013) and Krugman (2014) have advocated a rise in the inflation target from 2% to 4% and even 5% annually. The results are reported in Table 4. Increasing trend inflation from 2% to 4% with Calvo contracts would result into a steady-state inflation cost of 9% and a mean cost of 9.8%. By any standard, these are large increases in inflation costs. By comparison, inflation costs with Taylor contracts would increase by 1.07% conditioned on steady states and 1.08% conditioned on means.

A second scenario looks at the potential welfare gains of going from 7% trend inflation in the 1970s to 3% after the early 1980s.[16] With Calvo contracts, the welfare gains of reducing trend inflation from 7% to 3% are very large at 53% conditioned on steady states and 63% conditioned on means. The corresponding figures with Taylor contracts are 2.84% and 2.85%, respectively.

[16] Other parameters including those of the Taylor rule are kept at their baseline values. Accounting for a more aggressive policy reaction to inflation after 1983 as in Clarida, Galí, and Gertler (2000) and Coibion and Gorodnichenko (2011) would have no effect on steady-state welfare costs but would reduce mean inflation costs even more than reported here.

4.2 Sensitivity Analysis Under Taylor Contracting

We examine how plausible variations in key structural parameters would impact our results on welfare costs with Taylor contracts. We focus on Taylor contracts because of the high sensitivity of monopolistic distortions to trend inflation under Calvo contracting. We look at the effects of plausible variations in the elasticity of substitution between labor skills, σ, and the number of periods of nominal wage contracts, N_w.

Our baseline calibration sets $\sigma = 6$. Bayesian estimates reported in the literature suggest this elasticity could be around 8 (see Justiniano et al., 2010, 2011). Panel A of Table 5 reports steady-state inflation costs under Taylor contracting with $\sigma = 8$, for different levels of trend inflation.[17] Increasing σ from 6 to 8 generates a steady-state inflation cost of 0-4% trend inflation of 2.84%, which represents a significant increase relative to $\sigma = 6$. The steady-state welfare cost of 0%-7% trend inflation is 6.3% with $\sigma = 8$ compared to 3.94% with $\sigma = 6$. The welfare gains arising from a reduction of trend inflation from 7% to 3% are 4.47% with $\sigma = 8$ compared to 2.84% with $\sigma = 6$.

Panel B of Table 5 presents the welfare costs resulting from an increase in the average age of wage contracts. This exercise follows from micro evidence on nominal wage adjustment found in Barattieri et al. (2014), showing that the probability of wage change ranges roughly from 0.2 to 0.25 per quarter. A probability $\xi_w = 0.25$ implies $N_w = 7$, which is our baseline case. A probability $\xi_w = 0.2$ implies $N_w = 9$. With other parameters kept at their baseline values, $N_w = 9$ implies that the steady-state welfare cost of 0% to 4% trend inflation is 2.76% compared to 1.71% with $N_w = 7$. With 7% trend inflation, this cost rises to 6.16% compared to 3.94% with $N_w = 7$. The welfare gain of reducing trend inflation from 7% to 3% is 4.4%.

If we combine $\sigma = 8$ and $N_w = 9$, the steady-state welfare cost of 0-4% trend inflation is 4.55%, while that of 0-7% is 9.66%. The welfare gain resulting from a reduction in trend inflation of 7% to 3% is 6.8%. Since the Fed is held accountable for the decrease in trend inflation after the early 1980s, our findings suggest that the welfare gains resulting from the Fed's adoption of a "hawkish" policy after 1983 were potentially important.

5 Cyclical Implications of Taylor and Calvo Contracting

This section compares the cyclical implications of Taylor and Calvo contracting models. We show that the impulse responses of real variables to monetary policy, neutral technology and investment shocks are sensitive to trend inflation with Calvo contracts. With Taylor contracts, we find that

[17] We do not report the mean costs because with Taylor contracting they are not much different from the steady-state costs.

the impulse responses of real variables are almost completely immune against the distorting effects of trend inflation whether trend output growth is deterministic or stochastic, or whether investment shocks are more or less persistent. The response of inflation is persistent and hump-shaped following a monetary policy shock and an investment shock with Taylor contracts but not with Calvo contracts. The Taylor model also provides a better match of key business cycle moments when TFP shocks are more important than investment shocks.

5.1 Impulse Responses: Baseline Parametrization

We focus on the impulse responses of output, consumption and inflation. Our baseline case compares the impulse responses for a level of trend inflation of 0% and 3.52%. The first column of Figure 3 compares impulse responses to a negative shock to the nominal interest rate with Taylor and Calvo contracts. Both models generate persistent and hump-shaped responses of output and consumption following a shock to monetary policy whether trend inflation is 0 or 3.52%. While the responses of output and consumption are stronger and more persistent at medium forecast horizons with Calvo contracts, they are also persistent and hump shaped with Taylor contracts. Therefore, both models meet the challenge raised by Chari et al. (2000).

A notable difference between the two models concerns the response of inflation. With Calvo contracts, the response of inflation to a monetary policy shock is strongest on impact. That is, without the automatic indexation of non-reset wages and prices to inflation, the response of inflation does not display the typical hump-shaped pattern in the Calvo model.[18] By comparison, Taylor contracts help producing a persistent and hump-shaped response of inflation, with a peak occurring 5 quarters after the policy shock. Compared to the Calvo model, a model with Taylor contracts does not have to rely on backward wage and price indexation to be able to produce the hump-shaped pattern in the response of inflation. This also explains why the Taylor model provides a better match of the correlations between nominal and real variables.

The second column of Figure 3 displays the impulse responses to a TFP shock. The shape and magnitude of responses are broadly similar in the two models, with the exception of the response of inflation which is stronger on impact of the shock with Calvo contracts. Following a positive TFP shock, output and consumption weakly rise on impact of the shock, and then gradually increase over medium forecast horizons, to slowly return to their pre-shock level.[19]

[18] A similar finding is reported by Phaneuf, Sims, and Victor (2018). They show that adding a strong working capital channel to Calvo contracts will help produce a response of inflation which is hump shaped without indexation.

[19] This shock also has a contractionary effect on employment (not reported).

The third column of Figure 3 displays responses to an investment shock. An investment shock generates a persistent and hump-shaped response of output in the two models, although it somewhat stronger at medium forecast horizons with Calvo contracts. The response of consumption is weakly positive on impact of a positive investment shock, and rises at medium and longer forecast horizons. The response is however stronger with Calvo contracts. As we saw earlier, the non-negative response of consumption explains why both models are able to produce a positive correlation between consumption growth and investment growth despite a standard specification of preferences. Once more, an important difference between the two models is the response of inflation to an investment shock. While the response of inflation is strongest on impact of an investment shock in the Calvo model, it is hump shaped with Taylor contracts.

Still, another significant difference between the two models is that with Calvo contracts moderate trend inflation has a distorting impact on the impulse responses of output and consumption at medium forecast horizons, and this conditioned on each of the three types of shocks shocks, while it does not with Taylor contracts. In fact, the three shocks have stronger expansionary effects on consumption and output under moderate trend inflation than zero trend inflation.[20]

5.2 Higher Trend Inflation

We have shown that impulse responses are almost completely immune to the distorting effects of a moderate level of trend inflation with Taylor contracts, but not with Calvo contracts. But what if trend inflation reaches a higher level like 7% experienced during the 1970s? The results are presented in Figure 4 where we compare impulse responses corresponding to 0% and 7% trend inflation.

With Calvo contracts, the expansionary effects of the three shocks on output and consumption are stronger with a higher trend inflation, whereas they continue to be almost entirely immune to trend inflation with Taylor contracts. This helps understand why the welfare costs of higher trend inflation are about the same based on non-stochastic steady states and stochastic means with Taylor contracts. The responses of inflation to monetary policy and investment shocks still are hump shaped despite higher trend inflation with Taylor contracts, but not with Calvo contracts.

5.3 More Persistent TFP and Investment Shocks

We now ask how varying the persistence of TFP and investment shocks affects impulse responses in the Calvo and Taylor models. The first case we examine is that of a permanent TFP shock.

[20] See also Ascari, Phaneuf, and Sims (2018).

5.3.1 Permanent TFP Shock

In the literature, TFP shocks are sometime modeled as having a permanent impact on output and labor productivity.[21] We now assume that the TFP shock follows a random-walk process with drift while otherwise keeping our baseline parametrization. Impulse responses are presented in Figure 5 for a trend inflation of 0% and 3.52%.

There is no significant difference in impulse responses to monetary policy and investment shocks. Moderate trend inflation still has distorting effects on the responses of output and consumption with Calvo contracts, but not with Taylor contracts. The one big difference is that with Calvo contracts, the responses of output and consumption are now somewhat less expansionary following a TFP shock at medium forecast horizons when trend inflation gets higher. By contrast, with Taylor contracts there is almost no distorting effect of positive trend inflation on the responses to a permanent TFP shock.

5.3.2 Persistence of Investment Shocks

The investment shock is a stationary AR(1) process. We now assume that the AR(1) parameter of the investment shock is either lower or higher than our baseline of 0.8. Figure 6 displays impulse responses to a positive investment shock in the Calvo and Taylor models for AR(1) coefficients of 0.7, 0.8, 0.9 and 0.99.

With Calvo contracts, there is a strong interaction between the persistence of the investment shock and the distorting effect of trend inflation on impulse responses. For $\rho_I = 0.7$, 0.8 and 0.9, the effects of a positive investment shock on output and consumption are more expansionary with positive trend inflation. However, when ρ_I reaches 0.99, the responses of output and consumption become negative with positive trend inflation and the shapes of the responses are different. Meanwhile, the responses of output and consumption are almost immune to these distorting effects with Taylor contracts.

What explains this "sign flip" in the effect of trend inflation on the response of output (and consumption) as the investment shock gets highly persistent with Calvo contracts? Working from a Calvo model with sticky prices, Ascari (2004) shows that trend inflation flattens the Phillips Curve while at the same time making current inflation more sensitive to expected inflation. The investment shock is an aggregate demand shock which raises current demand for goods and pushes output and inflation in the same direction. With expected inflation held fixed, a flatter Phillips Curve due to the higher inflation trend implies that a positive demand shock ought to have a

[21] See for example Galí (1999).

bigger impact on output. This is exactly what we observe for moderate levels of persistence in the investment shock – output rises by more the higher trend inflation is. By contrast, holding fixed the slope of the Phillips Curve, a heightened sensitivity to the future due to higher trend inflation results in a shock that raises expected inflation and has a smaller impact on output. When the investment shock is sufficiently persistent, this expectations channel is quantitatively more important than the flattening of the Phillips Curve, and trend inflation exerts a dampening effect on the output response to an investment shock.

5.3.3 More Important TFP shocks

We now assume that the TFP shock is more important than the investment shock. It explains 50% of output fluctuations, the investment shock 35%, and the monetary policy shock 15%. We ask how this split affects the fit of Calvo and Taylor contracting models.[22]

Moments predicted by the two models are compared with those in the data in Table 6. The overall impression is that the Taylor model still provides a better fit of the data than the Calvo model. Note in particular that the correlations between nominal and real variables predicted by the Taylor model are even closer to the data than they were with our baseline calibration.

6 CONCLUSION

We have compared the welfare and cyclical implications of positive trend inflation in Taylor and Calvo nominal contracting frameworks. The evidence we provide in this paper gives the Taylor model a significant advantage over that of Calvo. The Calvo model has questionable welfare implications upon varying key parameter values in a plausible range. This is true even for a moderate level of trend inflation. Wage dispersion and the costs of inflation can be so high as to raise serious doubts about the Calvo model. The Taylor model seems more reliable to address issues related to the normative implications of positive trend inflation.

We have also shown that the Taylor model provides a better match of key business cycle moments, notably of the correlations between nominal and real variables. This is true whether investment shocks or TFP shocks are most important in driving business cycle fluctuations. Also, while Taylor contracting generates inflation responses to a monetary policy and an investment shock which are persistent and hump shaped without the help of indexation of wages and prices to inflation, the Calvo model does not.

[22] Note this would not have any effect on the welfare costs of trend inflation conditioned on non-stochastic steady states.

Finally, whereas the impulse responses of real variables are quite sensitive to trend inflation with Calvo contracts, they are almost completely immune to trend inflation under Taylor contracting.

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Table 1: Baseline Parameters

Panel A: Nonshock Parameters

Parameter	Assigned Value	Description
β	0.99	Discount factor
b	0.8	Internal habit formation
η	6	Labor disutility
χ	1	Frisch elasticity
κ	3	Investment adjustment cost
δ	0.025	Depreciation rate
γ_1	0.0457	Utilization adjustment cost linear term
γ_2	0.05	Utilization adjustment cost squared term
F	0.0314	Fixed cost of production.
N_p	5	Number of periods of price contracts
N_w	7	Number of periods of wage contracts
θ	4	Elasticity of substitution: goods
σ	4	Elasticity of substitution: labor
ϕ	0.5	Intermediate input share
α	1/3	Capital share
ρ_i	0.8	Taylor rule smoothing
α_π	1.5	Taylor rule inflation
α_y	0.2	Taylor rule output growth
π	1.0087	Steady State Gross Inflation

Panel B: Steady-State Trend Growth and Shock Parameters

Parameter	Assigned Value	Description
g_A	$1.0022^{1-\phi}$	Gross growth rate of neutral productivity
g_{ε^I}	1.0047	Gross growth rate of relative price of investment
ρ_A	0.95	AR coefficient of neutral productivity shock
ρ_I	0.80	AR coefficient of investment shock
σ_A	0.0031	Standard deviation of neutral productivity shock
σ_I	0.0195	Standard deviation of investment shock
σ_r	0.0021	Standard deviation of monetary policy shock

Note: This table shows the baseline values of parameters used in our quantitative analysis. A description of each parameter is provided in the right column. γ_1 is chosen to be consistent with a steady state normalization of utilization of 1. F is chosen so that profits equal zero in steady state. The standard deviation of each shock is chosen to match the observed volatility of output growth in the data, with the investment shock accounting for 50% of the variance of output growth, the neutral shock 35%, and the monetary shock 15%.

Table 2: Business Cycle Statistics

Panel A: Volatility

	$\sigma\,(\Delta Y)$	$\sigma\,(\Delta C)$	$\sigma\,(\Delta I)$	$\sigma\,(\Delta L)$	$\sigma\,(\pi)$	$\sigma\,(i)$
Data	0.0078	0.0047	0.0202	0.0079	0.0065	0.0082
Calvo	0.0077	0.0041	0.0176	0.0063	0.0025	0.0036
Taylor	0.0077	0.0029	0.0218	0.0070	0.0030	0.0039

Panel B: Correlation

	$\rho(\Delta Y, \Delta C)$	$\rho(\Delta Y, \Delta I)$	$\rho(\Delta Y, \Delta L)$	$\rho(\Delta C, \Delta I)$	$\rho(\Delta Y, \pi)$	$\rho(\Delta C, \pi)$
Data	0.75	0.92	0.63	0.44	-0.37	-0.42
Calvo	0.81	0.96	0.57	0.66	0.07	-0.15
Taylor	0.60	0.96	0.53	0.43	-0.20	-0.37

	$\rho(\Delta I, \pi)$	$\rho(\Delta L, \pi)$	$\rho(\Delta Y, i)$	$\rho(\Delta C, i)$	$\rho(\Delta I, i)$	$\rho(\Delta L, i)$
Data	-0.26	-0.13	-0.33	-0.30	-0.28	-0.20
Calvo	0.19	0.40	-0.07	-0.02	-0.01	-0.05
Taylor	-0.03	0.07	-0.28	-0.41	-0.18	-0.23

Panel C: Autocorrelation

	$\rho(\Delta Y_t, \Delta Y_{t-1})$	$\rho(\Delta Y_t, \Delta Y_{t-2})$	$\rho(\pi_t, \pi_{t-1})$	$\rho(\pi_t, \pi_{t-2})$	$\rho(i_t, i_{t-1})$	$\rho(i_t, i_{t-2})$
Data	0.36	0.34	0.91	0.86	0.95	0.89
Calvo	0.72	0.49	0.84	0.71	0.89	0.80
Taylor	0.68	0.42	0.88	0.73	0.85	0.71

Note: This table shows selected statistics generated from the Calvo and Taylor models. "σ " denotes standard deviation, "Δ " refers to the first difference operator, and ρ is a coefficient of correlation. The variables Y, I, C,L and π are the natural logs of these series. Moments in the data are computed for the sample 1960q1-2007q3 and are shown in parentheses.

Table 3: Price and Wage Dispersion in the Calvo and Taylor Models.

Panel A. Calvo: Price and Wage Dispersion

	0	2	4	7
υ^p_{ss}	1.0000	1.0003	1.0013	1.0043
υ^p_m	1.0001	1.0004	1.0014	1.0041
υ^w_{ss}	1.0212	1.1004	1.3310	5.2981
υ^w_m	1.0251	1.1090	1.3605	8.2445

Panel B. Taylor: Price and Wage Dispersion

	0	2	4	7
υ^p_{ss}	1.0000	1.0001	1.0004	1.0011
υ^p_m	1.0001	1.0001	1.0004	1.0012
υ^w_{ss}	1.0054	1.0190	1.0403	1.0854
υ^w_m	1.0071	1.0206	1.0419	1.0870

Table 4: Welfare Costs in the Calvo and Taylor Models.

Panel A. Calvo

	0-4	0-7	2-4	3-7
λ_{ss}	12.21	56.22	8.99	52.93
λ_m	13.29	66.09	9.83	63.31

Panel B. Taylor

	0-4	0-7	2-4	3-7
λ_{ss}	1.71	3.94	1.07	2.84
λ_m	1.73	3.96	1.08	2.85

Table 5: Sensitivity of Steady-State Inflation Costs to σ Under Taylor Contracting.

Panel A. $N_w = 7$.

	0-4	0-7	2-4	3-7
$\sigma = 6$	1.71	3.94	1.07	2.84
$\sigma = 8$	2.84	6.30	1.75	4.47

Panel B. $N_w = 9$.

	0-4	0-7	2-4	3-7
$\sigma = 6$	2.76	6.16	1.70	4.39
$\sigma = 8$	4.55	9.66	2.76	6.78

Table 6: Business Cycle Statistics: More Important TFP Shocks

Panel A: Volatility

	$\sigma\,(\Delta Y)$	$\sigma\,(\Delta C)$	$\sigma\,(\Delta I)$	$\sigma\,(\Delta L)$	$\sigma\,(\pi)$	$\sigma\,(i)$
Data	0.0078	0.0047	0.0202	0.0079	0.0065	0.0082
Calvo	0.0074	0.0043	0.0155	0.0065	0.0026	0.0035
Taylor	0.0077	0.0033	0.0201	0.0076	0.0032	0.0040

Panel B: Correlation

	$\rho(\Delta Y, \Delta C)$	$\rho(\Delta Y, \Delta I)$	$\rho(\Delta Y, \Delta L)$	$\rho(\Delta C, \Delta I)$	$\rho(\Delta Y, \pi)$	$\rho(\Delta C, \pi)$
Data	0.75	0.92	0.63	0.44	-0.37	-0.42
Calvo	0.85	0.96	0.45	0.71	-0.12	-0.33
Taylor	0.71	0.95	0.41	0.56	-0.35	-0.49

	$\rho(\Delta I, \pi)$	$\rho(\Delta L, \pi)$	$\rho(\Delta Y, i)$	$\rho(\Delta C, i)$	$\rho(\Delta I, i)$	$\rho(\Delta L, i)$
Data	-0.26	-0.13	-0.33	-0.30	-0.28	-0.20
Calvo	0.02	0.35	-0.15	-0.12	-0.10	-0.09
Taylor	-0.18	0.05	-0.33	-0.49	-0.24	-0.22

Panel C: Autocorrelation

	$\rho(\Delta Y_t, \Delta Y_{t-1})$	$\rho(\Delta Y_t, \Delta Y_{t-2})$	$\rho(\pi_t, \pi_{t-1})$	$\rho(\pi_t, \pi_{t-2})$	$\rho(i_t, i_{t-1})$	$\rho(i_t, i_{t-2})$
Data	0.36	0.34	0.91	0.86	0.95	0.89
Calvo	0.76	0.54	0.82	0.68	0.90	0.81
Taylor	0.73	0.48	0.87	0.71	0.85	0.72

Note: This table shows selected statistics generated from the Calvo and Taylor models. "σ " denotes standard deviation, "Δ " refers to the first difference operator, and ρ is a coefficient of correlation. The variables Y, I, C,L and π are the natural logs of these series. Moments in the data are computed for the sample 1960q1-2007q3 and are shown in parentheses.

Figure 1: Responses of Consumption to an Investment Shock

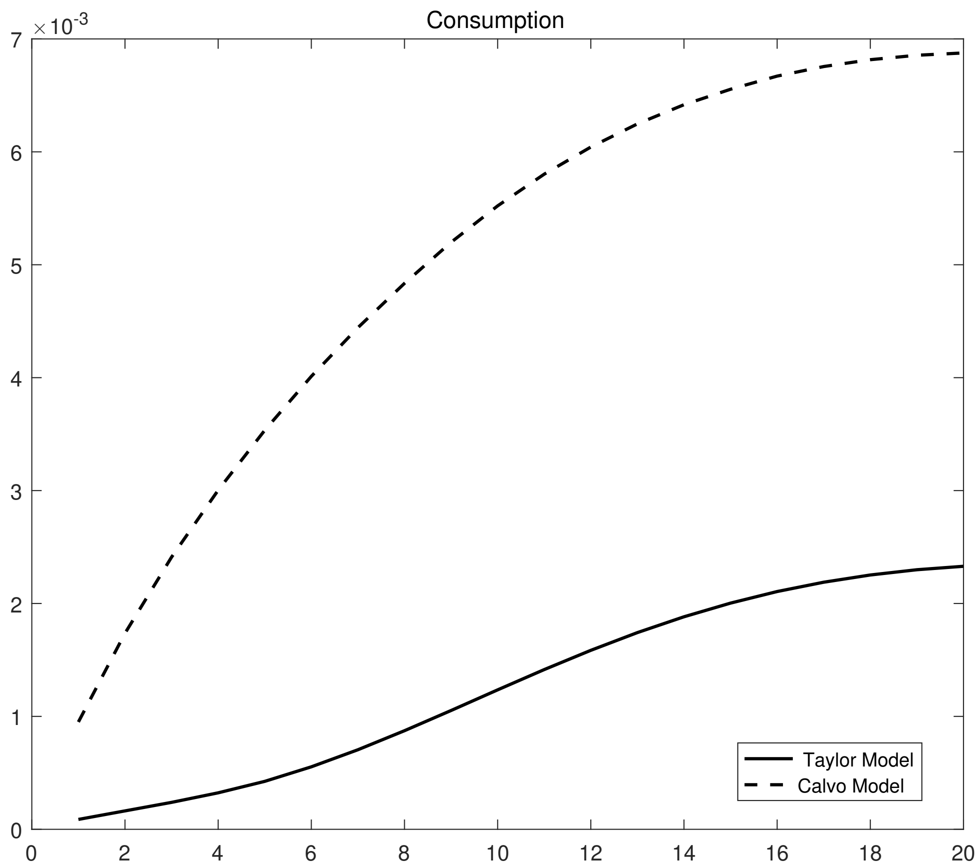


Figure 2: Sensitivity of Steady-State Wage Dispersion to Key Parameters

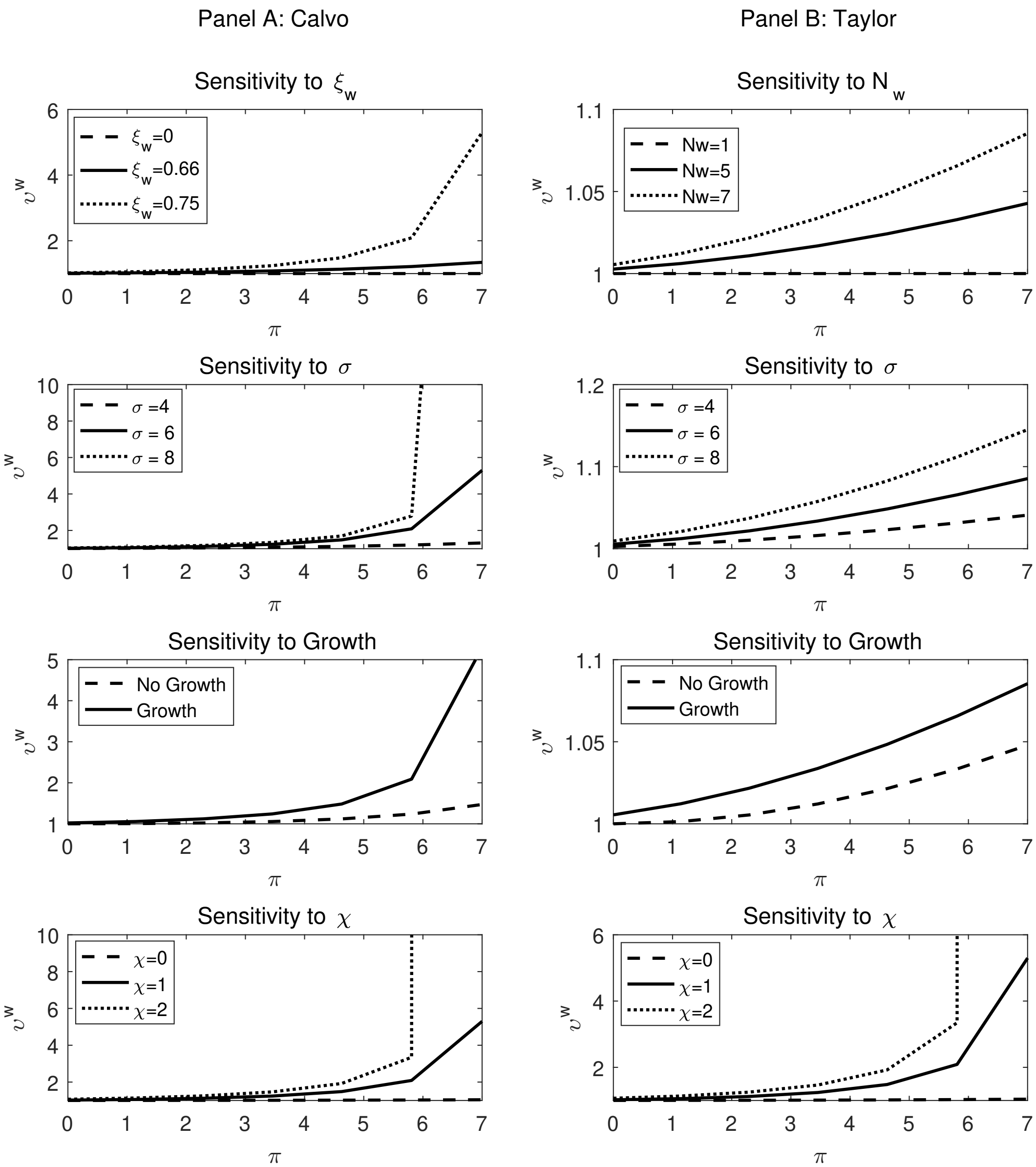


Figure 3: Impulse Response Functions of Key Macroeconomic Variables With Deterministic Growth

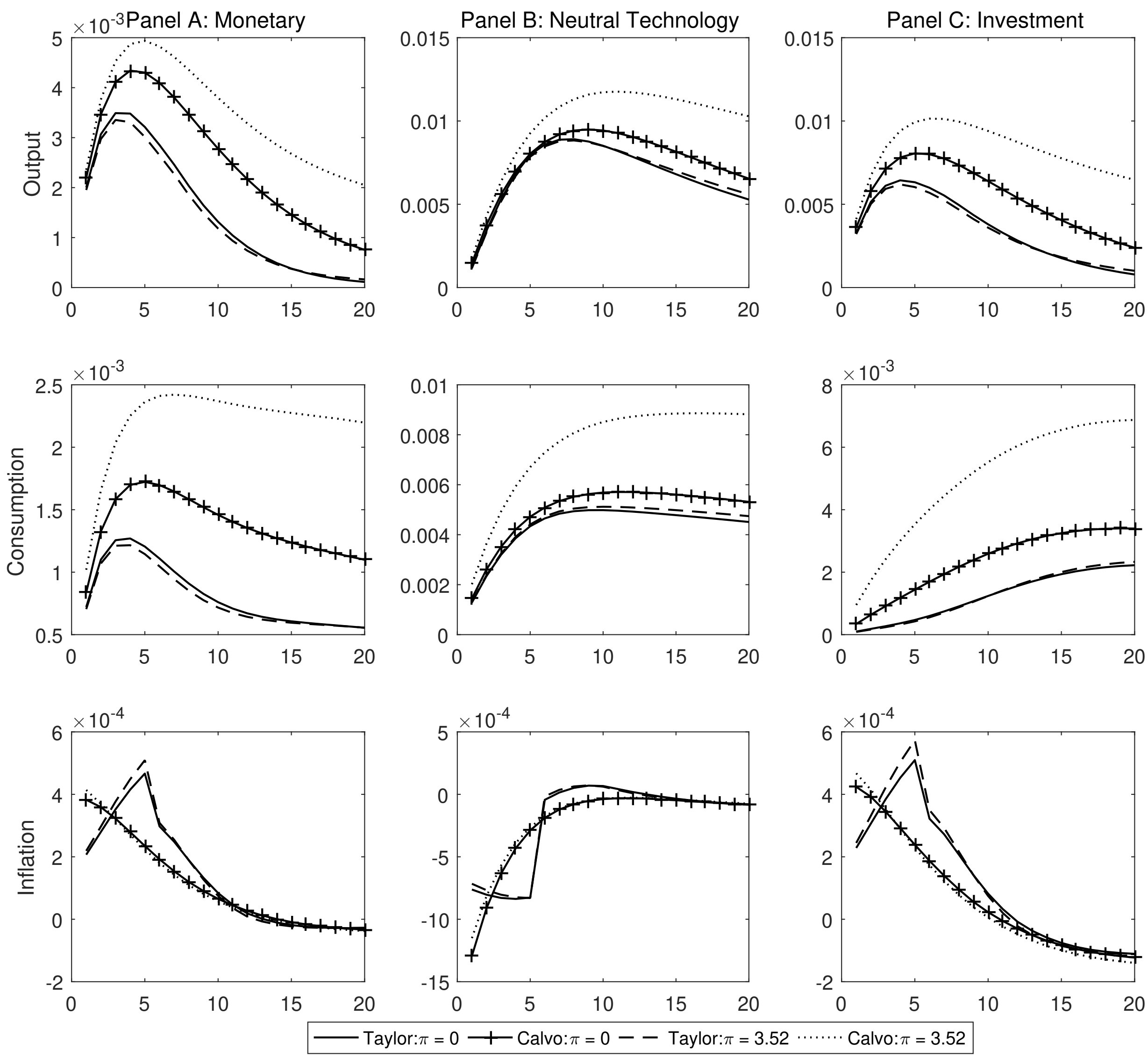


Figure 4: Impulse Response Functions of Key Macroeconomic Variables to Higher Trend Inflation

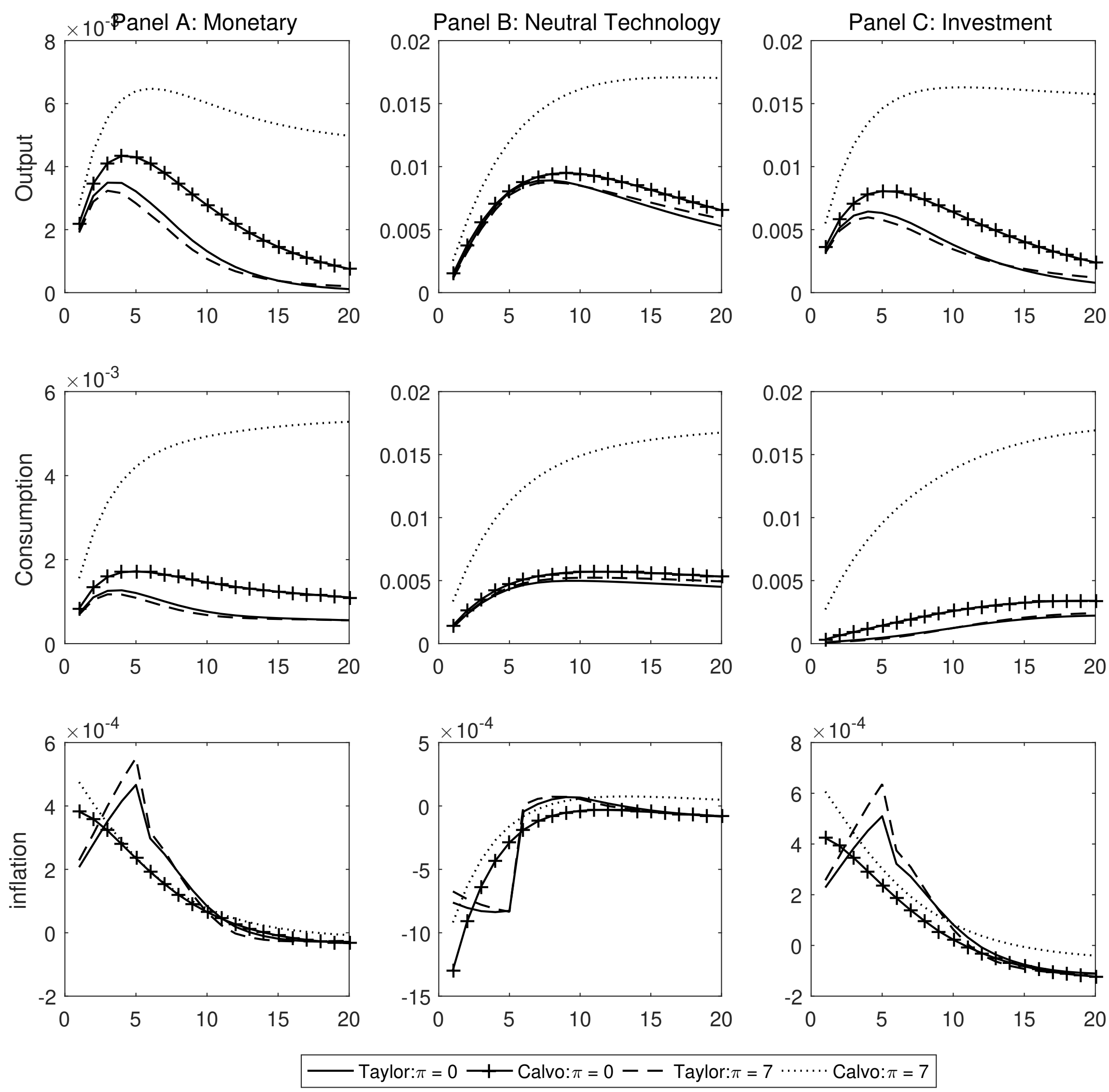


Figure 5: Impulse Response Functions of Key Macroeconomic Variables With Stochastic Growth

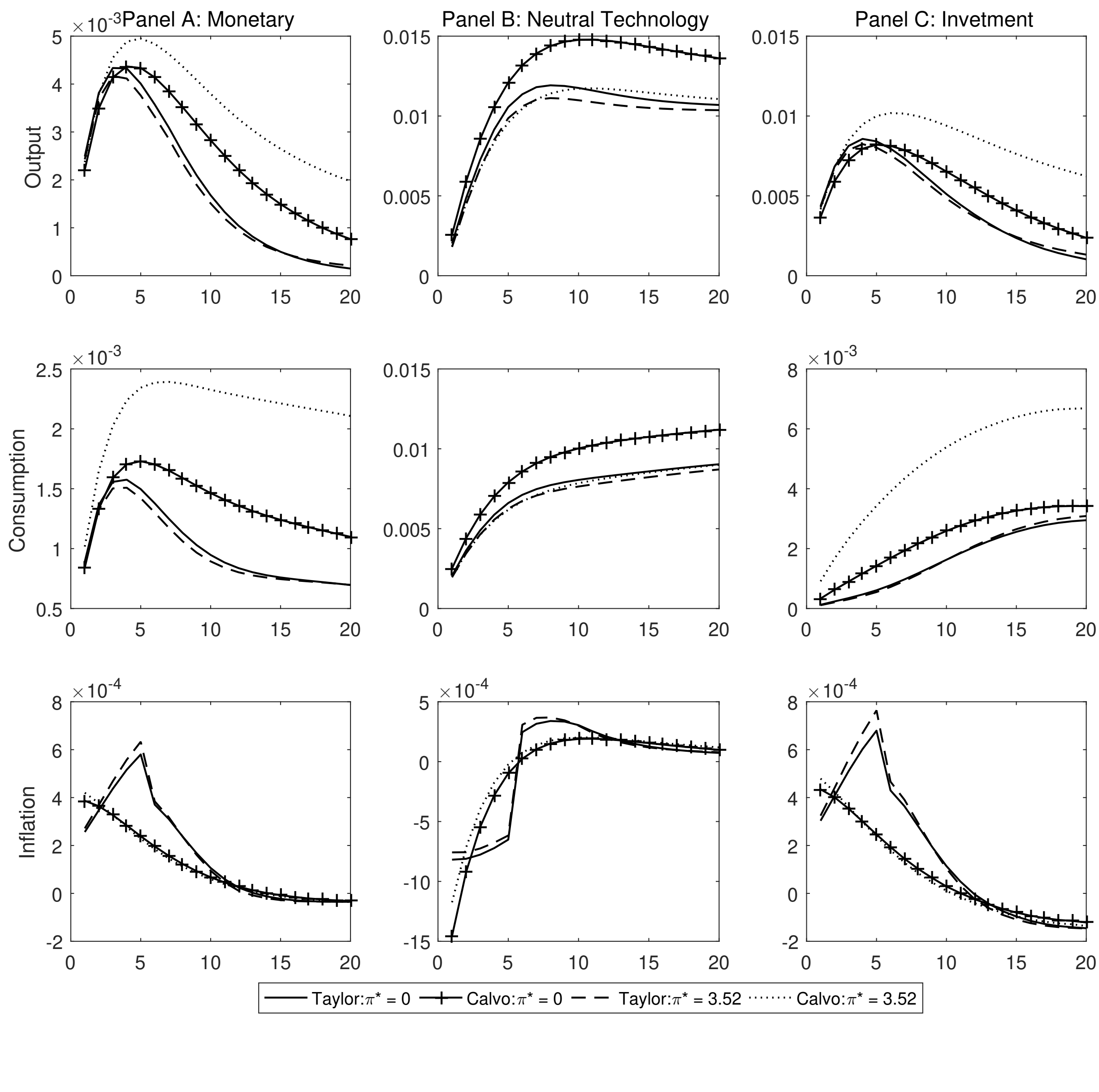
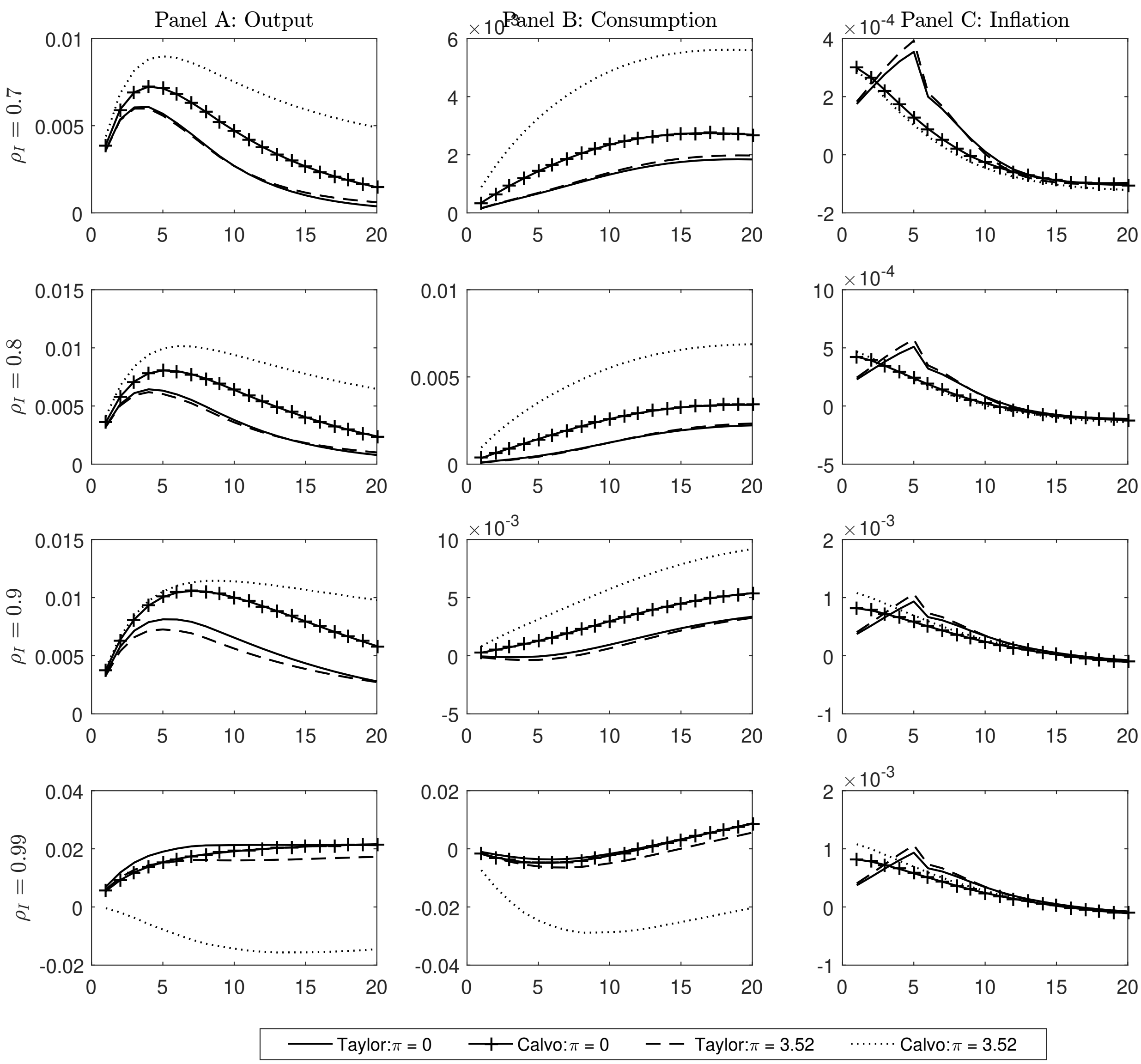


Figure 6: More or Less Persistent Stationary Investment Shock



A Set of Equilibrium Conditions for the Benchmark Model

This appendix lists the full set of equilibrium conditions for the benchmark model. These conditions are expressed in stationary transformations of variables, e.g. $\widetilde{X}_t = \frac{X_t}{\Upsilon_t}$ for most variables.

$$\widetilde{\lambda}^r_t = \frac{1}{\widetilde{C}_t - hg_Y^{-1}\widetilde{C}_{t-1}} - E_t \frac{h\beta}{g_Y\widetilde{C}_{t+1} - h\widetilde{C}_t} \tag{A1}$$

$$\widetilde{r}^k_t = \gamma_1 + \gamma_2(u_t - 1) \tag{A2}$$

$$\widetilde{\lambda}^r_t = \widetilde{\mu}_t \left(1 - \frac{k}{2}\left(\frac{\widetilde{I}_t}{\widetilde{I}_{t-1}}g_Y - g_Y\right)^2 - \kappa\left(\frac{\widetilde{I}_t}{\widetilde{I}_{t-1}}g_Y - g_Y\right)\frac{\widetilde{I}_t}{\widetilde{I}_{t-1}}g_Y\right) + \beta E_t g_Y^{-1}\widetilde{\mu}_{t+1}\kappa\left(\frac{\widetilde{I}_{t+1}}{\widetilde{I}_t}g_Y - g_Y\right)\left(\frac{\widetilde{I}_{t+1}}{\widetilde{I}_t}g_Y\right)^2 \tag{A3}$$

$$g_Y g_{\varepsilon^I}\widetilde{\mu}_t = \beta E_t \widetilde{\lambda}^r_{t+1}\left(\widetilde{r}^k_{t+1}u_{t+1} - \left(\gamma_1(u_{t+1} - 1) + \frac{\gamma_2}{2}(u_{t+1} - 1)^2\right)\right) + \beta(1-\delta)E_t\widetilde{\mu}_{t+1} \tag{A4}$$

$$\widetilde{\lambda}^r_t = \beta E_t g_Y^{-1} R_t \pi^{-1}_{t+1}\widetilde{\lambda}^r_{t+1} \tag{A5}$$

$$\widetilde{w}^*_t = \frac{\sigma}{\sigma - 1}\frac{\widetilde{w}_{1,t}}{\widetilde{w}_{2,t}} \tag{A6}$$

$$\widetilde{w}_{1,t} = \sum_{h=0}^{6} \eta\beta^h g_Y^{h\sigma(1+\chi)}\left(\frac{\widetilde{w}_{t+h}}{w^*_t}\right)^{\sigma(1+\chi)} \pi^{\sigma(1+\chi)}_{t+1,t+h} L^{1+\chi}_{t+h} \tag{A7}$$

$$\widetilde{w}_{2,t} = \sum_{h=0}^{6} \beta^h g_Y^{h(\sigma-1)}\pi^{(\sigma-1)}_{t+1,t+h}\left(\frac{\widetilde{w}_{t+h}}{w^*_t}\right)^{\sigma}\widetilde{\lambda}^r_{t+h}L_{t+h} \tag{A8}$$

$$\widetilde{\widetilde{K}}_t = g_{\varepsilon^I}g_Y\alpha(1-\phi)\frac{mc_t}{\widetilde{r}^k_t}\left(v^p_t\widetilde{X}_t + F\right) \tag{A9}$$

$$L_t = (1-\alpha)(1-\phi)\frac{mc_t}{\widetilde{w}_t}\left(v^p_t\widetilde{X}_t + F\right) \tag{A10}$$

$$\widetilde{\Gamma}_t = \phi mc_t\left(v^p_t\widetilde{X}_t + F\right) \tag{A11}$$

$$p^*_t = \frac{\theta}{\theta - 1}\frac{p_{1,t}}{p_{2,t}} \tag{A12}$$

$$p_{1,t} = \sum_{h=0}^{4}\beta^h\widetilde{\lambda}^r_{t+h}mc_{t+h}\pi^{\theta}_{t+1,t+h}X_{t+h} \tag{A13}$$

$$p_{2,t} = \sum_{h=0}^{4}\beta^h\widetilde{\lambda}^r_{t+h}\pi^{\theta-1}_{t+1,t+h}X_{t+h} \tag{A14}$$

$$1 = \frac{1}{5}\sum_{h=0}^{N_p-1}\left(\frac{p^*_{t-h}}{\pi_{t,t-h+1}}\right)^{1-\theta} \tag{A15}$$

$$\widetilde{w}^{1-\sigma}_t = \frac{1}{7}\sum_{h=0}^{6}\left(\frac{\widetilde{w}^*_{t-h}g_Y^{-h}}{\pi_{t,t-h+1}}\right)^{1-\sigma} \tag{A16}$$

$$Y_t = X_t - \Gamma_t \tag{A17}$$

$$v_t^p \widetilde{X}_t = \widetilde{\Gamma}_t^{\phi} \widetilde{\widehat{K}}_t^{\alpha(1-\phi)} L_t^{(1-\alpha)(1-\phi)} g_Y^{\alpha(\phi-1)} g_{\varepsilon^I}^{\alpha(\phi-1)} - F \tag{A18}$$

$$\widetilde{Y}_t = \widetilde{C}_t + \widetilde{I}_t + g_Y^{-1} g_{\varepsilon^I}^{-1} \left(\gamma_1 (u_t - 1) + \frac{\gamma_2}{2} (u_t - 1)^2 \right) \widetilde{K}_t \tag{A19}$$

$$\widetilde{K}_{t+1} = \left(1 - \frac{\kappa}{2} \left(\frac{\widetilde{I}_t}{\widetilde{I}_{t-1}} g_Y - g_Y \right)^2 \right) \widetilde{I}_t + (1-\delta) g_Y^{-1} g_{\varepsilon^I}^{-1} \widetilde{K}_t \tag{A20}$$

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R} \right)^{\rho_R} \left[\left(\frac{\pi_t}{\pi} \right)^{\alpha_\pi} \left(\frac{\widetilde{Y}_t}{\widetilde{Y}_{t-1}} \right)^{\alpha_y} \right]^{1-\rho_R} \varepsilon_t^r \tag{A21}$$

$$\widetilde{\widehat{K}}_t = u_t \widetilde{K}_t \tag{A22}$$

$$v_t^p = \frac{1}{5} \sum_{h=0}^{4} \left(\frac{p_{t-h}^*}{\pi_{t,t-h+1}} \right)^{-\theta} \tag{A23}$$

$$v_t^w = \frac{1}{7} \sum_{h=0}^{6} \left(\frac{w_t}{w_{t-h}^*} \pi_{t,t-h+1} \right)^{\sigma(1+\chi)} \tag{A24}$$

$$\widetilde{V}_t^c = \ln \left(\widetilde{C}_t - b g_Y^{-1} \widetilde{C}_{t-1} \right) + \beta g_Y E_t \widetilde{V}_{t+1}^c \tag{A25}$$

$$V_t^n = -\eta \frac{L_t^{1+\chi}}{1+\chi} v_t^w + \beta E_t V_{t+1}^n \tag{A26}$$

$$V_t = \widetilde{V}_t^c + \widetilde{V}_t^n + \frac{\beta \ln g_Y}{(1-\beta)^2} \tag{A27}$$

$$\widetilde{A}_t = \left(\widetilde{A}_{t-1} \right)^{\rho_A} \exp \left(\sigma_t^A \varepsilon_t^A \right) \tag{A28}$$

$$\vartheta_t = (\vartheta_{t-1})^{\rho_I} \exp(\sigma_I \varepsilon_t^I) \tag{A29}$$

Equation (A1) defines the real multiplier on the flow budget constraint. (A2) is the optimality condition for capital utilization. (A3) and (A4) are the optimality conditions for the household choice of investment and next period's stock of capital, respectively. The Euler equation for bonds is given by (A5). (A6)-(A8) describe optimal wage setting for households given the opportunity to adjust their wages. Optimal factor demands are given by equations (A9)-(A11). Optimal price setting for firms given the opportunity to change their price is described by equations (A12)-(A14). The evolutions of aggregate inflation and the aggregate real wage index are given by (A15) and (A16), respectively. Net output is gross output minus intermediates, as given by (A17). The aggregate production function for gross output is (A18). The aggregate resource constraint is (A19), and the law of motion for physical capital is given by (A20). The Taylor rule for monetary policy is (A21). Capital services are defined as the product of utilization and physical capital, as in (A22). The law of motion for price dispersion and wage dispersion is given by (A23) and (A24).

Recursive utility from consumption and labor are given by (A25)-(A26). (A28) is the aggregate welfare. (A28)-(A29) give the assumed laws of motion for neutral technology and investment shocks.

B Equilibrium Conditions Under Calvo-Contracts

Under Calvo-contracts the set of equilibrium conditions are the same as the benchmark model except for the equations describing *(i)* the optimal wage setting (A6)-(A8), *(ii)* the optimal price setting (A12)-(A14), *(iii)* the evolution of aggregate inflation (A15), *(iv)* the aggregate wage index (A16) and *(v)* the law of motion for price dispersion and wage dispersion (A23 and A24). Below we report the set of equations specific to Calvo-contract.

$$\widetilde{w}_{1,t} = \eta \left(\frac{\widetilde{w}_t}{\widetilde{w}_t^*}\right)^{\sigma(1+\chi)} L_t^{1+\chi} + \beta\xi_w E_t \pi_{t+1}^{\sigma(1+\chi)} \left(\frac{\widetilde{w}_{t+1}^*}{\widetilde{w}_t^*}\right)^{\sigma(1+\chi)} g_Y^{\sigma(1+\chi)} \widetilde{w}_{1,t+1} \tag{B1}$$

$$\widetilde{w}_{2,t} = \widetilde{\lambda}_t^r \left(\frac{\widetilde{w}_t}{\widetilde{w}_t^*}\right)^{\sigma} L_t + \beta\xi_w E_t \pi_{t+1}^{\sigma-1} \left(\frac{\widetilde{w}_{t+1}^*}{\widetilde{w}_t^*}\right)^{\sigma} g_Y^{\sigma-1} \widetilde{w}_{2,t+1} \tag{B2}$$

$$p_{1,t} = \widetilde{\lambda}_t^r mc_t \widetilde{Y}_t + \xi_p \beta \pi_{t+1}^{\theta} p_{1,t+1} \tag{B3}$$

$$p_{2,t} = \widetilde{\lambda}_t^r \widetilde{Y}_t + \xi_p \beta \pi_{t+1}^{\theta-1} p_{2,t+1} \tag{B4}$$

$$1 = \xi_p \pi_t^{\theta-1} + (1-\xi_p) p_t^{*1-\theta} \tag{B5}$$

$$\widetilde{w}_t^{1-\sigma} = \xi_w g_Y^{\sigma-1} \widetilde{w}_{t-1}^{1-\sigma} \pi_t^{\sigma-1} + (1-\xi_w) \widetilde{w}_t^{*1-\sigma} \tag{B6}$$

$$v_t^p = (1-\xi_p) p_t^{*-\theta} + \xi_p \pi_t^{\theta} v_{t-1}^p \tag{B7}$$

$$v_t^w = (1-\xi_w) \left(\frac{\widetilde{w}_t^*}{\widetilde{w}_t}\right)^{-\sigma(1+\chi)} + \xi_w \left(\frac{\widetilde{w}_{t-1}}{\widetilde{w}_t g_Y}\right)^{-\sigma(1+\chi)} \pi_t^{\sigma(1+\chi)} v_{t-1}^w \tag{B8}$$