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How much inflation is necessary to grease the wheels? ☆

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ABSTRACT

Tobin's proposition that inflation "greases" the wheels of the labor market is studied using a simple dynamic stochastic general equilibrium model with asymmetric wage adjustment costs. The simulated method of moments is used to estimate the nonlinear model based on its second-order approximation. Optimal inflation is determined by a benevolent government that maximizes the households' welfare. Econometric results indicate that nominal wages are downwardly rigid and that the optimal level of grease inflation for the U.S. economy is about 0.35% per year, with a 95% confidence interval ranging from 0.04% to 0.87%.

1. Introduction

In his presidential address to the American Economic Association in 1971, James Tobin suggests that a positive rate of inflation may be socially beneficial in an economy where nominal prices—in particular, nominal wages—are more downwardly rigid than upwardly rigid (Tobin, 1972). To illustrate Tobin's argument, suppose that the economy is hit by an exogenous shock that requires a decline in the real wage, such as a negative productivity shock. Two plausible adjustment paths are to keep the price level fixed and cut nominal wages, and to keep the nominal wages fixed and increase the price level. Tobin claims that the former path, which is characterized by a zero inflation rate, may involve significant social costs when nominal wages are downwardly rigid. Instead, the latter path, which features a positive inflation rate, may deliver the same reduction in the real wage at a lower cost. The idea that inflation eases the adjustment of the labor market by speeding the decline of real wages following an adverse shock is described in the literature by the catchphrase that inflation "greases the wheels of the labor market."

This paper uses a stylized dynamic stochastic general equilibrium model with asymmetric nominal rigidities to formally examine Tobin's proposition and to construct a theory-based estimate of the optimal amount of "grease" inflation for the U.S. economy. First, we develop a positive model where monetary policy is described by a Taylor-type rule and estimate the

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model by the Simulated Method of Moments (SMM). Then, using the SMM estimates of the structural parameters, we perform a normative analysis where optimal inflation is determined by a benevolent government that maximizes the households' welfare under commitment (i.e., the Ramsey policy). Finally, an estimate of optimal grease inflation is constructed by measuring how much additional inflation asymmetric costs yield compared to symmetric costs.

This subject matter is important because there is currently a discrepancy between economic theory—that prescribes a zero-to-negative optimal inflation rate—and monetary policy in practice—that explicitly or implicitly targets low, but strictly positive, inflation rates. The theoretical result that optimal inflation is negative is driven by Friedman's (1969) rule. Under Friedman's rule a rate of deflation equal to the real return on capital eliminates the wedge between social marginal cost of producing money, which is essentially zero, and the private marginal cost of carrying money, which is the nominal interest rate. Additional considerations like fiscal policy and price rigidity, deliver optimal inflation rates that are larger than Friedman's rule but still negative.[1]

The idea that wages are more downwardly (than upwardly) rigid dates at least to Keynes (1936, Chapter 21). Empirical evidence on downward wage rigidity using micro-level data takes the form of attitude surveys and the empirical analysis of wage distributions. Bewley (1995) and Campbell and Kamlani (1997) find that employers cut wages only in cases of extreme financial distress while worrying about the effect of nominal wage cuts on the worker's morale. Kahneman et al. (1986) find that individuals dislike nominal wage cuts more than an alternative scenario even when both of them involve the same real wage cut. Researchers who study the distribution of nominal wage changes at the individual level point out that it features a peak at zero and is positively skewed with very few nominal wage cuts. See, for example, McLaughlin (1994), Akerlof et al. (1996) and Card and Hyslop (1997) for the United States; Kuroda and Yamamoto (2003) for Japan; Castellanos et al. (2004) for Mexico; and Fehr and Goette (2005) for Switzerland. Holden and Wulfsberg (2008) find similar properties in the distribution of industry wage changes, which suggests that downward wage rigidity at the individual level survives aggregation. Institutional characteristics, like laws forbidding nominal wage cuts (Mexico) or making the current nominal wage the default outcome when union-employer negotiations fail, may also contribute to downward nominal wage rigidity.

This paper reports four main results. First, U.S. prices and wages are rigid, but in the case of wages, rigidity is asymmetric in the sense that they are more downwardly than upwardly rigid. This conclusion is based on an econometric estimate of the asymmetry in the wage adjustment cost function. Second, the Ramsey policy prescribes a (gross) rate of price inflation of about 1.0035 and an optimal grease inflation of about 0.35% per year. This result is driven by prudence, meaning that the benevolent planner prefers the systematic, but small, price and wage adjustment costs associated with a positive inflation rate rather than taking the chance of incurring the large adjustment costs associated with nominal wage decreases. Third, asymmetry in wage adjustment costs delivers non-trivial implications for optimal responses following a productivity shock. Finally, in the case where monetary policy were implemented by a strict inflation target, the optimal target is substantially larger than the unconditional inflation mean obtained under the Ramsey policy.

The paper is organized as follows. Section 2 constructs a model with imperfect competition and asymmetric wage adjustment costs where monetary policy is implemented by means of a Taylor-type rule. Section 3 presents the econometric methodology and reports estimates of the structural parameters. Section 4 describes the problem of the Ramsey planner, computes an estimate of optimal grease inflation, examines the dynamic implications of the model, and studies strict inflation targeting to better understand the degree of optimal grease inflation under the Ramsey policy. Finally, Section 5 concludes and discusses current and future work in our research agenda on asymmetric nominal rigidities.

2. The model

The model developed in this section is a small-scale, dynamic stochastic general equilibrium model with price and wage rigidities, and is representative of the recent monetary policy literature. The main modeling contribution is the use of a general functional form for adjustment costs that permits downward nominal wage rigidity as a special case.

2.1. Households

The economy is populated by a continuum of infinitely-lived households indexed by $n \in [0, 1]$. Households are identical, except for the fact that they have differentiated job skills which give them monopolistically competitive power over their labor supply. At time τ, household n maximizes

$$E_\tau \sum_{t=\tau}^{\infty} \beta^{(t-\tau)} \left(\frac{(c_t^n)^{1-\rho}}{1-\rho} - \chi h_t^n \right) u_t, \tag{1}$$

[1] See, among many others, Rotemberg and Woodford (1997), Chari and Kehoe (1999), Teles (2003), Khan et al. (2003), Kim and Henderson (2005), and Schmitt-Grohe and Uribe (2004a, 2006), as well as references therein. In addition to the asymmetric nominal rigidities studied here, another reason for positive inflation is the zero lower bound on nominal interest rates (see, for example, Billi, 2005).

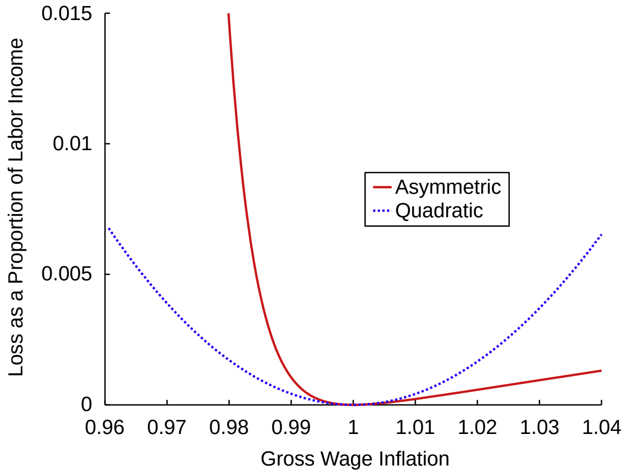

Fig. 1. Adjustment cost functions. The asymmetric-cost function corresponds to the special case where nominal wages are downwardly rigid ($\psi > 0$). The quadratic-cost function is the special case where $\psi \to 0$.

where E_τ denotes the expectation conditional on information available at time τ, $\beta \in (0,1)$ is the subjective discount factor, c_t^n is consumption, h_t^n is hours worked, ρ and χ are positive preference parameters, and u_t is an aggregate preference shock. The representation of the household's disutility of labor is based on the indivisible-labor model due to Hansen (1985). The preference shock shifts the overall utility level and disturbs the household's intertemporal substitution of consumption.[2] This shock follows the stochastic process

$$\ln(u_t) = \zeta \ln(u_{t-1}) + \upsilon_t,$$

where $\zeta \in (-1,1)$ and υ_t is an identically and independently distributed (i.i.d.) innovation with zero mean and variance σ_υ^2. Consumption is an aggregate of differentiated goods indexed by $i \in [0,1]$

$$c_t^n = \left(\int_0^1 (c_{i,t}^n)^{1/\mu} \, di \right)^{\mu}, \tag{2}$$

where $\mu > 1$. In this specification, the elasticity of substitution between goods is constant and equal to $\mu/(\mu-1)$. When $\mu \to 1$, goods become perfect substitutes and the elasticity of substitution tends to infinity. When $\mu \to \infty$, the aggregator becomes the Cobb–Douglas function and the elasticity is unity.

As monopolistic competitors, households choose their wage and labor supply taking as given the firms' demand for their labor type. Labor market frictions induce a cost in the adjustment of nominal wages. This cost takes the form of the linex function (as introduced by Varian, 1974)

$$\Phi_t^n = \Phi(W_t^n/W_{t-1}^n) = \phi \left(\frac{\exp(-\psi(W_t^n/W_{t-1}^n - 1)) + \psi(W_t^n/W_{t-1}^n - 1) - 1}{\psi^2} \right), \tag{3}$$

where W_t^n is the nominal wage, and ϕ and ψ are cost parameters. This functional form is attractive for four reasons. First, the cost depends on both the magnitude and sign of the wage adjustment. Consider, for example, the case where $\psi > 0$. As W_t^n increases over W_{t-1}^n, the linear term dominates and the cost associated with wage increases rises linearly. In contrast, as W_t^n decreases below W_{t-1}^n, it is the exponential term that dominates and the cost associated with wage decreases rises exponentially. Hence, nominal wage decreases involve a larger frictional cost than increases, even if the two percentage magnitudes are the same. The converse is true in the case where $\psi < 0$. Second, the function nests the quadratic form as a special case when ψ tends to zero.[3]Thus, the comparison between the model with asymmetric costs and a restricted version with quadratic costs is straightforward. Third, the linex function is differentiable everywhere and strictly convex for any $\phi > 0$. Finally, this function does not preclude nominal wage cuts that, although relatively rare, are observed in micro-level data. In order to develop further the readers' intuition, Fig. 1 plots the quadratic and asymmetric-cost functions, the latter in the case of a positive ψ.

There are two types of financial assets: one-period nominal bonds and Arrow–Debreu state-contingent securities. The household enters period t with B_{t-1} nominal bonds and a portfolio A_{t-1} of state-contingent securities, and then receives

[2] In preliminary work, we studied a more general formulation with an aggregate shock to the disutility of labor as well. However, results are very similar to the ones reported here because this shock behaves like the productivity shock introduced below in Section 2.2 and its estimated variance is relatively small.

[3] To see this, take the limit of $\Phi(\cdot)$ as $\psi \to 0$ by applying l'Hôpital's rule twice.

wages, interests, dividends and state-contingent payoffs. These resources are used to finance consumption and the acquisition of financial assets to be carried out to the next period. Expressed in real terms, the household's budget constraint is

$$c_t^n + \frac{Q_{t,t+1}A_t^n - A_{t-1}^n}{P_t} + \frac{B_t^n - I_{t-1}B_{t-1}^n}{P_t} = \left(\frac{W_t^n h_t^n}{P_t}\right)(1-\Phi_t^n) + \frac{D_t^n}{P_t},$$

for $t = \tau, \tau+1, \ldots, \infty$, where $Q_{t,t+1}$ is a vector of prices, I_t is the gross nominal interest rate, D_t^n are dividends and

$$P_t = \left(\int_0^1 (P_{i,t})^{1/(1-\mu)}\, di\right)^{(1-\mu)}, \tag{4}$$

is an aggregate price index with $P_{i,t}$ denoting the price of good i. Without loss of generality, it is assumed that the wage adjustment cost is paid by the household. Prices are measured in terms of a unit of account called "money," but the economy is cashless otherwise.

The household's utility maximization involves choosing $\{c_t^n, A_t^n, B_t^n, W_t^n, h_t^n\}_{t=\tau}^{\infty}$ subject to the initial asset holdings and the sequence of wages, labor demand, budget constraints, and a no-Ponzi-game condition. First-order necessary conditions include

$$(c_t^n)^{-\rho} u_t = \eta_t, \tag{5}$$

whereby the marginal utilities consumption and wealth are equalized at the optimum

$$\eta_t = \beta I_t E_t\left(\frac{\eta_{t+1}}{\Pi_{t+1}}\right), \tag{6}$$

where $\Pi_t = P_t/P_{t-1}$ is gross price inflation, and

$$\frac{\eta_t h_t^n}{P_t}\left(\left(\frac{1}{\theta-1}\right)(1-\Phi_t^n) + \left(\frac{W_t^n}{W_{t-1}^n}\right)(\Phi_t^n)'\right) = \frac{\eta_t}{P_t}(h_t^n(1-\Phi_t^n)) + \frac{\theta u_t}{\theta-1}\left(\frac{h_t^n}{W_t^n}\right) + \beta E_t\left(\frac{\eta_{t+1}}{P_{t+1}}\left(\frac{W_{t+1}^n}{W_t^n}\right)^2 h_{t+1}^n(\Phi_{t+1}^n)'\right), \tag{7}$$

where $\theta/(\theta-1)$ is the elasticity of substitution between labor types (as specified below in the firms' problem), and $(\Phi_t^n)'$ denotes the derivative of the cost function with respect to its argument.[4] Condition (7), usually referred to as the wage Phillips curve, equates the marginal costs and benefits of increasing W_t^n. The costs are the decrease in hours worked as firms substitute away from the more expensive labor input, and the wage adjustment cost. The benefits are the increase in labor income per hour worked, the increase in leisure time as firms reduce their demand for type-n labor, and the reduction in the future expected wage adjustment cost. Given nominal consumption expenditures, the optimal consumption of good i satisfies

$$c_{i,t}^n = \left(\frac{P_{i,t}}{P_t}\right)^{-\mu/(\mu-1)} c_t^n. \tag{8}$$

2.2. Firms

Each firm produces a differentiated good $i \in [0,1]$ using a production function featuring decreasing returns to scale

$$y_{i,t} = x_t h_{i,t}^{1-\alpha}, \tag{9}$$

where $y_{i,t}$ is output of good i, $h_{i,t}$ is labor input, $\alpha \in (0,1)$ is a production parameter, and x_t is an exogenous productivity shock. The productivity shock follows the process:

$$\ln(x_t) = \xi \ln(x_{t-1}) + \varepsilon_t,$$

where $\xi \in (-1,1)$ and ε_t is an i.i.d. innovation with mean zero and variance σ_ε^2 and independent of υ_t. Labor input is an aggregate of heterogeneous labor supplied by households

$$h_{i,t} = \left(\int_0^1 (h_{i,t}^n)^{1/\theta}\, dn\right)^{\theta}, \tag{10}$$

where $\theta > 1$. The price of the labor input is

$$W_{i,t} = \left(\int_0^1 (W_t^n)^{1/(1-\theta)}\, dn\right)^{1-\theta}, \tag{11}$$

[4] The other first-order condition (not shown) prices the portfolio of state-contingent securities.

where W_t^n is the wage demanded by the supplier of type-n labor. Product differentiation gives the firm monopolistically competitive power, so price is a choice variable. However, the adjustment of nominal prices is assumed to be costly. In particular, the real cost of a price change per unit is

$$\Gamma_t^i = \Gamma(P_{i,t}/P_{i,t-1}) = \gamma\left(\frac{\exp(-\varsigma(P_{i,t}/P_{i,t-1}-1)) + \varsigma(P_{i,t}/P_{i,t-1}-1)-1}{\varsigma^2}\right), \tag{12}$$

where $\gamma(>0)$ and ς are cost parameters. In what follows, we focus on the special case where $\varsigma \to 0$ (i.e., the quadratic-cost function proposed by Rotemberg, 1982) and price adjustment costs are, therefore, symmetric.[5]

At time τ, firm i maximizes the discounted sum of real profits

$$E_\tau \sum_{t=\tau}^{\infty} \beta^{(t-\tau)} \frac{\eta_t}{\eta_\tau P_t}\left((1-\Gamma_t^i)P_{i,t}c_{i,t} - \int_0^1 W_t^n h_t^n\, dn\right),$$

and $c_{i,t} = \int_0^1 c_{i,t}^n\, dn$ is total consumption demand for good i. Maximization is subject to the technology (9), the downward-sloping consumption demand function (8), and the condition that supply must meet the demand for good i at the posted price. First-order conditions equate the marginal productivity of labor with its cost

$$(1-\alpha)x_t h_{i,t}^{-\alpha} = W_{i,t}/P_t, \tag{13}$$

and the marginal costs with the marginal benefits of increasing $P_{i,t}$

$$\frac{1}{P_t}\left(\left(\frac{\mu}{\mu-1}\right)c_{i,t}(1-\Gamma_t^i) + \left(\frac{P_{i,t}}{P_{i,t-1}}\right)c_{i,t}(\Gamma_t^i)'\right) = \frac{1}{P_t}(c_{i,t}(1-\Gamma_t^i)) + \frac{\mu}{\mu-1}\left(\frac{\Psi_t y_{i,t}}{P_{i,t}}\right) + \beta E_t\left(\frac{\eta_{t+1}}{\eta_t}\frac{c_{i,t+1}}{P_{t+1}}\left(\frac{P_{i,t+1}}{P_{i,t}}\right)^2(\Gamma_{t+1}^i)'\right), \tag{14}$$

where Ψ_t is the real marginal cost. On the left-hand side of this price Phillips curve, the costs are the decrease in sales, which is proportional to the elasticity of substitution between goods, and the price adjustment cost. On the right-hand side, the benefits are the increase in revenue for each unit sold, the decrease in the marginal cost, and the reduction in the future expected price adjustment cost. Given nominal expenditures on labor, the optimal demand of type-n labor is

$$h_t^n = \left(\frac{W_t^n}{W_t}\right)^{-\theta/(\theta-1)} h_{i,t},$$

where $-\theta/(\theta-1)$ is the elasticity of demand for the labor of household n with respect to its relative wage.

2.3. Symmetric equilibrium

In the symmetric equilibrium, all households supply exactly the same amount of labor. This implies that $h_t^n = h_t$ and, consequently, $W_t^n = W_t$. Since households are identical in all other respects, it follows that their equilibrium choices will be same, that n subscripts can be dropped without loss of generality, and that net holdings of Arrow–Debreu securities and bonds can be neglected in the solution. Similarly, all firms are identical *ex post* meaning that they charge the same price and produce the same quantity. Hence, all relative prices are one and the i subscripts can also be dropped. Substituting the government's budget constraint and the profits of the (now) representative firm into the budget constraint of the (now) representative household delivers the economy-wide resource constraint

$$c_t = y_t(1-\Gamma_t) - w_t h_t \Phi_t, \tag{15}$$

where $w_t = W_t/P_t$ is the real wage.

2.4. Monetary policy

The government implements monetary policy by means of a Taylor-type rule whereby the nominal interest rate responds to its own lagged value, and to the inflation and employment deviations from their steady-state values.[6]

[5] In preliminary work, we estimated an unrestricted version of the model with possibly non-zero ς, but a t-test of $\varsigma = 0$ did not reject this hypothesis at the 5% level (p-value $= 0.41$). This finding indicates that price adjustment costs are approximately symmetric and is line with micro evidence reported by Peltzman (2000), Zbaracki et al. (2004) and Chen et al. (2008). Peltzman studies the pricing decisions of a Chicago supermarket chain at the level of individual goods and finds no asymmetry in its response to input price increases or decreases. Zbaracki et al. find that customers are antagonized by price changes, even when they involve a price decrease; price decreases are not always welcomed because passing lower prices downstream also involves adjustment costs and because current price cuts make future price increases more costly. Chen et al. find that the frequency of price adjustments is symmetric for changes larger than 10 U.S. cents.

[6] An alternative approach would be to assume that the government optimally sets the interest rate on the basis of an *ad hoc* loss function or the level of households' welfare. The approach we use here is more common in the literature because it is computationally simpler and describes actual monetary policy reasonably well. For example, Adolfson et al. (2008) construct an operational medium-scale DSGE model for the Swedish economy and find that the data are better explained as following a simple instrument rule than the optimal policy under commitment.

That is,

$$\ln(I_t/I) = \kappa_1 \log(I_{t-1}/I) + \kappa_2 \log(\Pi_t/\Pi) + \kappa_3 \log(h_t/h), \tag{16}$$

where $\kappa_1 \in (0,1)$, κ_2, and κ_3 are constant policy parameters and variables without time subscript denote steady-state values. Since our normative analysis of grease inflation will be based on the Ramsey policy, the Taylor-type rule is likewise specified without an error term.[7]

2.5. Model solution

Since this problem does not have a closed-form solution, we use a perturbation method that involves taking a second-order approximation of the private-sector equilibrium and government's monetary policy, and characterizing local dynamics around the deterministic steady state.[8] See Jin and Judd (2002), Schmitt-Grohé and Uribe (2004b), and Kim et al. (2008) for a detailed explanation of this approach.[9]

3. Estimation

The section describes the data and the econometric approach that are used to estimate the model. An important methodological contribution is to show that SMM is an attractive alternative to computationally intensive likelihood-based methods for the purpose of estimating nonlinear DSGE models.

3.1. Data

The data used to estimate the model are quarterly observations of hours worked, real consumption per capita, the price inflation rate, the wage inflation rate, and the nominal interest rate between 1964Q2 and 2006Q2. The sample starts in 1964 because aggregate data on wages and hours worked are not available prior to that year. The raw data were taken from the FRED database available at the Federal Reserve Bank of St. Louis web site (www.stls.frb.org). The rates of price and wage inflation are measured by the percentage change in the consumer price index (CPI) and the average hourly earnings for private industries, respectively. Hours worked are measured by the aggregate weekly hours index for total private industries produced by the Bureau of Labor Statistics (BLS). The nominal interest rate is the effective federal funds rate. Real consumption is measured by personal consumption expenditures per capita divided by the CPI. The population series corresponds to the quarterly average of the mid-month U.S. population estimated by the Bureau of Economic Analysis (BEA). Except for the nominal interest rate, all data are seasonally adjusted at the source. All series were logged and linearly detrended prior to the estimation of the model.

3.2. Econometric methodology

The second-order approximate solution of our nonlinear DSGE model is estimated using SMM. The application of SMM for the estimation of time-series models was proposed by Lee and Ingram (1991) and Duffie and Singleton (1993). Ruge-Murcia (2007) uses Monte-Carlo analysis to compare various methods used for the estimation of DSGE models and reports that moment-based estimators are generally more robust to misspecification than Maximum Likelihood (ML). This is important because economic models are stylized by definition and misspecification of an unknown form is likely.[10] Method of moments estimators are also attractive for the estimation of nonlinear DSGE models because the numerical evaluation of its objective function is relatively cheap. This means, for example, that the researcher can afford to use genetic algorithms for its optimization. These algorithms require a larger number of function evaluations than alternative gradient-based methods, but greatly reduce the possibility of converging to a local optimum—rather than the global one.

Define $\boldsymbol{\theta}$ to be a $q \times 1$ vector of structural parameters, $\mathbf{g}_t$ to be a $p \times 1$ vector of empirical observations on variables whose moments are of our interest, and $\mathbf{g}_\iota(\boldsymbol{\theta})$ to be the synthetic counterpart of $\mathbf{g}_t$ whose elements come from simulated data generated by the model. Then, the SMM estimator, $\widehat{\boldsymbol{\theta}}$, is the value that solves

$$\min_{\{\boldsymbol{\theta}\}} \mathbf{G}(\boldsymbol{\theta})'\mathbf{W}\mathbf{G}(\boldsymbol{\theta}), \tag{17}$$

[7] Our results are generally robust to similar formulations of the policy rule. For example, they are robust to using output (rather than employment) as measure of real economic activity. Note also that under the method of moments approach used here to estimate the model, the absence of an error term does not mean that (16) would be fit by the data perfectly.

[8] Benigno and Ricci (2008) solve analytically a model similar to ours but where shocks follow Brownian motions and the adjustment cost function has an "L" shape. This shape implies that wage cuts are infinitely costly while wage increases are costless, and may be obtained as a special case of our cost function when $\psi \to \infty$.

[9] The codes that we employed were adapted from those originally written by Stephanie Schmitt-Grohé and Martin Uribe. The dynamic simulations of the nonlinear model are based on the pruned version of the model, as suggested by Kim et al. (2008).

[10] On the other hand, under the assumption that the model is correctly specified, ML is statistically more efficient than the method of moments. This means that, even though both methods deliver consistent parameter estimates, those obtained by ML would typically have smaller standard errors.

where

$$\mathbf{G}(\boldsymbol{\theta}) = (1/T)\sum_{t=1}^{T}\mathbf{g}_t - (1/\lambda T)\sum_{\iota=1}^{\lambda T}\mathbf{g}_\iota(\boldsymbol{\theta}),$$

T is the sample size, λ is a positive constant, and $\mathbf{W}$ is a $q \times q$ weighting matrix. Under the regularity conditions in Duffie and Singleton (1993)

$$\sqrt{T}(\widehat{\boldsymbol{\theta}} - \boldsymbol{\theta}) \to N(\mathbf{0}, (1+1/\lambda)(\mathbf{D}'\mathbf{W}^{-1}\mathbf{D})^{-1}\mathbf{D}'\mathbf{W}^{-1}\mathbf{S}\mathbf{W}^{-1}\mathbf{D}(\mathbf{D}'\mathbf{W}^{-1}\mathbf{D})^{-1}), \tag{18}$$

where

$$\mathbf{S} = \lim_{T\to\infty} Var\left((1/\sqrt{T})\sum_{t=1}^{T}\mathbf{g}_t\right), \tag{19}$$

and $\mathbf{D} = E(\partial\mathbf{g}_\iota(\boldsymbol{\theta})/\partial\boldsymbol{\theta})$ is a $q \times p$ matrix assumed to be finite and of full column rank.[11]

In this application, $\boldsymbol{\theta}$ contains the curvature parameter of the utility function (ρ), the parameters of the adjustment cost functions (ϕ, ψ and γ) and shock processes (ξ, ζ, σ_ε and σ_u), and the monetary policy rule (κ_1, κ_2, and κ_3). The weighting matrix $\mathbf{W}$ is the diagonal of the inverse of the matrix with the long-run variance of the moments, $\mathbf{S}$, which was computed using the Newey-West estimator. The derivatives in the Jacobian matrix $\mathbf{D}$ are numerically computed at the optimum. For the simulation of the model, innovations are drawn from a normal distribution and the number of simulated observations is five times larger than the sample size (that is, $\lambda = 5$).[12] The moments in $\mathbf{G}(\boldsymbol{\theta})$ are all five variances, ten covariances and five autocovariances of the data series.

In order to economize degrees of freedom and sharpen identification, we use additional information to fix some parameter values to economically plausible numbers during the estimation routine. The curvature parameter of the production $(1-\alpha)$ is set to $\frac{2}{3}$, based on data from the U.S. National Income and Product Accounts (NIPA) which show that the share of labor in total income is approximately this value. The discount factor (β) is set to 0.997, which is the mean of the inverse ex post real interest rate during the sample period. The weight of labor disutility in the utility function (χ) is set to 1. The elasticities of substitution between goods and between labor types are fixed to $\mu = 1.1$ and $\theta = 1.4$, respectively. This value for μ is standard in the literature. Sensitivity analysis with respect to θ indicates that results are robust to using similarly plausible values. Finally, for the steady-state (gross) inflation target (Π) in the monetary policy rule we considered two values: a benchmark rate of 1.0 and a rate of 1.0112, which is the average quarterly inflation rate during the sample period. Parameters estimates were basically the same in both cases and so, in order to save space, we report below results for the former case only.

3.3. SMM estimates

SMM parameter estimates based on the second-order approximate solution of the model are reported in the first column of Panel A in Table 1. The coefficient that determines the consumption curvature (ρ) is larger than, and statistically different from, unity meaning that the utility function is more concave than implied by logarithmic preferences. The parameters of the interest-rate rule indicate substantial policy smoothing—which is consistent with earlier findings in the empirical literature on monetary policy rules (see, for example, Taylor, 1999)—and positive and statistically significant responses to inflation and employment deviations from their steady-state values. Estimates of the parameters of the process of the productivity and preference shocks are very similar to those reported in earlier empirical work.

Regarding the parameters of the adjustment cost functions, the hypotheses that $\phi = 0$ and $\gamma = 0$ can be rejected against the respective alternatives that $\phi > 0$ and $\gamma > 0$ at the 5% significance level. In other words, the data rejects the hypothesis that nominal wages and prices are flexible in favor of the alternative that they are rigid.[13] The estimate of the wage asymmetry parameter (ψ) is 3844.4 with a standard error of 1186.7. Because this estimate is positive and statistically different from zero at the 5% level, we conclude that nominal wages are more downwardly than upwardly rigid.

Since this asymmetry parameter is an object of special interest in this project, it is important to determine the features of the data that deliver its statistical identification. To that end, we pursue the following strategy.[14] Holding all other parameters constant, we vary ψ from its estimated value towards zero and study how the second moments predicted by the model change along this path. In particular, we compute the percentage change in each moment, at each value of ψ,

[11] An alternative approach is to analytically compute the moments predicted by the model based on the pruned quadratic solution and use them in the objective function instead of $(1/\lambda T)\sum_{\iota=1}^{\lambda T}\mathbf{g}_\iota(\boldsymbol{\theta})$. We followed this GMM approach in preliminary work but found it problematic because first-order dynamics are independent of the asymmetry parameter, and, consequently, ψ is not identified. Notice that for the pruned version of nonlinear DSGE models, SMM is not statistically equivalent to GMM as $\lambda \to \infty$. In contrast, the two are asymptotically equivalent in the case of linear models (see Ruge-Murcia, 2007).

[12] Sensitivity analysis indicates that estimates are robust to using larger values of λ. However, we also found that the time required to compute the objective function increases rapidly with λ.

[13] In the context of linearized DSGE models, a similar finding is reported by Kim (2000), Ireland (2001, 2003), Christiano et al. (2005), and Bouakez et al. (2005), among many others.

[14] We are very thankful to Angelo Melino for suggesting this approach.

Table 1
SMM estimates.

Description	Notation	Wage adjustment costs	
		Asymmetric	Quadratic
A. Structural parameters			
Consumption curvature	ρ	1.542*	0.598*
		(0.146)	(0.175)
Wage adjustment cost	ϕ	280.4*	1033.4*
		(64.7)	(294.7)
Price adjustment cost	γ	37.8*	69.5*
		(12.4)	(28.7)
Wage asymmetry	ψ	3844.4*	–
		(1186.7)	
Interest-rate smoothing	κ_1	0.381*	0.692*
		(0.121)	(0.105)
Inflation coefficient	κ_2	1.176*	0.506*
		(0.178)	(0.131)
Employment coefficient	κ_3	0.068*	0.004
		(0.030)*	(0.018)
AR coefficient technology shock	ξ	0.960*	0.934*
		(0.007)	(0.019)
SD technology innovation	σ_ε	0.012*	0.014*
		(0.001)	(0.002)
AR coefficient preference shock	ζ	0.812*	0.995*
		(0.031)	(0.056)
SD preference innovation	σ_u	0.026*	0.039
		(0.003)	(0.024)
B. Optimal inflation (*annualized*)			
Mean inflation under Ramsey		1.0035	0.99998
Lower bound 95% CI		1.0004	0.99995
Upper bound 95% CI		1.0087	1.00000

Notes: The figures in parenthesis are standard errors. The superscripts * and † denote the rejection of the hypothesis that the true parameter value is zero at the 5% and 10% significance level, respectively.

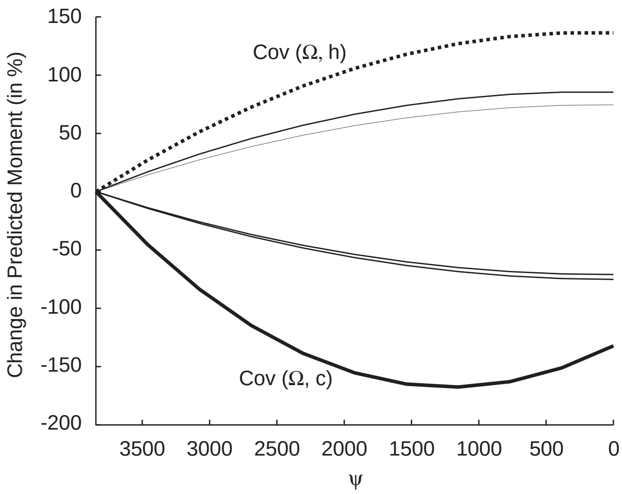

Fig. 2. Identification of the wage asymmetry parameter. This figure plots the percentage change in second moments predicted by the model as one varies ψ from its estimated value towards zero, holding all other parameters constant. In order to simplify the figure, only the six moments that change the most are plotted. That is, the moments that are not reported change by less than those plotted in the figure.

compared with its magnitude at the SMM estimate. Suppose that a given moment does not change along the path, then it follows that this moment does not contribute (at least locally) to the identification of ψ. Suppose instead that a given moment varies a lot along the path, then it follows that this moment is informative about ψ and therefore helpful for its identification.

Fig. 2 plots the percentage change in second moments predicted by the model. In order to simplify the figure, only the six moments that change the most are plotted. In Fig. 2, we can see that two moments are specially helpful for identifying

ψ. These moments are the covariance of hours with wage inflation, and the covariance of consumption with wage inflation. Other things equal, values of ψ smaller than the SMM estimate imply a much larger (smaller) covariance of hours (consumption) with wage inflation than the SMM estimate does.

In order to examine the properties of our model, it is useful to have as benchmark a restricted version of the model with quadratic wage adjustment costs. This restricted version corresponds to the special case where $\psi \to 0$. SMM estimates of this model are reported in the second column of Table 1. Note that estimates of the parameters of the shock processes are very similar to those reported for the asymmetric model, but that there are some differences in the preference, policy rule and adjustment cost parameters. For example, the quadratic-cost model delivers a smaller curvature of the utility function and more interest rate smoothing than the asymmetric model. The most important difference, however, concerns the parameters of the wage and price adjustment cost functions. Both prices and wages appear to be more rigid under the quadratic than under the asymmetric model, and the relative magnitudes of the estimates imply that wages are substantially more rigid than prices. A similar conclusion is reached, for example, by Christiano et al. (2005) using a linearized DSGE model that implicitly imposes symmetry in the adjustment costs of nominal variables. This implication of symmetric models is not necessarily at odds with the data, except that our results add to this finding the caveat that most of the observed nominal wage rigidity is in the downward direction.

Having obtained parameters estimates under a plausible description of actual monetary policy, we turn to the normative implications of downward nominal rigidity. To that end, we now study the Ramsey policy based on our SMM estimates of the private-sector parameters.

4. Optimal policy

In order to study optimal monetary policy in an economy where wages are downwardly rigid, this section solves the problem of a government that follows the Ramsey policy of maximizing the households' welfare subject to the resource constraint and the first-order conditions of firms and households. In this case, the monetary policy rule is endogenously determined by the solution of the government's dynamic programming problem. We focus our analysis on both the optimal inflation rate and on the optimal response to shocks. The economy parameters are those reported in Table 1.

Under the optimal policy, the government chooses $\{c_t, \eta_t, h_t, w_t, i_t, \Omega_t, \Pi_t\}_{t=\tau}^{\infty}$ to maximize

$$E_\tau \sum_{t=\tau}^{\infty} \beta^{(t-\tau)} \left(\frac{(c_t)^{1-\rho}}{1-\rho} - h_t \right),$$

where $\Omega_t = W_t/W_{t-1}$ is gross wage inflation, subject to conditions (5)–(7), (13), and (14), and taking as given previous values for wages, goods prices, and shadow prices. Notice that in the formulation of the government's problem, it is assumed that the discount factor used to evaluate future utilities is the same as that used by households. It is also assumed that the government can commit to the implementation of the optimal policy.

The solution of the Ramsey problem endogenously pins down the optimal deterministic steady-state inflation rate, which in this case is 1. The intuition is that, absent any uncertainty, optimal price (and wage) inflation would be such that no adjustment costs would have to be paid by either firms or households, and this rate is $\Pi = \Omega = 1$.

4.1. Optimal grease inflation

This section constructs a measure of optimal grease inflation for the U.S. economy by calculating how much asymmetric costs increase expected inflation compared with symmetric (i.e., quadratic) costs. For this purpose, we compute via simulation the unconditional inflation mean implied by the Ramsey policy under the two versions of our model, and the results are reported in Panel B of Table 1.

Consider first the model with quadratic costs (the right column). The unconditional mean of annual gross inflation is basically 1: the point estimate is 0.99998 with the 95% confidence interval of [0.99995, 1.00000].[15] Consider now the model with asymmetric costs (the left column). The estimate of the unconditional mean of annual gross inflation is 1.0035 with 95% confidence interval spanning [1.0004, 1.0087]. Since this confidence interval does not include 1, the null hypothesis that optimal gross inflation is unity can be safely rejected at the 5% significance level. This means that optimal expected inflation is statistically larger than the inflation rate in the deterministic steady state. This result reflects the model's departure from certainty equivalence. Optimal inflation is larger than 1 because the monetary authority acts prudently and reduces the probability of facing highly costly downward nominal wage adjustment by choosing an average rate of price (and wage) inflation above unity.

This paper defines the measure of grease inflation as the difference between the two figures reported above. Subtracting optimal gross inflation under the asymmetric-cost model from its corresponding value under the quadratic-cost model delivers an estimate of optimal grease inflation for the U.S. economy of approximately 0.0035, that is, 0.35% per year. Since

[15] The lower and upper bounds of this interval are computed as follows. First, we draw 240 independent realizations of $\boldsymbol{\theta}$ from the empirical joint density function of the SMM estimates. Then, for each realization of $\boldsymbol{\theta}$, we compute the expected inflation rate. Finally, the bounds of the confidence interval are the 2.5th and 97.5th quantiles of the simulated expected inflation rates.

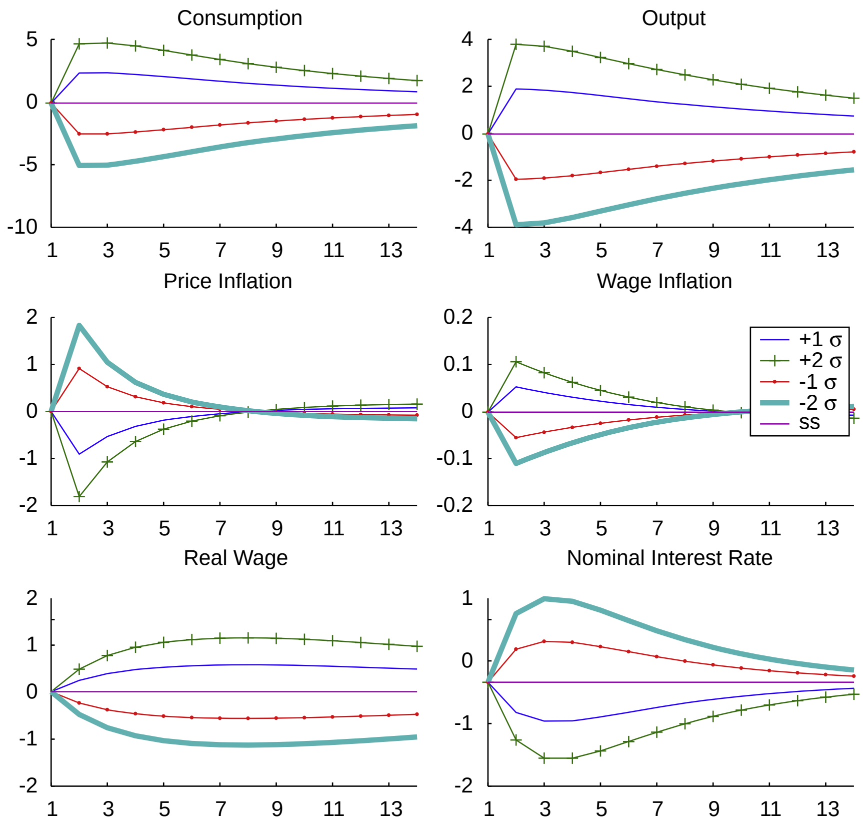

Fig. 3. Optimal responses to productivity shocks when wage adjustment costs are quadratic.

the confidence interval of the quadratic-cost model is extremely narrow and near unity, a 95% confidence interval for the optimal grease inflation would roughly range from 0.04% to 0.87%.

4.2. Impulse responses

This section studies the optimal response to economic shocks using impulse responses. Starting at the stochastic steady state, the economy is subjected to an unexpected temporary shock, and the responses of consumption, output, price inflation, wage inflation, the real wage, and the nominal interest rate are then plotted as a function of time. In linear models, the response to a shock of size ε is one-half that to a shock size 2ε and the mirror image of that to a shock of size $-\varepsilon$. Thus, any convenient normalization (e.g., $\varepsilon = 1$) summarizes all the relevant information. However, in nonlinear models like ours, a response will typically depend on both the sign and the size of the shock.[16] Thus, we plot responses to innovations of size $+2$, $+1$, -1, and -2 standard deviations.

Responses to productivity shocks when $\psi = 0$ and 3844.4 are reported in Figs. 3 and 4, respectively. The vertical axis is the percentage deviation from the deterministic steady state, and the rates of price inflation, wage inflation and nominal interest are annualized. The flat line is the level of the stochastic steady state. The distance between this line and zero depends on the effect of uncertainty on the unconditional first-moments of the variables, that is, on the model's departure from certainty equivalence. Since the log of expected inflation under the quadratic model is essentially zero, the distance in Fig. 4 between the stochastic and deterministic steady states of price and wage inflation measures the degree of optimal grease inflation.[17]

First, consider the responses in Fig. 3, where $\psi = 0$. Following a negative shock, consumption, output, wage inflation, and the real wage decrease, while price inflation and the nominal interest rate increase. The converse happens following a positive shock. There is very little asymmetry between positive and negative, and between small and large shocks. Thus, the propagation mechanism of this model is close to linear.[18]

[16] See Gallant et al. (1993), and Koop et al. (1996) for more complete treatments of impulse-response analysis in nonlinear systems.

[17] In particular, this distance is 100 log(1.0035), where the term in the parenthesis is expected inflation when $\psi = 3844.4$.

[18] The distance between the stochastic and deterministic steady states of the nominal interest rate is driven by the variance of the preference shock which, as we explain at the end of this section, affects only this variable under the Ramsey policy.

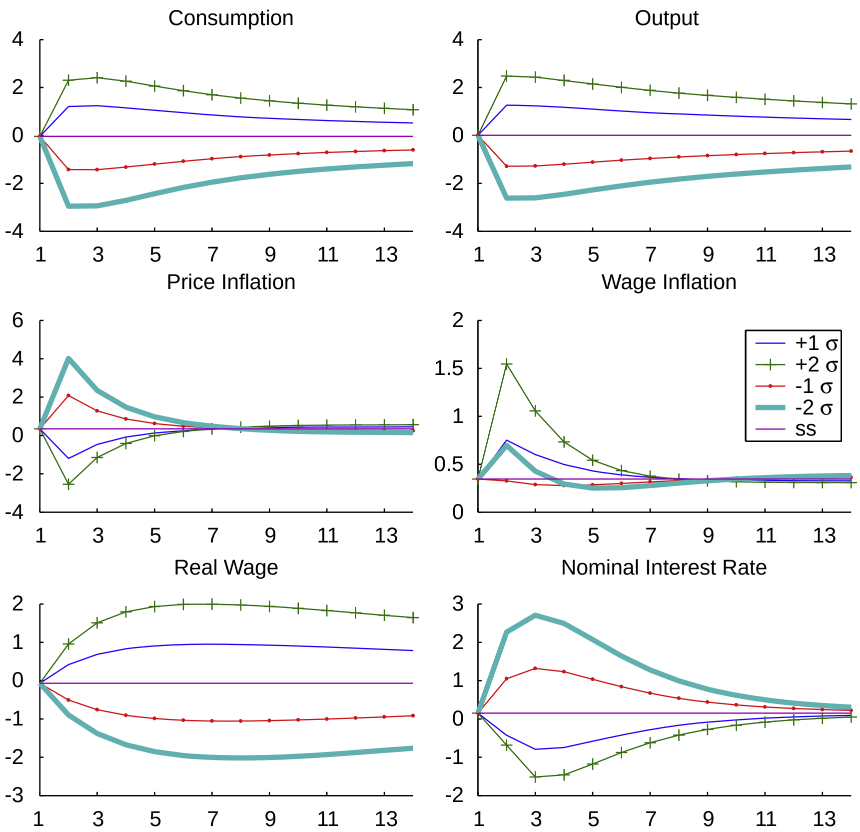

Fig. 4. Optimal responses to productivity shocks when wage adjustment costs are asymmetric.

Now, consider the responses in Fig. 4, where $\psi = 3844.4$. A negative productivity shock decreases the marginal productivity of labor and consequently the real wage must fall. This is an example of the type of shock that Tobin had in mind in his presidential address to the American Economic Association. From Figs. 3 and 4, it is apparent that the real wage does indeed fall, and the adjustment path of the real wage indicates that there is no more real wage rigidity in the asymmetric compared with the quadratic model. However, the optimal adjustment of nominal variables depends on the size of the asymmetry parameter ψ.

When $\psi = 0$, the nominal wage decreases and price level increases (see Fig. 3). In contrast, when $\psi > 0$, the Ramsey policy involves positive rates of price and wage inflation (see Fig. 4). Thus, the nominal wage still increases after a negative productivity shock and, furthermore, wage inflation may be initially larger than its steady state if the shock is sufficiently large. It follows that the reduction in the real wage is achieved by an even bigger increase in the price level. A positive productivity shock leads to an increase in the real wage but, as before, the optimal adjustment path depends on the value of ψ. In general, the adjustment involves a decrease in the price level and an increase in the nominal wage, with both responses quantitatively larger when $\psi > 0$ than when $\psi = 0$.

The responses of consumption and output in Fig. 4 are approximately symmetric and proportional to the shock size but those of the nominal interest rate are asymmetric. In particular, the optimal interest rate response is quantitatively larger for negative than for positive shocks, and the response to a large shock of -2σ is more than twice that to a smaller shock of $-\sigma$.

Responses to preference shocks under the Ramsey policy (not shown) are zero for all model variables, except for the nominal interest rate. The reason is that this shock affects the model only by disturbing the household's Euler equation for consumption but the Ramsey planner can adjust the nominal interest rate to perfectly undo its effects. Hence, decision rules for all variables, except for the nominal interest rate, are independent of this shock.[19]

[19] Since all decision rules depend on the preference shock under the Taylor-type rule, parameter estimates are likely to be sensitive to the monetary policy regime assumed in the analysis. This sensitivity is especially relevant if the estimation procedure uses data on the nominal interest rate, as we do in this paper.

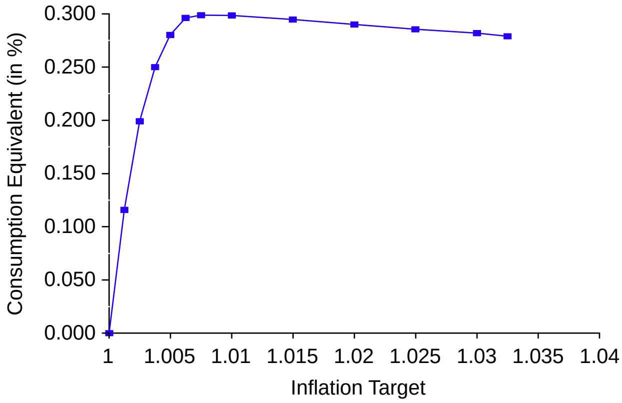

Fig. 5. Welfare under inflation targeting. This figure reports the increase in unconditional welfare when the monetary authority follows a strict inflation targeting regime compared with that at the zero inflation rate. The welfare increase is expressed in consumption equivalents.

4.3. Comparison with strict inflation targeting

In order to better understand the degree of optimal grease inflation under the Ramsey policy, this section computes the inflation rate that delivers the highest (unconditional) welfare when the monetary authority follows a simple rule that strictly hits the inflation target. Fig. 5 plots unconditional welfare, expressed in consumption equivalents, for different values of the inflation target.

This figure indicates that, given the estimated parameters, the optimal inflation target would be around 0.75% per year, which is more than twice as large as that of the Ramsey policy. The reason is that positive inflation in a model with downward wage rigidity is driven by prudence. With limited knowledge and less flexibility with respect to shocks, the strict-targeting government needs a larger buffer above zero inflation (compared with Ramsey) to eschew paying the costs associated with nominal wage cuts. The welfare increase is approximately 0.30% of consumption, compared with that at the zero inflation rate, and declines slowly as inflation rises further. Since many inflation targeting regimes target (net) inflation rates between 1% and 3% per year, Fig. 5 implies that such regimes are significantly welfare improving compared with a policy of strict price stability, understood to be a zero inflation rate.

5. Conclusions

This paper investigates Tobin's proposition that inflation greases the wheels of the labor market in the context of a simple but fully-specified dynamic general equilibrium model. Previous research based on linearized DSGE models did not examine this issue because, by construction, linearization eliminates the asymmetries of the underlying model. Although microeconomic research documents asymmetries in the raw wage data, the micro data itself contains elements of both economic structure and individual behavior and cannot fully reveal the mechanism through which downward wage rigidity may generate aggregate implications. Furthermore, the question is important because of the current discrepancy between theory—that prescribes zero-to-negative inflation rates—and actual practice—where central banks target low, but positive, inflation rates.

SMM estimates based on the second-order approximation of model indicate that U.S. nominal wages are downwardly rigid, that optimal grease inflation is approximately 0.35% per year, and that downward wage rigidity has non-trivial implications for the dynamics of aggregate variables. Needless to say, the estimate of optimal grease inflation may depend on the model specification. For example, in a model with *ex post* heterogeneity, optimal grease inflation may be larger because productivity growth (and hence real wages) would vary across agents. In contrast, in a model with technological growth, optimal grease inflation may be smaller because a positive trend growth in real wages would decrease the need for nominal wage cuts. In ongoing and future work, we study these questions in the context of a fully-fledged monetary economy, examine the role of asymmetric shocks and time-varying volatility, and derive the business cycle implications of asymmetric nominal rigidities.

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