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ABSTRACT

We calculate the welfare cost of nominal inertia in a New Neoclassical Synthesis model with wage and price stickiness, capital formation, and empirically estimated rules for government spending and the cental bank's interest rate policy. We calibrate our model to U.S. data, and we show that it captures many aspects of the U.S. business cycle. Moreover, our model is capable of generating the kind of volatility that has been observed in the efficiency gaps emphasized by Erceg, Henderson and Levin (2000) and Gali, Gertler and Lopez-Salido (2002). We also highlight some of the empirical shortcomings of the model; in particular, demand side shocks appear to be either missing or improperly modeled. We calculate the cost of nominal inertia under two specifications of monetary policy. The bottom line is that, under our preferred specification of monetary policy, the model implies a conservative estimate of the cost that is twenty to sixty times larger than Lucas's (2003) estimate: the "average" household in our model would be willing to give up one to three percent of consumption each period to be free of the effects of wage and price stickiness. Wage inertia appears to be the major source of these welfare costs.

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1. Introduction

The New Neoclassical Synthesis (NNS) is characterized by monopolistic competition, wage and/or price stickiness, and demand determination of output and employment.[1] The NNS has been used to revisit the central issues of stabilization policy, and a number of theoretical insights have emerged. Rotemberg and Woodford (1997) showed that smoothing output – which was strongly emphasized in traditional Keynesian analyses – can lower household welfare in a model driven by productivity shocks. A number of papers have shown that the tradeoffs for monetary policy can depend on the type of nominal inertia that is postulated. For example, King and Wolman (1999) showed that there was no inflation - output tradeoff in a model with staggered price setting; subsequently, Erceg, Henderson and Levin (2000) (EHL) showed that an inflation - output tradeoff can emerge in a model with both staggered wage setting and staggered price setting.[2]

Are these theoretical insights of any practical relevance? An important challenge hanging over this new literature is Lucas's (2003, page 1) claim that the macroeconomic stabilization problem has been solved: "Taking U.S. performance over the past 50 years as a benchmark, the potential for welfare gains from better long-run, supply side policies exceeds *by far* the potential from further improvements in short-run demand management." Calibrating an ingeniously simple model to the U.S. data, Lucas argued that a typical American household would only be willing to give up one twentieth of one percent of consumption each period to be free of all fluctuations in consumption about trend, no matter how the fluctuations were generated.

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[1] Goodfriend and King (1997) outlined the New Neoclassical Synthesis, and gave it the name. Woodford (2003) provides a masterful introduction to this class of models. Clarida, Gali and Gertler (1999) provide an early guide to the implications for monetary policy; Canzoneri, Cumby and Diba (2003) discuss more recent contributions to the literature on monetary policy.

[2] Blanchard (1997) noted early on that wage rigidity would modify the argument for price stability.

In this paper, we will argue that the theoretical insights from NNS models may be of considerable practical importance, and that there may well be room for improvement in demand management policies. And in so doing, we will provide alternative – and generally much larger – estimates of the welfare cost of U.S. business cycles.

NNS models typically envision a production economy with complete consumption risk sharing. In such an environment, it is natural to associate the welfare cost of nominal rigidity with variations in the gap between the marginal product of labor (MPL) and the marginal rate of substitution (MRS) between consumption and leisure. EHL motivated their analysis in this way, but the welfare losses they found were quite small, suggesting that the variations in this gap generated by their model were also small. By contrast, Gali, Gertler and Lopez-Salido (2002) (GGLS) developed empirical proxies for the MRS - MPL gap, and found that the gap was much more volatile than output.[3] GGLS did not present a model, so it was not clear that an NNS model could generate the gap volatility that they observed in the data.

There are at least two possible interpretations of the contrasting results of EHL and GGLS. Productivity shocks are the only source of uncertainty in EHL's model, and the monetary policies that EHL consider are all reasonably good in NNS models that are driven by productivity shocks; in particular, their policies do not fall into the trap described by Rotemberg and Woodford (1997). So, one interpretation is that U.S. monetary policy was quite a bit worse than the policies EHL studied, or that the EHL model is missing some of the shocks that have caused the MRS - MPL gap

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[3] GGLS calculated the MRS-MPL gap by plugging U.S. data into a gap derived from a standard utility function. GGLS also found that movements in the MRS-MPL gap were closely associated with movements in the gap between the MRS and the real wage. Hence, they argued that wage rigidity played an important role in the gap's volatility.

to fluctuate in the U.S. data. The second interpretation has already been alluded to: NNS models may simply be incapable of generating the volatility in the gap that GGLS found in the data.[4]

In this paper, we study the welfare cost of nominal inertia in an NNS model with wage and price stickiness, capital accumulation, and empirically estimated rules for government spending and the cental bank's interest rate policy. We calibrate our model to fit quarterly U.S. data, and we show that our model captures many aspects of the U.S. business cycle. Moreover, we show that our model is capable of generating most of the volatility in the MRS - MPL gap that has been observed in the data. We also discuss some of the model's shortcomings. In particular, demand side shocks seem to be either absent or incorrectly modeled; or equivalently, productivity shocks seem to be doing more than they should in the model. Finally, we calculate welfare – with and without nominal rigidities – using a second order approximation to both the model and the welfare function. The difference between the two is what we call the cost of nominal inertia.

Our estimate of the cost of nominal inertia depends crucially on what we assume about the Frisch elasticity of labor supply; an inelastic labor supply reflects a rapidly increasing marginal disutility of work, and this in turn implies large utility costs for fluctuations in work effort. RBC models have to assume a highly elastic labor supply curve – much more elastic than estimates coming from the labor economics literature – to generate the volatility in hours worked that is observed in the data. In our NNS model, wages are inertia ridden and the work effort is demand determined. The elasticity of notional labor supply is essentially a free parameter in our model; its

[4] Of course, any business cycle model can 'explain' the MRS-MPL gap by allowing for sufficiently large preference shocks. The question we address here is whether an NNS model – with wage rigidity, but no preference shocks – can explain the observed volatility in the gap.

value has little to do with the model's ability to fit moments in the data.[5] Consequently, we can choose the parameter to conform with the labor economists' estimates, and this will be seen to result in rather large welfare costs for business cycles.

Our estimate of the cost of nominal inertia also depends importantly on what we assume about the central bank's interest rate policy. The interest rate rule we use to characterize monetary policy has lagged interest rates, inflation, an output gap, and a residual (which we call the interest rate shock). In estimating the rule, we define the output gap to be the difference between actual output and the CBO's estimate of potential output.[6] The interest rate rule and its estimation are quite conventional, but it is not clear how the rule should be interpreted in our NNS model: there is no CBO (or Federal Reserve) in the model to provide estimates of potential output. So, we consider two specifications of monetary policy in our model simulations: in what we will call the 'good' policy rule, the output gap is defined as the difference between actual output and the flexible wage/price output (as defined by Neiss and Nelson (2003)); in the 'bad' policy rule, the output gap is defined as the difference between actual output and output in the non-stochastic steady state.

As might be expected, our new estimates of the welfare cost of nominal inertia are much smaller under the 'good' policy rule than under the 'bad' policy rule. This is what the work of Rotemberg and Woodford (1997) would suggest: smoothing output is not good policy in a model where productivity shocks play a very significant role. However, it is not clear that the Federal Reserve has been able to implement anything close to the 'good' policy rule, since estimating

[5] We have learned (in private conversation) from Frank Smets, that the Bayesian estimation procedure used in Smets and Wouters (2003) is also essentially silent on the value of the Frisch elasticity.

[6] Both output figures are measured as logarithms of real per-capita GDP.

potential output is very difficult in practice. And indeed, we will show that our model 'fits' the data better with the 'bad' policy rule; for this reason, we take it to be our benchmark case.

The bottom line of our welfare calculations is as follows: Using the 'bad' policy rule, we conservatively estimate the cost of nominal inertia to be twenty to sixty times larger than Lucas's (2003) figure: the 'average' household in our model would be willing to give up one to three percent of consumption to be free of the effects of wage and price stickiness. We also find that wage inertia is the primary source of this welfare cost. Using the 'good' policy rule, our model implies a cost that is only a quarter the size – one to three quarters of a percent of consumption. These numbers are much larger than Lucas's estimate (1/20 of one percent), but they are clearly less worrisome. If the 'good' policy rule is an accurate description of monetary policy, then our results are not inconsistent with Lucas's basic claim: the demand management problem may have been largely solved. If on the other hand the 'bad' rule is a better description of monetary policy in practice, then there would appear to be considerable room for improvement. We are inclined to accept the latter view, based upon the way in which the model fits the data under the two specifications of monetary policy.

The rest of our paper is organized as follows: In Section 2, we describe our NNS model. Calvo-style wage and price contracts create inefficiencies that interact with inefficiencies due to monopolistic competition to produce what we call the welfare cost of nominal inertia. In Section 3, we discuss the implications of our benchmark model. We explain how we calibrated the model, and we demonstrate that the model is capable of replicating some of the basic features of the U.S. business cycle. We also identify some weakness in our modeling effort. Finally, we derive a welfare measure that is closely related to Lucas's, and we calculate the welfare cost of nominal inertia under the benchmark (or 'bad') interest rate rule. In Section 4, we perform two robustness exercises. We show how our positive and normative results depend upon assumptions about the degree of wage and price inertia, and upon our specification of monetary policy. In the conclusion, Section 5, we will argue that our 'good' policy rule is far from 'optimal', and that the room for improvement in demand management is therefore far greater than the difference between the costs of nominal inertia under our 'good' and 'bad' policy rules.

2. An NNS Model with Price and Wage Inertia and Capital Formation

Like other NNS models, our model is characterized by optimizing agents, monopolistic competition, and nominal inertial. It is most closely related to the models of Erceg, Henderson and Levin (2000) and Collard and Dellas (2003): as in Collard and Dellas (2003), we allow for capital accumulation, and we calculate second order approximations to both the model and the welfare function; and as in Erceg, Henderson and Levin (2000), we allow for both wage and price inertia.[7] Staggered price setting leads to a dispersion in the firms' prices that creates an inefficiency in household consumption decisions, and staggered wage setting leads to a dispersion in the households' wages that creates an inefficiency in firm hiring decisions. Our purpose here is to get an idea of the magnitude of these inefficiencies in NNS models.

2.1. Firms' price setting behavior –

There is a continuum of firms indexed by f on the unit interval. Each firm rents capital $K_{t-1}(f)$ at the rate R_t, hires a labor bundle $N_t(f)$ (to be defined below) at the rate W_t (also defined below), and produces a differentiated product using the Cobb-Douglass technology

[7] Erceg, Henderson and Levin (2000) employ the Linear-Quadratic approach pioneered by Julio Rotemberg and Michael Woodford; see Woodford (2003).

(1) $Y_t(f) = Z_t K_{t-1}(f)^{\nu} N_t(f)^{\nu-1}$,

where $0 < \nu < 1$, and Z_t is an economy wide productivity shock. Z_t follows a simple auto regressive process – $\log(Z_t) = \rho\log(Z_{t-1}) + \epsilon_{p,t}$; our estimation of this process is described in Appendix B. The firm's cost minimization problem implies[8]

(2) $R_t/W_t = [\nu/(1-\nu)](N_t(f)/K_{t-1}(f))$,

and the firm's marginal cost can be expressed as (see Appendix A)

(3) $MC_t(f) = [\nu^{\nu}(1-\nu)^{(1-\nu)}]^{-1} R_t^{\nu} W_t^{1-\nu}/Z_t$.

The modeling of monopolistic competition is now standard in the NNS literature. The first step is to derive a demand curve for each firm's product. Following Chari, Kehoe and McGrattan (2000), we assume the artifice of a competitive 'bundler': the bundler acquires the firms' products $Y_t(f)$, paying the prices $P_t(f)$, and assembles a composite product

(4) $Y_t = [\int_0^1 Y_t(f)^{(\phi p-1)/\phi p} df]^{\phi p/(\phi p-1)}$, $\phi_p > 1$,

which the bundler then sells to households and the government, as either a consumption good or capital. The constant elasticity aggregator, (4), reflects household and government preferences; so, the bundler chooses the same combination of the firms' products that the households' and the government would, and the bundler's demand for the output of firm f is equal to total demand.[9] Cost minimization (and the zero profit condition) implies that the bundler's price is

(5) $P_t = [\int_0^1 P_t(f)^{1-\phi p} df]^{1/(1-\phi p)}$,

and the bundler's demand for the product of firm f is

[8] $K_{t-1}(f)$ is the firm's demand for capital in period t. The aggregate capital stock is predetermined at the beginning of the period t, hence the dating of the subscript.

[9] For a fuller discussion of this, and equations (5) and (6) that follow, see Canzoneri, Cumby and Diba (2003).

(6) $Y^d_t(f) = (P_t / P_t(f))^{\phi p} Y_t$.

The bundler's price, P_t, can be interpreted as the aggregate price level.

Following Calvo (1983), firms set prices in staggered 'contracts' of random duration. In any period t, each firm gets to announce a new price with probability (1-α); otherwise, the old contract, and its price, remains in effect.[10] With this scheme, the average duration of a price contract is $(1-\alpha)^{-1}$ periods (quarters, in what follows).

If firm f gets to announce a new contract in period t, it chooses a new price $P^*_t(f)$ to maximize the value of its profit stream over states of nature in which the new price is expected to hold:

(7) $E_t \sum_{j=t}^{\infty} (\alpha\beta)^{j-t} \lambda_j [P^*_t(f) Y_j(f) - TC_j(f)]$,

where TC(f) is the firm's total cost, β is the households' discount factor, and λ_j is the households' marginal utility of nominal wealth (to be defined below). The firm's first order condition is

(8) $P^*_t = \mu_p (PB_t / PA_t)$,

where $\mu_p = \phi_p / (\phi_p - 1)$ is a monopoly markup factor, and

(9) $PB_t = E_t \sum_{j=t}^{\infty} (\alpha\beta)^{j-t} \lambda_j MC_j(f) P_j^{\phi p} Y_j = \alpha\beta E_t PB_{t+1} + \lambda_t MC_t(f) P_t^{\phi p} Y_t$

(10) $PA_t = E_t \sum_{j=t}^{\infty} (\alpha\beta)^{j-t} \lambda_j P_j^{\phi p} Y_j = \alpha\beta E_t PA_{t+1} + \lambda_t P_t^{\phi p} Y_t$

As $\alpha \rightarrow 0$, all firms reset their prices each period (the flexible price case), and $P^*_t(f) \rightarrow \mu_p MC_t(f)$. Since the markup is positive ($\mu_p > 1$), output will be inefficiently low in the flexible price solution.

2.2. Households' wage setting behavior and capital accumulation –

There is a continuum of households indexed by h on the unit interval. Each household supplies a differentiated labor service to all of the firms in the economy. Once again, we assume the

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[10] We set steady state inflation equal to zero. But, our results would be the same if we let the contract price rise with a non-zero steady state rate of inflation; see EHL (2000).

artifice of a competitive bundler: the bundler acquires the households' labor services $L_t(h)$, paying the wages $W_t(h)$, and assembles a composite labor service

(11) $N_t = [\int_0^1 L_t(h)^{(\phi w-1)/\phi w} dh]^{\phi w/(\phi w-1)}$, $\phi_w > 1$,

which the bundler then supplies to firms at the wage rate W_t. The constant elasticity aggregator, (11), reflects the firms' production technology; so, the bundler chooses the same combination of household labor services that the firms would, and the bundler's demand for the labor of household h is equal to the total demand. Cost minimization (and the zero profit condition) implies that the bundler's wage is

(12) $W_t = [\int_0^1 W_t(h)^{1-\phi w} dh]^{1/(1-\phi w)}$,

and the bundler's demand for the labor of household h is

(13) $L_t^d(h) = (W_t/W_t(h))^{\phi w} N_t$.

The utility of household h is

(14) $U_t(h) = E_t \sum_{\tau=t}^{\infty} \beta^{\tau-t}[(1-\theta)^{-1} C_\tau(h)^{1-\theta} - (1+\chi)^{-1} L_\tau(h)^{1+\chi}]$,

where $C_t(h)$ is the household's consumption of Y_t, and the second term on the RHS reflects the disutility of work.[11] θ is the coefficient of relative risk aversion. Lucas (2003) focused much of his attention on this parameter, arguing that the welfare cost of fluctuations in consumption are negligible unless θ is incredibly high. We will restrict ourselves to log utility ($\theta = 1$), and focus attention on χ, which will be an important parameter in determining the welfare costs of nominal

[11] The utility function (and budget constraint below) should also include a term in real money balances, but we follow much of the NNS literature in assuming that this term is negligible. Since we specify an interest rate rule for monetary policy, there is no real need to model money explicitly.

inertia.[12]

The budget constraint of household h is

(15) $E_t[\Delta_{t,t+1}B_{t+1}(h)] + P_t[C_t(h) + I_t(h) + T_t] = B_t(h) + W_t(h)L_t^d(h) + R_tK_{t-1}(h) + D_t(h)$

where the first term on the LHS is a portfolio of contingent claims; I_t is the household's investment in capital, T_t is a lump sum tax (used by the government to balance its budget constraint each period), and the last three terms on the RHS are the household's wage, rental and dividend income.[13] The household's capital accumulation is governed by

(16) $K_t(h) = (1 - \delta)K_{t-1}(h) + I_t(h) - ½\psi[(I_t(h)/K_{t-1}(h)) - \delta]^2K_{t-1}(h)$,

where δ is the depreciation rate, and the last term is the cost of adjusting the capital stock.

Household h maximizes utility, (14), subject to its budget constraint, (15), its labor demand curve, (13), and its capital accumulation constraint, (16). We begin with the wage setting decision. Following Calvo (1983), households set wages in staggered 'contracts' of random duration. In any period t, each household gets to announce a new wage with probability (1-ω); otherwise, the old contract, and its wage, remains in effect. The average duration of a wage contract is $(1-\omega)^{-1}$ periods.

If household h gets to announce a new contract in period t, it chooses the new wage

(17) $W_t^{*1+\phi w\chi} = \mu_w(WB_t/WA_t)$,

where $\mu_w = \phi_w/(\phi_w\text{-}1)$ is a monopoly markup factor, and

(18) $WB_t = E_t\sum_{j=t}^{\infty}(\omega\beta)^{j-t}N_j^{1+\chi}W_j^{\phi w(1+\chi)} = \omega\beta E_tWB_{t+1} + N_t^{1+\chi}W_t^{\phi w(1+\chi)}$,

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[12] Our welfare results are not very sensitive to changes in the value of θ between 1 and 4.

[13] $B_{t+1}(h)$ is the number of (period t+1) dollar claims in the portfolio, contingent on a given state's occurring; $\Delta_{t,t+1}$ is the stochastic discount factor (the price of a dollar claim divided by the probability of the state); and E_t is an expectation over all the states of nature. For a concise discussion of state contingent claims, see Chapter 3 of Cochrane (2001).

(19) $WA_t = E_t\sum_{j=t}^{\infty}(\omega\beta)^{j-t}\lambda_j N_j W_j^{\phi w} = \omega\beta E_t WA_{t+1} + \lambda_t N_t W_t^{\phi w}$,

where λ_j is the household's marginal utility of nominal wealth (to be defined below). As $\omega \rightarrow 0$, all households get to reset their wages each period (the flexible wage case), and $W_t^*(h) = \mu_w N_t^{\chi}/\lambda_t$; that is, the wage is a markup over the (dollar value of the) marginal disutility of work. Since the markup is positive ($\mu_w > 1$), the labor supplied will be inefficiently low in the flexible wage solution. Note that $1/\chi$ is the Frisch (or constant λ_t) elasticity of labor supply; this parameter will play a prominent role in the next section.

When wages are sticky ($\omega > 0$), wage rates will generally differ across households, and firms will demand more labor from households charging lower wages. Our model is inherently one of heterogeneous agents, but our assumption of complete contingent claims markets makes households identical in terms of their consumption and investment decisions.[14] In equilibrium, aggregate consumption will be equal each household's consumption and to per capita consumption – $C_t = \int_0^1 C_t(h)dh = C_t(h)\int_0^1 dh = C_t(h)$ – and the same is true of the aggregate capital stock. So, we can write the equilibrium versions of the households' first order conditions for consumption and investment in terms of aggregate values:

(20) $1/P_tC_t = \lambda_t$,

(21) $\beta E_t[\lambda_{t+1}/\lambda_t] = E_t[\Delta_{t,t+1}] = (1+i_t)^{-1}$

(22) $\lambda_t P_t = \xi_t - \xi_t\psi[(I_t/K_{t-1}) - \delta]$,

(23) $\xi_t = \beta E_t\{\lambda_{t+1}R_{t+1} + \xi_{t+1}[(1-\delta) - ½\psi[(I_{t+1}/K_t) - \delta]^2 + \psi[(I_{t+1}/K_t) - \delta](I_{t+1}/K_t)\}$,

where λ_t and ξ_t are the Lagrangian multipliers for the households' budget and capital accumulation

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[14] The FOC for $B_{t+1}(h)$ is: $\Delta_{t,t+1} = \lambda_{t+1}(h)/\lambda_t(h)$, where $\lambda_t(h)$ is the marginal utility of wealth. All households face the same discount factor, $\Delta_{t,t+1}$; so, if all households have the same initial wealth, $\lambda_t(h) = \lambda_t$ for all h. First order conditions for $C_t(h)$, $I_t(h)$ and $K_t(h)$ are identical for all h.

constraints, and i_t is the return on a 'risk free' bond.[15]

2.3. The aggregate price and wage levels, aggregate employment and aggregate output –

The aggregate price level can be written as

(24) $P_t = [\int_0^1 P_t(f)^{1-\phi p}df]^{1/(1-\phi p)} = [\sum_{j=0}^{\infty} (1-\alpha)\alpha^j(P^*_{t-j}(f))^{1-\phi p}]^{1/(1-\phi p)}$,

since the law of large numbers implies that $(1-\alpha)\alpha^j$ is the fraction of firms that set their prices t-j periods ago, and have not gotten to reset them since. It is straightforward to show that

(25) $P_t^{1-\phi p} = (1-\alpha)P_t^{*1-\phi p} + \alpha(P_{t-1})^{1-\phi p}$.

Similarly, the aggregate wage (defined by equation (12)) can be written as

(26) $W_t^{1-\phi w} = (1-\omega)W_t^{*1-\phi w} + \omega(W_{t-1})^{1-\phi w}$.

These calculations illustrate the beauty of the Calvo scheme for wage and price setting.[16] It allows us to convert the aggregate wage and price levels – complicated integrals over households and firms – into infinite sums, which can then be converted into non-linear difference equations that the computer can solve. This trick will be used below to calculate various wage, price and employment dispersion terms.

In Appendix A, we show that aggregate output can be written as

(27) $Y_t = Z_t K_{t-1}^{\nu} N_t^{1-\nu}/DP_t$,

where $N_t = \int_0^1 N_t(f)df$ is aggregate employment, $K_{t-1} = \int_0^1 K_{t-1}(h)dh = \int_0^1 K_{t-1}(f)df$ is the aggregate capital stock, and $DP_t = \int_0^1 (P_t/P_t(f))^{\phi p}df$ is a measure of price dispersion across firms; DP_t can be written as

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[15] Consider a bond that costs 1 dollar in period t and pays $1+i_t$ dollars in all states of nature in period t+1. $1 = E_t[\Delta_{t,t+1}(1+i_t)]$ (see Chapter 3 of Cochrane (2001)); so, $1/(1+i_t) = E_t[\Delta_{t,t+1}]$.

[16] The ugliness of the Calvo scheme is that there is some probability that any given wage (or price) contract may last for a very long period of time.

(28) $DP_t = (1\text{-}\alpha)(P_t/P^*_t(f))^{\phi p} + \alpha(P_t/P_{t-1})^{\phi p}DP_{t-1}$.

It should be noted that $N_t(f)$ is the firm's demand for a composite labor service (defined by the aggregator (11)). So, our definition of aggregate employment – $N_t = \int_0^1 N_t(f)df$ – is not the simple sum of individual household's work efforts. Similarly, our definition of aggregate output Y_t (defined in equation (4)) is not the simple sum of firm's outputs, and our aggregate price level P_t (equation (5)) does not correspond exactly to measured CPI. Nevertheless, in the empirical work that follows, we will identify N_t, Y_t and P_t with the aggregate employment, output and price levels in the data.[17]

The inefficiency due to price dispersion can be seen in equation (27). Each firm has the same marginal cost (equation (3)); so, consumers should choose equal amounts of the firms' products to maximize the consumption good aggregator (4) for a given resource cost. If prices are flexible ($\alpha = 0$), then $P_t(f) = P_t$ for all f, and this efficiency condition will be met; if prices are sticky ($\alpha > 0$), then product prices will differ, and consumption decisions will be distorted. This distortion is manifested in equation (27). If prices are flexible, $DP_t = 1$ and aggregate output is maximized for a given labor input; if prices are sticky, $DP_t > 1$ and output will be less for a given labor input.

2.4. Monetary and fiscal policy –

Monetary policy and government spending are given empirical specifications; we make no claim that these policies are optimal in any normative sense. We use a standard interest rate rule to describe monetary policy:

(29) $i_t = 0.222 + 0.824i_{t-1} + 0.35552\pi_t + 0.032384(\text{output gap})_t + \epsilon_{i,t}$,

where $\pi_t = \log(P_t/P_{t-1})$ and the standard error of the interest rate shock, $\epsilon_{i,t}$, is .00245. We estimated

[17] Erceg, Henderson and Levin (2000) show that, to a first order of approximation, the difference between our aggregators and a simple linear sum is just a constant. Therefore, the distinction does not matter for the standard deviations we calculate below.

this rule over the Volcker and Greenspan years (1979.3 - 2003.2); Appendix B outlines our estimation procedure and gives our data sources. Here it is important to note that for estimation purposes we define the output gap to be actual GDP minus the Congressional Budget Office's 'potential' GDP.[18]

As noted in the introduction, the interest rate rule and its estimation are quite conventional, but it is not clear how the rule should be interpreted in our NNS model. There is no CBO in the model to provide estimates of potential output. So, we will consider two specifications of monetary policy in our model simulations. Our benchmark case will be what we have called the 'bad' policy rule, where the output gap is defined as the difference between actual output and output in the non-stochastic steady state. The alternative is a 'good' policy rule, where the output gap is defined as the difference between actual output and output that would prevail in the flexible wage/price solution (as defined by Neiss and Nelson (2003)). We have taken the 'bad' policy rule as our benchmark since (as we shall see) the model explains some aspects of the data better with it.

We use an auto regressive process for government spending:

(30) $\log(G_t) = \zeta + 0.973\log(G_{t-1}) + \epsilon_{g,t}$,

where the intercept term, ζ, is chosen to make G/Y = 0.20 in the steady state, and the standard error of the fiscal shock, $\epsilon_{g,t}$, is about 0.01; see Appendix B.

2.5. Welfare –

Our measure of welfare is

(31) $U_t = E_t\sum_{\tau=t}^{\infty}\beta^{\tau-t}[\log(C_\tau) - (1+\chi)^{-1}AL_\tau]$,

where C_t (= $\int_0^1 C_t(h)dh = C_t(h)$ for all h) is per capita consumption, and $AL_t = \int_0^1 L_t(h)^{1+\chi}dh$ is the

[18] Both variables are measured in real percapita terms, and expressed in logarithms.

average disutility of work. If wages are flexible ($\omega = 0$), then $W_t(h) = W_t$ for all h, and firms hire the same amount of work from each household; $AL_t = \int_0^1 L_t(h)^{1+\chi}dh = L_t(h)^{1+\chi}\int_0^1 dh = L_t(h)^{1+\chi}$ for all h. In this special case, households are identical, and our measure of welfare, U_t, reduces to individual household utility $U_t(h)$ (defined by equation (14)).

If wages are sticky ($\omega > 0$), then there is a dispersion of wages that makes firms hire different amounts of work from each household. This creates an inefficiency similar to the inefficiency due to price dispersion: the composite labor service used by firms – $N_t = \int_0^1 L_t(h)^{(\phi w-1)/\phi w}dh]^{\phi w/(\phi w-1)}$ – will not be maximized for a given aggregate labor input $\int_0^1 L_t(h)dh$. This distortion in firms' hiring decisions manifests itself in the AL term in equation (31). In appendix A, we show that

(32) $AL_t = N_t^{1+\chi}DW_t$

(33) $DW_t = (1-\omega)(W_t^*(h)/W_t)^{-\phi w(1+\chi)} + \omega(W_{t-1}/W_t)^{-\phi w(1+\chi)}DW_{t-1}$.

where $DW_t = \int_0^1 (W_t(h)/W_t)^{-\phi w(1+\chi)}dh$ is a measure of wage dispersion, analogous to DP_t for prices.

In summary, nominal inertia creates two distortions in our model: Calvo-style price setting creates a price dispersion – captured by DP_t – that distorts households' consumption decisions, and Calvo-style wage setting creates a wage dispersion – captured by DW_t – that distorts firms' hiring decisions. These distortions interact with the distortions created by monopolistic competition to create what we call the 'welfare cost of nominal inertia'. In the next section, we solve our model numerically to get an idea of the quantitative magnitude of this cost.

3. Implications of the Benchmark Model

Christiano, Eichenbaum and Evans (2001) showed that a more elaborate NNS model was capable of explaining the persistence of monetary shocks exhibited by U.S. data; subsequently, Smets and Wouters (2003) added a rather large number of shocks to their model and showed that an NNS model could replicate many aspects of the U.S. business cycle. Here, we show that a stripped down NNS model, with only a few easily measured shocks, is capable of capturing some basic features of the data. We also show that the model captures much of the volatility of the efficiency gaps emphasized by EHL and GGLS. Once this is established, we use the model to measure the welfare cost of various kinds of nominal inertia. Finally, we discuss some of the ways in which our model may be deficient, and how these deficiencies may affect our welfare calculations.

It should be noted that we are using the ‘bad’ interest rate rule (where the output gap is defined as actual output minus steady state output) in all of the model simulations reported in this section; we have taken the ‘bad’ policy rule as our benchmark case. In the next section, we will show what happens to the model’s fit, and to our estimate of the cost of nominal inertia, if instead we use the ‘good’ interest rate rule (where the output gap is defined as actual output minus flexible wage/price output).

3.1. Matching Model Moments with Moments in the Quarterly U.S. data –

Table 1 specifies the parameters we use in our benchmark calibration. In Appendix B, we discuss our choice of parameter values, our estimation of the interest rate rule and the stochastic processes for productivity and government spending, and our data. Here, we focus attention on just three parameters: $1/\chi$, the Frisch (or constant λ_t) elasticity of labor supply; ρ, the autoregressive parameter in the stochastic process for productivity; and σ, the standard deviation of the innovation in the productivity process.

The Frisch elasticity will be important in our welfare analysis: as explained in the introduction, low values of $1/\chi$ imply high costs of nominal inertia. Empirical estimates of the Frisch elasticity range from 0.05 to 0.35.[19] So, our benchmark specification – $1/\chi = 0.33$ – is quite conservative for the purposes of our welfare analysis. In what follows, we will consider a range of values for $1/\chi$ – 0.14, 0.20, 0.33 and 1.00 – corresponding to $\chi = 7, 5, 3$ and 1; all are conservative in the sense that they in the upper half of the estimated range and beyond.

The persistence and volatility of productivity shocks will also be important in our welfare analysis: high values of ρ and σ imply high costs of nominal inertia. As explained in Appendix B, we have three different estimates of the productivity process, each of which has some merit. Our benchmark is $(\rho, \sigma)_2 = (0.930, 0.008)$, which comes from an estimate of the 1960 - 2002 data (with a linear trend). Our alternative estimates are $(\rho, \sigma)_3 = (0.979, 0.007)$, which comes from King and Rebelo's (1999) review of RBC models, and $(\rho, \sigma)_1 = (0.843, 0.007)$, which comes from an estimate of the 1980 - 2002 data (again, with a linear trend).[20]

Table 2 compares results from our calibrated model with quarterly data from the U.S. economy. The model's variables are expressed as log deviations from a non-stochastic steady state. The U.S. data are also in logs, and both the model data and the actual data have been HP-filtered. We used Dynare (see Juillard (2003)) to calculate the model's steady state, to find a first order approximation, and to calculate the moments reported in Table 2. The table reports results for our benchmark value of $1/\chi$ (0.33) and the alternative values of $1/\chi$ (1, 0.20 and 0.14), and for the U.S. data. Beginning with the row for output and the column headed $1/\chi = 0.33$, 0.014 is the model's standard deviation of output; it is slightly smaller than the standard deviation of output in the data,

[19] See Bayoumi, Laxton and Pesenti (2003) and Gali, Gertler and Lopez-Salido (2002) for a discussion of these studies.

[20] This data period corresponds to the one for our interest rate rule. The two data periods produced very similar estimates for the government spending process; see Appendix B.

0.016, which is given in the last column. Proceeding to the row for consumption and the column for $1/\chi = 0.33$, 0.839 is the ratio of the standard deviation of consumption to the standard deviation of output in the model, and 0.962 is the correlation between consumption and output. These are close to the corresponding statistics in the data. The following three rows provide the same statistics (standard deviations relative to the standard deviation of output and correlations with output) for investment, hours and real wages.[21] The model comes fairly close to matching the data for all these variables, except that real wages and output are more positively correlated in the model than they are in the data.[22]

More to the point for us, Table 2 suggests that the value of $1/\chi$ has almost no effect on the model's moments. Real Business Cycle models need a very elastic labor supply curve to generate the employment volatility that is observed in the data; $1/\chi = 4$ is not unusual in that literature.[23] Employment and output are demand determined in NNS models, and workers may be off their notional labor supply curves. Thus, we do not need an elastic labor supply to match the volatility of employment; we can let $1/\chi$ conform to the empirical estimates.

The rows for inflation, wage inflation and the nominal interest rate in Table 2 alert us to potential weaknesses in the model, weaknesses that may play a role in the welfare analysis that follows. The relative volatilities of price inflation and particularly wage inflation in the model are substantially less than they are in the data. Moreover, the nominal interest rate, price inflation and

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[21] We set the adjustment cost coefficient ψ to make the model's standard deviation of investment relative to the standard deviation of output virtually identical to the corresponding ratio, 3.12, in the data.

[22] This is in contrast to a familiar criticism of an earlier generation of sticky wage models on the grounds that they imply counter-cyclical variation in the real wage.

[23] See for example King and Rebelo (1999).

wage inflation are all negatively correlated with output in the model; by contrast, the interest rate and price inflation are positively correlated with output in the data, while wage inflation is essentially uncorrelated with output. All of these facts suggest that the model may be missing some shocks, or that the shocks that have been included may not have been modeled correctly. We will return to this issue later in Sections 3.3 and 4. Once again, however, the value of $1/\chi$ hardly seems to matter for the model's fit.

The row for the output gap in Table 2 reflects the fact that we are using the 'bad' monetary policy rule in our initial model simulations: the output gap is defined as actual output minus steady state output; so, the gap has the same standard deviation as output, and it is perfectly correlated with output. The interesting thing to note here is that the output gap in the data – output minus the CBO's 'potential' output – comes very close to matching these statistics. This suggests that the CBO's measure of potential output (which was used in the estimation of the policy rule) is essentially detrended output.

The work of Erceg, Henderson and Levin (2000) and (especially) Gali, Gertler and Lopez-Salido (2002) suggests that we may also be able to test our model against the data in a way that is more directly related to welfare. Economic efficiency requires that the marginal rate of substitution (MRS) between consumption and work be equal to the marginal product of labor (MPN). Figure 1, which is borrowed from GGLS, illustrates this efficiency gap. n1 would be employment under perfect competition, n2 is the flexible wage/price solution, and nt is the solution with nominal inertia. Neglecting constant terms,

(34) $gap_t = \log(MRS_t) - \log(MPN_t) = \log(C_t) + \chi\log(N_t) - [\log(Y_t) - \log(N_t)]$,

The efficiency gap can be partitioned into a wage gap,

(35) $wgap_t = \log(MRS_t) - \log(W_t/P_t) = \log(C_t) + \chi\log(N_t) - \log(W_t/P_t)$,

and a price gap,

(36) $pgap_t = \log(W_t/P_t) - \log(MPN_t) = \log(W_t/P_t) - [\log(Y_t) - \log(N_t)]$.

GGLS calculate the volatility of these gaps, using U.S. data, and make inferences about the cost to welfare that this volatility implies. The overall gap is very volatile, and GGLS claim that the welfare cost of U.S. business cycles is high.

Table 3 shows the volatility in these efficiency gaps, both in our model and in the U.S. data. The first number in each cell is the standard deviation of the gap; the second number is the correlation between the gap and output. Our NNS model is capable of generating much of the volatility that is observed in the data.[24] The wage gap is much more volatile than the price gap, suggesting that it is the major source of the welfare costs, as GGLS claim.

3.2. Measuring the welfare cost of nominal inertia –

Let V_t be the value function for aggregate welfare in period t. In light of (31), V_t is given by

(37) $V_t = \log(C_t) - (1+\chi)^{-1}AL_t + \beta E_t[V_{t+1}]$.

In this section, we use Dynare to calculate a second order approximation of V_t under various assumptions about nominal inertia and other key parameters in the model. Assuming state variables are at their deterministic steady state values at time 0, let $V_0(\alpha, \omega)$ represent aggregate utility for an economy with a given type of nominal inertia (characterized by α and ω).[25] The welfare cost of nominal inertia in this economy is

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[24] Our results support GGLS's claim that the observed gaps can be explained without giving an important role to labor supply shocks at business cycle frequencies.

[25] The list of state variables depends on the type of nominal inertia present; for notational simplicity, we have suppressed any reference to state variables in the definition of the V function.

(38) $CC(\alpha, \omega) = V_0(0, 0) - V_0(\alpha, \omega)$.

CC is a cardinal number, and its units are hard to understand. However, following Lucas (2003), we can interpret CC as something that does have comprehensible units. Lucas, in his basic thought experiment, asked how much consumption households would be willing to give up to be free of observed fluctuations in consumption. Let $E_0\sum_{j=0}^{\infty}\beta^j C_{A,j}^{1-r}$ be the utility of actual consumption $\{C_{A,j}\}$, let $E_0\sum_{j=0}^{\infty}\beta^j C_{T,j}^{1-r}$ be the utility of trend consumption $\{C_{T,j}\}$, and let ξ solve the equation $E_0\sum_{j=0}^{\infty}\beta^j((1+\xi)C_{A,j})^{1-r} = E_0\sum_{j=0}^{\infty}\beta^j C_{T,j}^{1-r}$. ξ is Lucas's measure of the welfare cost of fluctuations in consumption; it is the percentage of consumption that households would give up each period to get $\{C_{T,j}\}$ in place of $\{C_{A,j}\}$. How big is ξ? Calibrating this simple model to U.S. consumption data, Lucas argued that ξ is only about one twentieth of one percent of consumption (for values of r less than 4). An implication of Lucas's ingeniously simple calculation is that the welfare cost of nominal inertia – which is after all not the only source of fluctuations in consumption – must be small indeed. As we shall see, our NNS model suggests otherwise.

Our household utility function includes work effort (or leisure), and our model is inherently one of heterogeneous agents. So, it is not obvious how to compare our utility calculations to Lucas'. However, we have already defined an "average" utility function, (31), and we have assumed a log specification for the utility of consumption. So, our $CC(\alpha, \omega)$ can be interpreted as the percentage of consumption households would on average be willing to give up to be free of a particular type of nominal inertia, *assuming that the work effort is held constant*.

To see this, let $\{C_j^*\}$ and $\{AL_j^*\}$ be consumption and the average disutility of work in the flexible wage/price solution, let $\{C_j\}$ and $\{AL_j\}$ be consumption and the average disutility of work in the solution with nominal inertia, and let ξ solve:

(39) $V_0(0,0) = E_0\sum_{j=0}^{\infty}\beta^j[\log(C_j^*) - (1+\chi)^{-1}AL_j^*] = E_0\sum_{j=0}^{\infty}\beta^j[\log((1+\xi)C_j) - (1+\chi)^{-1}AL_j]$

$$= \xi/(1-\beta) + E_0\sum_{j=0}^{\infty}\beta^j[\log(C_j) - (1+\chi)^{-1}AL_j] = \xi/(1-\beta) + V_0(\alpha,\omega)$$

or

(40) $\xi = (1-\beta)[V_0(0,0) - V_0(\alpha,\beta)] = .01*[V_0(0,0) - V_0(\alpha,\omega)]$,

for our assumed value of β. Our $CC(\alpha,\omega) = 100*\xi$, which expresses the costs as percentages of consumption (instead of fractions).

Table 4 presents the consumption cost of our benchmark type of nominal inertia – $(\alpha, \omega) = (0.67, 0.75)$. In our benchmark parameterization – $1/\chi = 0.33$ and $(\rho, \sigma)_2$ – the cost is 1.03% of consumption. Recall that $1/\chi = 0.33$ is at the upper end of the range of empirical estimates for the Frisch elasticity of labor supply. If we use a value closer to the middle of the estimated range – $1/\chi = 0.14$ – the cost of nominal inertia is 2.13% of consumption; if we use a values at the bottom of the range, the cost goes up to 5 or 6%. If we keep the benchmark elasticity of labor supply, but use a productivity process typical of the RBC literature – $(\rho, \sigma)_3$ – the cost is 6 or 7%.

In summary, our NNS model conservatively estimates the cost of nominal inertia to be between 1 and 3% of consumption each period. The costs would certainly seem to be significant.

3.3. Which shocks are important in the model? Is something missing? –

As noted above, our model fails to match the data in a number of potentially important ways. It may be possible to address some of the model's failures by adding shocks and modeling features that have been used in earlier work.[26] However, the negative correlations between (wage and price)

[26] For example, Smets and Wouters (2003) introduced several shocks, including shocks to wage and price setting behavior, that may improve the model's ability to replicate the observed volatilities of wage and price inflation. Our model also lacks the features used by Christiano

inflation and output, and between the nominal interest rate and output, that are generated by the model suggest an absence of demand side shocks.[27] In conventional Keynesian models (like the IS-LM model) an increase in aggregate demand (a shift of the IS curve) raises output and interest rates, and leads to inflationary pressures. Such a demand shock would bring our model closer to matching the positive correlations observed in the data.

Table 5 would seem to confirm these suspicions. It shows a variance decomposition for the model's shocks – the productivity shock, ϵ_p; the interest rate shock, ϵ_i; and finally the government spending shock, ϵ_g. The productivity shock and the interest rate shock each explain about half of the variation in output, consumption, and investment. The interest rate shock explains most of the variation in employment and wage inflation, and the productivity shock explains most of the variation in the real wage rate and price inflation. Clearly, these two shocks play a major role in the welfare calculations of the last section. By contrast, the government spending shock explains very little of the variation in any variable of interest.

The impulse response functions in Figure 2 show what a government spending shock does in our model. Output and inflation go up, causing the central bank to raise the nominal and real interest rates, and investment is crowed out. All of this is consistent with the evidence from the VARs found in Blanchard and Perotti (2001), Canzoneri, Cumby and Diba (2002) and elsewhere. However, consumption is also crowed out in our model, and this is not consistent with the evidence

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Eichenbaum and Evans (2001) to generate persistence. Adding more persistence to wage and price inflation could help increase their standard deviations.

[27] The strong negative correlation between the interest rate and output in our model is also present when we eliminate the nominal rigidity (by setting α and ω equal to zero), and therefore the effect of demand shocks.

from the VARs.[28]

To summarize, wage and price inflation are less volatile in our model than they are in the data, and their correlations with output are negative in the model, but not in the data. Interest rates in our model have a strong negative correlation with output, while the corresponding correlation in the data is positive. Moreover, as we noted in Section 3.1, real wages are more positively correlated with output in the model than they are in the data. The impulse response functions in Figure 2 suggest that the government spending shock should help with all of these problems, but the variance decompositions in Table 5 suggest that government spending shocks are not having much effect in our model. All of these facts suggest that the model may be missing some important demand side shocks, or that government spending shocks have not been modeled correctly; or put in a different way, productivity shocks may be playing a more important role than they should.

4. Two Robustness Exercises

Here, we consider two variants of the model that was analyzed in the last section. We show how each variation affects the model's fit, and how each variation affects our estimate of the cost of nominal inertia. First, we experiment with the degree of nominal inertia. Since our benchmark model does not generate enough variability in wage and price inflation, it seems natural to ask how our results would change if we lowered the degree of nominal rigidity. We also assess the relative importance of wage and price rigidities for welfare. Second, we experiment with the monetary policy rule. In particular, we show how our results would change if we switched to the 'good' interest rate policy (where potential output is represented by the natural rate of output). We also try

[28] RBC models have the same difficulty; see Fatas and Mihov (2000a, b).

eliminating the interest rate shocks.

4.1. Changing the degree of nominal rigidity

In the benchmark calibration, the Calvo parameters are set at α = .67 and ω = .75; the average durations of price and wage contracts are, respectively, three and four quarters. As explained in Appendix B, these settings are standard in the literature. However, Table 2 shows that the volatility of price and (especially) wage inflation is too low in the benchmark calibration. Table 6 reports the same calibration exercise, but with the Calvo parameters (α and ω) set equal to 0.5; that is, we reduce the average duration of both price and wage contracts to two quarters.

Lowering the degree of nominal inertia helps with some of the problems noted in Table 2, but it also creates some new problems. Specifically, Table 6 shows that the model now generates enough variability in price inflation. Wage inflation becomes more variable than it was in Table 2, but is still less variable than in the data. The correlation between wage inflation and output is now consistent with the data. Price inflation and interest rates are still negatively correlated with output, which is not consistent with the data. And other aspects of the model's fit deteriorate somewhat; most notably, hours worked now have less volatility than in the data.

Table 7 presents the consumption costs of different degrees of nominal inertia, under the conservative benchmark assumption that the Frisch elasticity is $1/\chi = 0.33$, and under the more typical estimated value of $1/\chi = 0.14$. The first row of Table 7 is taken from Table 4; it is the cost of nominal inertia in our benchmark case – $(\alpha, \omega) = (0.67, 0.75)$. The second row gives the cost of the wage and price inertia specified in Table 6 – $(\alpha, \omega) = (0.50, 0.50)$. The costs are now about half of what they were in the benchmark case, but they are still quite large compared to Lucas's (2003) figures. In particular, for $1/\chi = 0.14$, which is in the middle of the range of estimates from the labor literature, the cost of nominal inertia is still about one percent of consumption.

The third and forth rows of Table 7 examine the relative importance of wage and price rigidities for welfare. The third row gives the cost of price inertia with flexible wages – $(\alpha, \omega) = (0.67, 0)$; and the last row gives the cost of wage inertia with flexible prices – $(\alpha, \omega) = (0, 0.75)$. Wage inertia appears to be much more costly than price inertia.[29] This result is consistent with the fact that the volatility of the wage gap in Table 3 is much larger than the volatility of the price gap.

4.2. Changing the Monetary Policy Rule

As noted in the introduction, Rotemberg and Woodford (1997) have shown that a policy of smoothing output can lower household welfare in a model that is driven by productivity shocks. We have already noted that productivity shocks play an important role – perhaps too important a role – in our NNS model. Consequently, our benchmark interest rate rule (which defines the output gap as the difference between actual output and steady state output) might be expected to do poorly in terms of welfare; that is why we have called it the 'bad' policy rule. Here, we show how a switch to the 'good' policy rule (which defines the output gap as the difference between actual output and the flexible wage/price output) affects the model's fit and our estimate of the cost of nominal inertia.

In a similar fashion, one might question our interpretation of the residuals in the estimated policy rule. We have treated them as interest rate shocks. An alternative interpretation would be that these deviations from the structural part of the rule represent the Federal Reserve's use of other indicator variables, and that treating the residuals as shocks paints an overly pessimistic view of monetary policy during this period. So, we will also show how eliminating the interest rate shock

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[29] In fact, in the presence of wage inertia, price inertia appears to be welfare improving. There are a number of distortions in our NNS model. Eliminating just one – price inertia – need not increase welfare.

affects the model's fit and our estimate of the cost of nominal inertia.

Table 8 reports the consumption costs of nominal inertia for the 'good' and 'bad' policy rules, with and without the interest rate shock. The interest rate shock does not seem to play a major role in generating the large consumption costs reported in Table 4, but our benchmark definition of the output gap does. Under the 'good' monetary policy rule, consumption costs are about a quarter of what they were in the benchmark case; with the interest rate shock, they are however still five to ten times larger than Lucas's (2003) figure of 1/20th of one percent.

In assessing the cost of nominal inertia, it is clearly important to distinguish between the 'good' and 'bad' policy rules. One way of doing this is to ask which rule makes the model fit the data better. Table 9 compares the model's fit under the 'good' policy rule and the 'bad' policy rule, with the interest rate shock in each case. (Neither rule does well without the interest rate shock; the volatility of employment, for example, falls by half.) The fit deteriorates somewhat as we go from the benchmark (or 'bad') interest rate policy to the 'good' interest rate policy. Most notably, the 'good' policy's output gap does not perform as well as the 'bad' policy's gap; it does not fluctuate enough, and it's correlation with output is not strong enough. Here again, this may be an indication that productivity shocks play too important a role in the model.

5. Conclusion

In this paper, we specified a rather rudimentary NNS model with price and wage inertia, capital formation, and estimated rules describing monetary and fiscal policy. We showed that the model was capable of capturing some features of the U.S. business cycle. However, we also argued that productivity shocks were playing too important a role, or equivalently, that demand side shocks were either missing or improperly modeled; moreover, the model may exhibit too much nominal inertia, especially in wage inflation. These are issues for future research.

We have already summarized our basic results in the introduction: Using the 'bad' policy rule, we estimated the cost of nominal inertia to be twenty to sixty times larger than what Lucas (2003) found: the 'average' household in our model would be willing to give up one to three percent of consumption each period to be free of the effects of wage and price stickiness. If the persistence of productivity shocks is increased to levels used in the RBC literature, or if the elasticity of labor supply is taken from the lower end of the microeconomic estimates, the costs are doubled. We also found that wage stickiness is the primary source of this welfare cost. Using the 'good' policy rule, the cost is however only a quarter the size: one to three quarters of a percent of consumption. These costs are still considerably higher than Lucas's figure (1/20 of one percent), but they are clearly not as alarming. If the 'good' policy rule is an accurate description of monetary policy, then our NNS model is broadly consistent with Lucas's claim; there would not appear to be much room for further improvement in demand management policy. If on the other hand the 'bad' rule is a better description of monetary policy in practice, then there would appear to be considerable room for improvement.

As stated in the introduction, we are inclined to accept the latter view, based upon the way in which the model fits the data under the two specifications of monetary policy. We therefore regard the difference between the consumption costs of nominal inertia under the 'good' and 'bad' policy rules as a rather conservative estimate of the room for improvement in demand management policy.

The estimate is conservative since we have not made any attempt to find, or even characterize, the optimal monetary policy rule in our NNS model. We strongly doubt that the optimal rule will look much like what we have called the 'good' policy rule. Recent theoretical work by Benigno and Woodford (2004) suggests that the optimal rule will also include a wage inflation term, and recent numerical simulations of our own (Canzoneri, Cumby and Diba (2004)), suggest that this wage inflation term can have a very important effect on welfare. So, our estimate of the room for improvement in demand management policy is probably quite conservative.[30]

Two other issues are worth mention before closing. The first is that firms and workers probably derive some benefit from nominal inertia. Why else would they engage in it? Our model does not address the factors that give rise to nominal inertia, and it may therefore overstate the benefits of eliminating it. The second issue – which may well be related to the first – is that our model assumes wage stickiness matters. Goodfriend and King (2001) question the relevance of observed wage inertia on theoretical grounds: "... there is a fundamental asymmetry between product and labor markets. The labor market is characterized by long term relationships where there is opportunity for firms and workers to neutralize the allocative effects of temporarily sticky nominal wages. ... (However), spot transactions predominate in product markets where there is much less opportunity for the effects of sticky nominal prices to be privately neutralized." On the other hand, a growing empirical literature suggests that wage inertia helps NNS models explain the U.S. data: Christiano, Eichenbaum and Evans (2001) found that wage stickiness helps explain persistence in the effects of monetary shocks, and Smets and Wouters (2003) showed that wage stickiness also

[30] Central banks already devote considerable resources to predicting potential output; it may be difficult in practice to obtain much improvement along these lines. Responding to wage inflation (in addition to price inflation) is clearly feasible.; the potential for improvement along these lines deserves more research.

helps explain other features of the data.

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Table 1: Parameters for the Benchmark Calibration

$1/\chi$	ρ	σ	α	ω	ϕ_p	ϕ_w	δ	ψ	ν	β
0.33	0.930	0.008	0.67	0.75	7	7	0.025	8	0.25	0.99

Source: see Appendix B.

Table 2: The Benchmark Calibration of the Model

std / cor	$1/\chi = 1$	$1/\chi = 0.33$	$1/\chi = 0.20$	$1/\chi = 0.14$	actual data
Output	0.014 1.000	0.014 1.000	0.014 1.0000	0.014 1.000	0.016 1.000
Consumption	0.832 0.963	0.839 0.962	0.840 0.961	0.840 0.961	0.799 0.871
Investment	3.112 0.990	3.133 0.992	3.111 0.992	3.118 0.992	3.122 0.893
Hours	0.965 0.633	0.972 0.635	0.972 0.636	0.972 0.636	0.894 0.857
Real wage	0.497 0.577	0.497 0.553	0.493 0.547	0.500 0.543	0.470 0.243
Inflation	0.259 -0.381	0.259 -0.389	0.257 -0.391	0.257 -0.391	0.357 0.330
Wage Inflation	0.084 -0.212	0.077 -0.270	0.076 -0.284	0.076 -0.290	0.375 0.020
Interest rate	0.203 -0.998	0.203 -0.998	0.201 -0.998	0.201 -0.998	0.253 0.333
Output gap	1 1	1 1	1 1	1 1	0.962 0.965

Notes:

1. Both model data and actual data are in logarithms, and have been HP-filtered.
2. Model data was generated by Dynare, using 1[st] order approximations.
3. Actual data are computed using a sample of 1960:1 to 2003:2.
4. Standard deviations for the y column are the first number in each cell. For other columns standard deviations relative to standard deviation of output are the first numbers in each cell. As both n and w are for the nonfarm business sector, we normalize their standard deviations by the standard deviation of real GDP of the nonfarm business sector.
5. Correlations with output are the second number in each cell.
6. The benchmark calibration uses the ‘bad’ monetary policy rule.

Table 3: The Benchmark Calibration of the Efficiency Gaps

std \ correlation	model mrs-mpl gap	model wage gap	model price gap	data mrs-mpl gap	data wage gap	data price gap
$1/\chi = 1$	0.025 0.580	0.022 0.741	0.008 -0.188	0.029 0.730	0.028 0.844	0.011 -0.230
$1/\chi = 0.33$	0.053 0.611	0.050 0.689	0.008 -0.196	0.064 0.807	0.063 0.862	0.011 -0.230
$1/\chi = 0.20$	0.082 0.659	0.078 0.705	0.008 -0.151	0.099 0.826	0.098 0.862	0.011 -0.230
$1/\chi = 0.14$	0.110 0.623	0.106 0.661	0.008 -0.198	0.134 0.834	0.133 0.861	0.011 -0.230

Table 4: Consumption Cost of the Benchmark Wage and Price Inertia, CC(0.67, 0.75)

	$(\rho, \sigma)_1 =$ (0.843, 0.007)	$(\rho, \sigma)_2 =$ (0.923, 0.0086)	$(\rho, \sigma)_3 =$ (0.979, 0.007)
$1/\chi = 1$	0.15	0.47	1.39
$1/\chi = 0.33$	0.28	1.02	3.54
$1/\chi = 0.20$	0.42	1.57	5.71
$1/\chi = 0.14$	0.55	2.11	7.88
$1/\chi = 0.10$	0.58	2.94	11.15
$1/\chi = 0.05$	1.46	5.72	22.19

Table 5: Variance Decomposition for benchmark parameters (in percent)

	ϵ_p	ϵ_i	ϵ_g
consumption	54.94	39.75	5.31
investment	45.95	53.75	0.30
output	52.30	47.60	0.10
hours	9.12	90.70	0.18
real wage rate	98.87	1.09	0.04
inflation	94.94	5.06	0.00
wage inflation	78.09	21.81	0.10
interest rate	49.59	50.38	0.02
marginal cost	85.09	14.90	0.01
real rental rate	22.43	77.45	0.12
mrs-mpl gap	9.65	90.32	0.03
wage gap	6.45	93.52	0.04
price gap	87.07	12.92	0.01

Note: model output is HP-filtered.

Table 6: Calibration with Less Nominal Inertia ($\alpha = \omega = 0.5$)

std / correlation	$1/\chi = 0.33$	$1/\chi = 0.14$	actual data
Output	0.014 1.000	0.014 1.000	0.016 1.000
Consumption	0.840 0.964	0.860 0.962	0.799 0.871
Investment	3.118 0.990	3.042 0.991	3.122 0.893
Hours	0.743 0.634	0.741 0.630	0.894 0.857
Real wage	0.597 0.757	0.601 0.754	0.470 0.243
Inflation	0.354 -0.363	0.357 -0.376	0.357 0.330
Wage Inflation	0.153 0.044	0.154 0.010	0.300 -0.005
Interest rate	0.194 -0.994	0.196 -0.998	0.256 0.349
Output Gap	1 1	1 1	0.962 0.965

Notes:

1. Both model data and actual data are in logarithms, and have been HP-filtered.
2. Model data was generated by Dynare, using 1st order approximations.
3. Actual data are computed using a sample of 1960:1 to 2003:2.
4. Standard deviations for the y column are the first number in each cell. For other columns standard deviations relative to standard deviation of output are the first numbers in each cell. As hours, real wages, and nominal wage inflation are for the nonfarm business sector, we normalize their standard deviations by the standard deviation of real GDP of the nonfarm business sector.
5. Correlations with output are the second number in each cell.
6. This calibration uses the ‘bad’ monetary policy rule.

Table 7: Consumption Costs with Alternative Degrees of Wage and Price Inertia

	$1/\chi = 0.33$	$1/\chi = 0.14$
CC(0.67, 0.75)	1.02	2.11
CC(0.50, 0.50)	0.45	0.95
CC(0.67, 0)	0.13	0.22
CC(0, 0.75)	1.13	2.40

Note: The productivity process, the monetary rule, and other parameters are the benchmark specifications.

Table 8: Consumption Costs with Alternative Policies
(Benchmark Wage/Price Inertia and Productivity Shocks)

	$1/\chi = 1$	$1/\chi = 0.33$	$1/\chi = 0.14$
Policy 1	0.47	1.02	2.11
Policy 2	0.43	0.92	1.92
Policy 3	0.12	0.23	0.46
Policy 4	0.07	0.14	0.26

Notes:

Policy 1 (the 'bad' policy rule):

$i_t = 0.824\, i_{t-1} + (1 - 0.824)\, [\, -\log(\beta) + 2.02\, \pi_t + 0.184\, (\, y_t - \bar{y}\,)\,] + \epsilon_{i,t}$,

$\bar{y}$ is output in the non-stochastic steady state

Policy 2 (the 'bad' policy rule, no shock):

$i_t = 0.824\, i_{t-1} + (1 - 0.824)\, [\, -\log(\beta) + 2.02\, \pi_t + 0.184\, (\, y_t - \bar{y}\,)\,]$

$\bar{y}$ is output in the non-stochastic steady state

Policy 3 (the 'good' policy rule):

$i_t = 0.824\, i_{t-1} + (1 - 0.824)\, [\, -\log(\beta) + 2.02\, \pi_t + 0.184\, (\, y_t - y_{f,t}\,)\,] + \epsilon_{i,t}$,

$y_{f,t}$ is potential output calculated using the level of employment
<u>and</u> the capital stock of the corresponding economy with no nominal rigidity

Policy 4 (the 'good' policy rule, no shock):

$i_t = 0.824\, i_{t-1} + (1 - 0.824)\, [\, -\log(\beta) + 2.02\, \pi_t + 0.184\, (\, y_t - y_{f,t}\,)\,]$

$y_{f,t}$ is potential output calculated using the level of employment
<u>and</u> the capital stock of the corresponding economy with no nominal rigidity

Table 9: The Model Calibration under Alternate Interest Rate Rules (for $1/\chi = 0.33$)

std / cor	c	inv	y	n	w	inf	output gap
Policy 1	0.839 0.962	3.133 0.992	0.014 1.000	0.972 0.635	0.497 0.553	0.259 -0.389	1 1
Policy 3	0.846 0.976	3.044 0.993	0.018 1.000	0.808 0.817	0.368 0.608	0.143 -0.444	0.593 0.808
actual data	0.799 0.871	3.122 0.893	0.016 1.000	0.894 0.857	0.470 0.243	0.357 0.330	0.962 0.965

Notes:

1. Policy 1 is the 'bad' policy rule, with interest rate shock.
2. Policy 3 is the 'good' policy rule, with interest rate shock.

Figure 1: Welfare Gaps

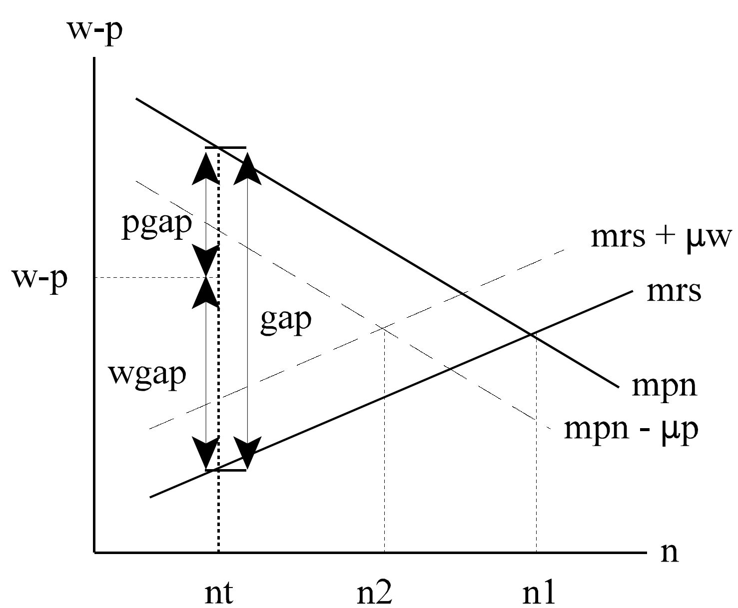
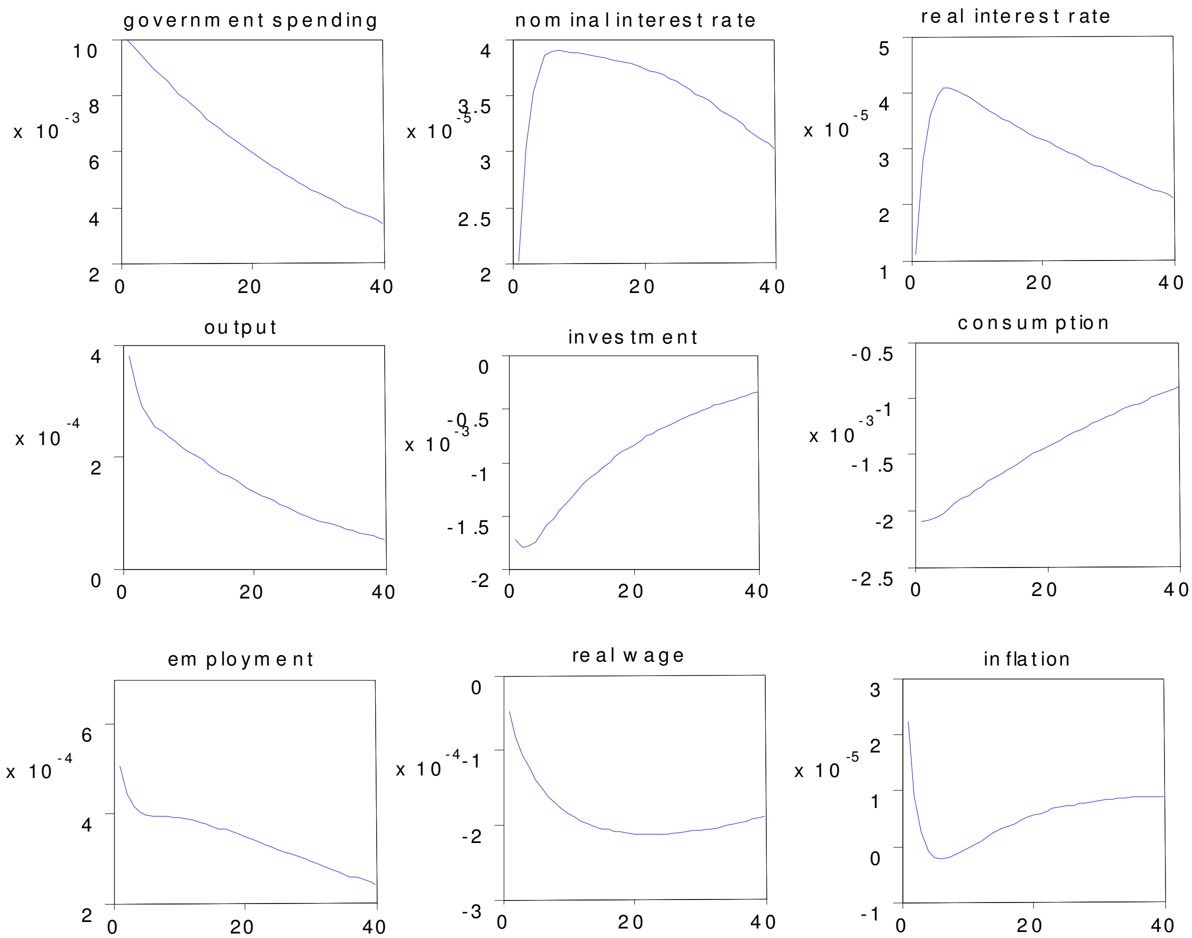


Figure 2: Model's IRF for a Government Spending Shock



Appendix A: Derivations.

Here, we provide derivations for some of the expressions that were asserted in the main text.

A1: The firm's marginal cost (equation (3) in the text) –

Firm f chooses $K_{t-1}(f)$ and $N_t(f)$ to minimize total cost

(A1.1) $TC_t(f) = R_tK_{t-1}(h) + W_tN_t(f)$ s.t. $\bar{Y}_t(f) = Z_tK_{t-1}(f)^{\nu}N_t(f)^{-\nu}$

Ignoring time subscripts and the firm index, the FOC's for this minimization imply

(A1.2) $R/W = [\nu/(1-\nu)](N/K)$

Using this condition in the production function, $Y = ZK^{\nu}N^{1-\nu}$, it is straight forward to see that

(A1.3) $K = (Y/Z)[(W/R)\nu/(1-\nu)]^{1-\nu}$ and $N = (Y/Z)[(W/R)\nu/(1-\nu)]^{-\nu}$

So, total cost can be written as

(A1.4) $TC = RK + WN = (Y/Z)\{R[(W/R)(\nu/(1-\nu))]^{1-\nu} + W[(W/R)\nu/(1-\nu)]^{-\nu}\}$

$= (Y/Z)\{R^{\nu}W^{1-\nu}[\nu/(1-\nu)]^{1-\nu} + W^{1-\nu}R^{\nu}[\nu/(1-\nu)]^{-\nu}\}$

$= (Y/Z)(R^{\nu}W^{1-\nu})\{[\nu/(1-\nu)]^{1-\nu} + [\nu/(1-\nu)]^{-\nu}\} = (Y/Z)(R^{\nu}W^{1-\nu})/[\nu^{\nu}(1-\nu)^{(1-\nu)}]$

and marginal cost can be written as equation (3) in the text.

A2: Aggregate output (equations (27) and (28) in the text) –

Using (A1.3), and the demand curves for the firms output (equation (5) in the text) aggregate employment of the labor bundle can be written as

(A2.1) $N_t = \int_0^1 N_t(f)df = (1/Z_t)[(R_t/W_t)(1-\nu)/\nu]^{\nu}\int_0^1 Y(f)_t df = (1/Z_t)[(R_t/W_t)(1-\nu)/\nu]^{\nu}Y_tDP_t$

where $DP_t \equiv \int_0^1 (P(f)_t/P_t)^{-\phi p}df$. Or equivalently, the aggregate output is

(A2.2) $Y_t = [\nu/(1-\nu)]^{\nu}Z_t(W_t/R_t)^{\nu}N_t/DP_t = Z\{[\nu/(1-\nu)](W_t/R_t)N_t\}^{\nu}N_t^{1-\nu}/DP_t$

Using (A1.2), the aggregate capital stock can be written as

(A2.3) $K_{t-1} = \int_0^1 K(f)_{t-1}df = (W_t/R_t)[\nu/(1-\nu)]\int_F N(f)_t = (W_t/R_t)[\nu/(1-\nu)]N_t$.

In light of (A2.3), (A2.2) becomes

(A2.4) $Y_t = Z_t K_{t-1}{}^{\nu} N_t{}^{1-\nu}/DP_t$,

which is equation (27) in the text.

Recalling that $(1-\alpha)\alpha^j$ is the fraction of firms that reset their prices t-j period ago, and have not gotten to reset them since,

$$\text{(A2.5) } DP_t = \int_0^1 (P_t(f)/P_t)^{-\phi p} df = P_t{}^{\phi p}\int_0^1 (P_t(f)^{-\phi p} df = P_t{}^{\phi p}[\textstyle\sum_{j=0}^{\infty}(1-\alpha)\alpha^j P_{t-j}{}^*(f)^{-\phi p}]$$

$$= P_t{}^{\phi p}(1-\alpha)\textstyle\sum_{j=0}^{\infty}\alpha^j P_{t-j}{}^*(f)^{-\phi p}] = P_t{}^{\phi p}(1-\alpha)P_t{}^*(f)^{-\phi p} + P_t{}^{\phi p}(1-\alpha)\sum_{j=1}^{\infty}\alpha^j P_{t-j}{}^*(f)^{-\phi p}$$

$$= (1-\alpha)(P_t/P_t{}^*(f))^{\phi p} + (P_t/P_{t-1})^{\phi p}[P_{t-1}{}^{\phi p}(1-\alpha)\textstyle\sum_{j=0}^{\infty}\alpha^{j+1}P_{t-j-1}{}^*(f)^{-\phi p}]$$

$$= (1-\alpha)(P_t/P_t{}^*(f))^{\phi p} + (P_t/P_{t-1})^{\phi p}\alpha[P_{t-1}{}^{\phi p}(1-\alpha)\textstyle\sum_{j=0}^{\infty}\alpha^{j}P_{t-j-1}{}^*(f)^{-\phi p}]$$

$$= (1-\alpha)(P_t/P_t{}^*(f))^{\phi p} + (P_t/P_{t-1})^{\phi p}\alpha DP_{t-1}$$

which is equation (28) in the text.

A3: Aggregate disutility of work (equations (30) and (31) in the text) –

Recalling that $L_t^d(h) = (W_t(h)/W_t)^{-\phi w}N_t$, and that $(1-\omega)\omega^j$ is the fraction of households that reset their wages t-j period ago, and have not gotten to reset them since,

$$\text{(A3.1) } AL_t = \int_0^1 L_t(h)^{1+\chi}dh = N_t{}^{1+\chi}\int_0^1 (W_t(h)/W_t)^{-\phi w(1+\chi)}dh = N_t{}^{1+\chi}\textstyle\sum_{j=0}^{\infty}(1-\omega)\omega^j(W_{t-j}^*(h)/W_t)^{-\phi w(1+\chi)}.$$

$DW_t = \int_0^1 (W_t(h)/W_t)^{-\phi w(1+\chi)}dh$ represents wage dispersion (analogous to DP_t above), then

$$\text{(A3.2) } DW_t = (1-\omega)[(W_t^*(h)/W_t)^{-\phi w(1+\chi)} + \textstyle\sum_{j=1}^{\infty}\omega^j(W_{t-j}^*(h)/W_t)^{-\phi w(1+\chi)}]$$

$$= (1-\omega)[(W_t^*(h)/W_t)^{-\phi w(1+\chi)} + (W_{t-1}/W_t)^{-\phi w(1+\chi)}\textstyle\sum_{j=1}^{\infty}\omega^j(W_{t-j}^*(h)/W_{t-1})^{-\phi w(1+\chi)}]$$

$$= (1-\omega)(W_t^*(h)/W_t)^{-\phi w(1+\chi)} + \omega(W_{t-1}/W_t)^{-\phi w(1+\chi)}DW_{t-1}.$$

So finally, we have equations (30) and (31) in the text:

(A3.3) $AL_t = N_t{}^{1+\chi}DW_t$

(A3.4) $DW_t = (1-\omega)(W_t^*(h)/W_t)^{-\phi w(1+\chi)} + \omega(W_{t-1}/W_t)^{-\phi w(1+\chi)}DW_{t-1}$.

Appendix B: Choosing Parameters for the Benchmark Calibration.

I. Estimated Parameters.

Interest rate rule: A substantial literature suggests that monetary policy during the Volker and Greenspan eras can be well described by an interest rate rule of the form,

$$i_t = \gamma_0 + \gamma_1 i_{t-1} + (1-\gamma_1)\gamma_2 \pi_t + (1-\gamma_1)\gamma_3 (y_t - y_t^*) + \epsilon_{i,t},$$

We use nonlinear least squares to estimate the interest rate rule from 1979:3 - 2003:2 and obtain,

γ_0	γ_1	γ_2	γ_3	$\sigma_{\epsilon i}$
0.222 (0.288)	0.824 (0.046)	2.020 (0.342)	0.184 (0.090)	$2.44\text{x}10^{-3}$

Standard errors are in parentheses. Details on all data series are found below.

Productivity: We take the deviation of the log of total factor productivity, z_t, from an estimated linear trend and estimate the autoregression, $z_t = \rho z_{t-1} + \epsilon_{p,t}$ over two sample periods. The first, 1960:1 - 2003:2, yields our benchmark parameterization. The second, 1979:3 - 2003:2, we use for sensitivity analysis. We chose a longer sample to estimate our benchmark processes for productivity because of our concern that shorter samples might be excessively influenced by cyclical factors. The shorter sample, which coincides with the sample used to estimate the interest rate rule, is used for sensitivity analysis because the evidence in Stock and Watson (2002) suggests that several macroeconomic time series have become less volatile since some time around 1980.

Sample	ρ	$\sigma_{\epsilon p}$
1960:1 - 2003:2	0.923 (0.027)	8.61×10^{-3}
1979:3 - 2003:2	0.843 (0.055)	6.74×10^{-3}

Government Purchases: As with productivity, we take the deviation of the log of government purchases from an estimated linear trend and estimate the autoregression, $g_t = \zeta + \rho_g g_{t-1} + \epsilon_{g,t}$. Using the same two samples, we obtain,

Sample	ρ_g	$\sigma_{\epsilon g}$
1960:1 - 2003:2	0.973 (0.015)	1.00×10^{-2}
1979:3 - 2003:2	0.973 (0.023)	9.31×10^{-3}

We then set the constant term in this process so that the model produces a value of G/Y = 0.20 in the steady state.

II. Other Parameters

α: Firms reset prices each quarter with probability $1-\alpha$, so that the mean time between price changes is $(1-\alpha)^{-1}$. Taylor (1999) surveys a large literature and concludes, "price changes and wage changes have about the same average frequency – about one year." This would suggest that we set $\alpha = 0.75$. His conclusion is consistent with the results reported in Gali and Gertler (1999) and Spordone (2001). More recently, Begnino and Woodford (2003) state that survey evidence suggests prices are set slightly less frequently than twice a year, which would suggest using a value for α close to 0.5. Bils and Klenow (2002) report evidence that consumer prices are adjusted on average considerably more frequently than once a year. Like Rotemberg and Woodford (1997), we set $\alpha = 0.67$ so that prices are set on average once each three quarters. This value has the advantage of lying between other values chosen in the literature and is consistent with Blinder's (1994) survey evidence.

ω: Workers reset wages each quarter with probability $1-\omega$, so that the mean time between wage changes is $(1-\omega)^{-1}$. We follow the evidence surveyed in Taylor (1999) and set $\omega = 0.75$ so that wages are reset annually on average.

ϕ_p: We set the elasticity of substitution across goods, $\phi_p = 7$, so that the markup of price over marginal cost, $\mu_p = \phi_p/(\phi_p-1)$ is about 17 percent. Estimates of the markup reported in the literature vary across sectors from about 11 percent to 23 percent. See Bayoumi, Laxton, and Pesenti (2003). Although the evidence suggests that the15 percent markup used by Rotemberg and Woodford (1997) is a reasonable value for the U.S. manufacturing sector, the evidence cited in Bayoumi, Laxton, and

Pesenti indicates that markups outside of manufacturing are higher. As a result we selected a value in the middle of the range of values in Bayoumi, Laxton, and Pesenti.

ϕ_w: We set the elasticity of substitution across workers, $\phi_w = 7$, so that the wage markup, $\mu_w = \phi_w/(\phi_w-1)$ is about 17 percent. This is based on evidence on inter-industry wage differentials discussed in Bayoumi, Laxton, and Pesenti (2003).

ν: We set the capital share to be 0.25. Prices are set so that $P = \mu_p MC$, and marginal cost can be written as the ratio of wages to the marginal product of labor. Thus $P = \mu_p [WN/(1-\nu)Y]$ and $(1-\nu) = \mu_p[WN/PY]$. The labor share of compensation (compensation of employees plus two-thirds of proprietors' income relative to GDP - indirect business taxes) in U.S. data averaged about two-thirds between 1960:1 - 2003:2. With a markup of about 17 percent, this suggests a value of ν = 0.25.

δ: We set $\delta = 0.025$ so that 2.5 percent of the capital stock depreciates each quarter. This value is widely used in the literature. When combined with our value of ν and our steady state calibration of G/Y = 0.20, this assumption yields steady state values of I/Y = 0.15 and C/Y = 0.65.

ψ: We set the capital adjustment cost parameter, $\psi = 8.0$, in order to match the relative volatilities of investment and output as closely to the data as possible.

β: We set the discount factor, $\beta = 0.99$.

III. The Data

G: Real government consumption and gross investment per capita. Real government consumption and gross investment is from NIPA Table 1.2 and population is from NIPA Table 8.7.

I: Real fixed investment per capita. Real fixed investment is computed as the ratio of fixed investment to the implicit price deflator for fixed investment. Fixed investment is from NIPA Table 1.1, the implicit deflator for fixed investment is from NIPA Table 7.1, and population is from NIPA Table 8.7

i: Effective Federal Funds rate from the historical data from Federal Reserve Release H.15. They are reported in percent per annum. Before running the regressions for the interest rate rule, we divided by 1200 to convert to a decimal amount per month.

K: Real nonresidential fixed assets. We follow Stock and Watson (1999) in constructing our measure of the capital stock. We begin by computing real nonresidential fixed assets by taking the ratio of nonresidential fixed assets to the implicit deflator for fixed investment. This yields an annual series for fixed capital. We create a quarterly series by interpolating using the quarterly values for real fixed investment.

N: Hours worked per capita. We take hours worked from the BLS index of aggregate hours worked in the nonfarm business sector from historical data from Table 2 of the BLS Productivity and Cost releases. Population is from NIPA Table 8.7.

π: Inflation, computed as $\log(P_t/P_{t-1})$, where P_t is the CPI-U.

W: Real hourly compensation. We take real hourly compensation for the nonfarm business sector from historical data from Table 2 of the BLS Productivity and Cost releases. Nominal wages are computed by multiplying real wages by the nonfarm business deflator.

y: Real per capita GDP, taken from NIPA Table 8.7.

y*: Per capita potential GDP. We use the Congressional Budget Office's estimate of potential GDP. The data are from Backup Data for Table 2-5, Key Assumptions in CBO's Projection of Potential GDP (By calendar year) The Budget and Economic Outlook: Fiscal Years 2004-2013, January 2003 and are posted on the CBO web site. Population is from NIPA Table 8.7.

z: Total factor productivity, computed as $z_t = ynfb_t - \nu \log(K_t) - (1-\nu) \log(N_t)$. The log of real GDP in the nonfarm business sector (ynfb) is from NIPA table 1.8. In computing total factor productivity, we use aggregate hours worked, rather than aggregate hours worked per capita.