

On the Transmission of Monetary Policy Shocks

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September 2000

Abstract

Empirical studies reveal that a monetary shock typically leads to persistent changes in real GDP and a weakly procyclical response of real wages. Traditional Keynesian models with sticky wages are often dismissed because of their countercyclical real wages implication. The standard sticky price models, on the other hand, tend to generate strongly procyclical real wage movements. More recently, the debate on whether sticky price or sticky wage models can generate persistent real effects of monetary shocks has held a central stage in the literature. This paper explores the role of three popular mechanisms in transmitting monetary shocks in a dynamic general equilibrium environment: staggered price-setting, staggered wage-setting, and a round-about input-output structure. We show that, with reasonable parameter values, the model with all three types of rigidities goes a long way in explaining the observed output persistence and the cyclical behavior of real wages following monetary shocks. Further, contrary to the common belief, our analysis reveals that a model that simply combines sticky prices and sticky wages does not generate acyclical or weakly procyclical real wages when capital is used in production; but a model that also incorporates intermediate goods does.

Key Words: staggered contracts; input-output structure; persistence; real wage cyclicity; monetary policy. *JEL classification:* E31, E32, E52

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1 Introduction

The identification of an appropriate monetary transmission mechanism has held a central stage in macroeconomics for decades. Over the years, a common criterion used in the literature to judge the empirical validity of competing theories has been to examine their ability to explain the observed weakly procyclical real wage movements following a monetary policy shock.¹ Traditional Keynesian models with sticky nominal wages are often criticized because they imply countercyclical real wages in response to aggregate demand shocks (e.g., McCallum (1986) and Romer (1996, p. 216)). On the other hand, models with sticky prices usually predict real wage movements that are too procyclical following a monetary shock (e.g., Christiano, Eichenbaum, and Evans (1997)). More recently, much attention has been shifted to identifying monetary transmission mechanisms in a dynamic general equilibrium (DGE) environment where individuals' optimizing behaviors are explicitly considered. In this strand of literature, alternative models are commonly evaluated based on their ability to explain the observed persistent movements of real output in response to a monetary policy shock (e.g., Chari, Kehoe, and McGrattan (2000), Huang and Liu (1998), and Bergin and Feenstra (2000)). Yet, few attempts have been made to judge a model's empirical relevance based on both criteria. We argue in this paper that looking at both criteria can play an important role in the search of a proper monetary transmission mechanism in a DGE environment.

To illustrate this point, we first construct a DGE model that features three types of rigidities, including staggered price contracts, staggered wage contracts, and the use of intermediate goods in production. Then we establish that any subset of the model with fewer rigidities cannot explain the observed effects of a monetary shock on *both* real wages and aggregate output, while the model with all three ingredients is more successful in explaining these empirical regularities.

In our model with the three types of rigidities, pricing and wage decisions are staggered (e.g., Taylor (1980) and Blanchard (1983)). That is, in each period, there is only a fraction of firms (households) who can adjust prices (wages) and once adjusted, a price (wage) remains effective for several periods. We derive optimal pricing and wage-setting rules by assuming monopolistic competition in both the goods market and the labor market (e.g., Blanchard and Kiyotaki (1987)). In the model, each firm is endowed with a production technology that requires labor, capital, and intermediate goods as inputs and yields a differentiated product

¹For some recent evidence on the weak and positive response of real wages following an expansionary monetary shock, see Christiano, Eichenbaum, and Evans (1997, 1999).

as an output. The capital input and the intermediate goods are both composites of all types of goods, while the labor input is a composite of all types of labor skills supplied by the households. Each household is endowed with a differentiated labor skill and derives utility from consumption of a composite good, real money balances, and leisure time. It supplies capital and its own labor skill to all firms. There is a government that conducts monetary policy by injecting newly created money into the economy through lump-sum transfers to the households. We find that both the nominal rigidities in the forms of staggered price and wage contracts and the real rigidity introduced through the input-output structure are crucial in explaining the observed persistent fluctuations of real output and the weakly procyclical movements of real wages following a monetary shock.

In the literature, staggered price (or wage) contracts have been considered a promising avenue to explain the observed persistent real effects of money supply. The recent literature has been focused on examining the implications of Taylor type of nominal contracts in a DGE environment, with pricing and wage-setting rules being derived from individual optimization. A leading example is Chari, et al. (2000). They find that a staggered price mechanism, by itself, is not able to generate the observed real persistence because, in a DGE environment, the key persistence parameter is linked to fundamental parameters in preferences and technologies, and under calibrated values of the fundamental parameters, the implied persistence parameter is inadequate to reproduce the observed persistence. We further show here that the response of real wages to a money supply shock in the staggered price model is *strong* and procyclical for reasonable parameter values, in contrast to a weak response in the data. On the other hand, Huang and Liu (1998) address the persistence issue by looking instead at a model with staggered *wage* contracts. They derive optimal wage-setting rules by assuming monopolistic competition in the labor market and show that the model generates a substantial amount of real persistence. Yet, as we show here, the response of real wages in their model is strong and countercyclical.²

It seems intuitively appealing that a model incorporating both staggered price and staggered wage contracts can potentially dampen the response of real wages while generating substantial output persistence. This intuition was initially suggested by Blanchard (1986) who argues that, in a model that combines both types of nominal rigidities, aggregate demand

²The recent literature on the real effects of money in DGE models with nominal rigidities also includes Rotemberg (1996), Yun (1996), Gust (1997), Rotemberg and Woodford (1997), Dotsey, et al. (1997, 1999), Ambler, et al. (1999), and Erceg, et al. (2000).

shocks should have long-lasting effects on real output while producing no systematic relation between real wages and output. We find here that, in a DGE environment, this intuition is only partially true. Within a reasonable range of parameter values, such a model does generate more real persistence than does a staggered price model and it does produce a weaker response of real wages than does either a staggered price model or a staggered wage model. But compared to the model with staggered wages, it does not help magnify output persistence while it does share with the staggered wage model the prediction that the real wage response is countercyclical.

The reason why the real wage response is countercyclical when both types of nominal rigidities are combined is that the price level is less sticky than the wage index in equilibrium. This follows from the quick change in marginal production cost in response to the shock, where the marginal cost is a weighted average of the nominal wage index and the nominal rental rate on capital. Since nominal wages are sticky while the capital rental rate is not, the marginal cost changes more quickly than does the wage index. Yet, compared to the model with staggered wage contracts, the real wage response is here weaker because, given that pricing decisions are also staggered, the price level becomes more sticky than in the model with only staggered wage contracts.

When we introduce intermediate goods in production along the lines of Basu (1995), the models' implications are quite different. Basu's model features a roundabout input-output production structure. He shows that the input-output connections among firms allow sticky-price models to explain much larger output fluctuations.³ We show that adding intermediate goods is however insufficient to make the predictions of either the staggered price model or the staggered wage model empirically plausible, as it does not reverse the counter-factual predictions of these models about the cyclical response of real wages. Yet, incorporating intermediate goods goes a long way in improving the predictions of a model that combines both type of nominal rigidities because it helps generate more real persistence and more importantly, it helps produce a weakly procyclical response of real wages following a monetary shock. The main reason behind this finding is that, with intermediate goods, the price level enters as an additional component of the marginal cost and the rigidity in the price level due to staggered contracts helps reduce the variability of the marginal cost and hence increases the rigidity

³The literature on the importance of input-output structure in magnifying aggregate fluctuations can be traced back at least to Means (1935). More recent literature includes Blanchard (1983, 1987), Gordon (1990), Duper (1999), Horvath (1998, 2000), Clark (1999), Huang and Liu (1999), and Bergin and Feenstra (2000).

in firms' pricing decisions. The larger the share of intermediate goods in production, the more sluggish is the price adjustment and, given the stickiness of nominal wages, the more likely for the real wage to rise following an expansionary monetary shock. The input-output structure thus creates a real rigidity in the sense of Ball and Romer (1990), which, coupled with staggered price and staggered wage contracts, magnifies the real persistence and yields a weakly procyclical response of real wages in accordance with empirical evidence.

In what follows, we present the model in Section 2, describe the calibration methods in Section 3, summarize the findings in Section 4, and conclude in Section 5.

2 The model

The economy is populated by a large number of households and firms. There is a government conducting monetary policy. In each period t , a shock s_t is realized. The history of events up to date t is denoted by $s^t \equiv (s_0, \dots, s_t)$, with probability $\pi(s^t)$. The initial realization s_0 is given.

A household $i \in [0, 1]$ is endowed with a differentiated labor skill $L(i, s^t)$. It purchases a composite of differentiated goods $X(i, s^t)$ that can be either consumed or invested. It derives utility from consumption $C(i, s^t)$, real money balances $M(i, s^t)/\bar{P}(s^t)$, and leisure $1 - L(i, s^t)$, where the total time endowment is normalized to unity. The utility function is given by

$$U^i \equiv \sum_{t=0}^{\infty} \sum_{s^t} \beta^t \pi(s^t) [\ln C^*(i, s^t) + \eta \ln(1 - L(i, s^t))], \quad (1)$$

where $\beta \in (0, 1)$ is a discount factor and $C^*(i) \equiv [bC(i)^\nu + (1 - b)(M(i)/\bar{P})^\nu]^{1/\nu}$ is a CES composite of consumption and real money balances. In each period t and for each event s^t , the household faces a budget constraint given by

$$\begin{aligned} \bar{P}(s^t)X(i, s^t) + \sum_{s^{t+1}} D(s^{t+1}|s^t)B(i, s^{t+1}) + M(i, s^t) \leq \\ W(i, s^t)L^d(i, s^t) + R^k(s^t)K(i, s^{t-1}) + \Pi(i, s^t) + B(i, s^t) + M(i, s^{t-1}) + T(i, s^t), \end{aligned} \quad (2)$$

where $B(i, s^{t+1})$ is i 's holding of a nominal bond that costs $D(s^{t+1}|s^t)$ dollars at s^t and pays one dollar in period $t+1$ if s^{t+1} is realized, $W(i, s^t)$ is a nominal wage of i 's labor skill, $L^d(i, s^t)$ is a demand schedule for type i labor, $R^k(s^t)$ is a nominal rental rate on capital, $K(i, s^{t-1})$ is i 's beginning-of-period capital stock, $\Pi(i, s^t)$ is its share of profits, and $T(i, s^t)$ is a lump-sum transfer it receives from the government. The composite good $X(i, s^t)$ can be either consumed

or invested. Thus

$$X(i, s^t) = C(i, s^t) + K(i, s^t) - (1 - \delta)K(i, s^{t-1}) + \psi \frac{(K(i, s^t) - K(i, s^{t-1}))^2}{K(i, s^{t-1})}, \quad (3)$$

where $\delta \in (0, 1)$ is a capital depreciation rate and the quadratic term is a capital adjustment cost with a scale parameter $\psi > 0$.

The consumption or investment good $X(i, s^t)$ is a CES composite of a continuum of differentiated goods (e.g., Dixit and Stiglitz (1977)). In particular,

$$X(i, s^t) = \left[\int_0^1 X(i, j, s^t)^{\frac{\theta-1}{\theta}} dj \right]^{\frac{\theta}{\theta-1}}, \quad (4)$$

where $\theta > 1$ is an elasticity of substitution between differentiated goods. Minimizing expenditures on all goods subject to (4) results in the demand function of i for good j . It is given by

$$X^d(i, j, s^t) = \left(\frac{P(j, s^t)}{\bar{P}(s^t)} \right)^{-\theta} X(i, s^t), \quad (5)$$

where $\bar{P}(s^t) \equiv \left(\int_0^1 P(j, s^t)^{1-\theta} dj \right)^{\frac{1}{1-\theta}}$ is a price index. The total demand of all households for good j is the sum of all individual demand, that is,

$$X^d(j, s^t) = \left(\frac{P(j, s^t)}{\bar{P}(s^t)} \right)^{-\theta} \int_0^1 X(i, s^t) di. \quad (6)$$

Good $j \in [0, 1]$ is produced using an intermediate good $Z(j, s^t)$, a capital stock $K(j, s^t)$, and a composite of labor skills $L(j, s^t)$. The production function is given by

$$Y(j, s^t) = Z(j, s^t)^\phi K(j, s^t)^{(1-\phi)\alpha} L(j, s^t)^{(1-\phi)(1-\alpha)}, \quad (7)$$

where $\phi \in [0, 1]$ is the share of intermediate goods in production and $\alpha \in (0, 1)$ is the share of capital in value added. The intermediate good is a composite of all types of goods. That is,

$$Z(j, s^t) = \left[\int_0^1 Z(j, k, s^t)^{\frac{\theta-1}{\theta}} dk \right]^{\frac{\theta}{\theta-1}}. \quad (8)$$

The capital input is also a composite good supplied by the households. The labor input is a composite of all types of labor skills. Specifically,

$$L(j, s^t) = \left[\int_0^1 L(j, i, s^t)^{\frac{\sigma-1}{\sigma}} di \right]^{\frac{\sigma}{\sigma-1}}, \quad (9)$$

where $\sigma > 1$ is an elasticity of substitution between differentiated labor skills.

Solving firm j 's cost-minimization problem results in factor demand functions and a demand function for the intermediate goods. They are given by

$$K^d(j, s^t) = \frac{(1 - \phi)\alpha V(s^t)}{R^k(s^t)} Y(j, s^t), \quad (10)$$

$$L^d(j, i, s^t) = \left(\frac{W(i, s^t)}{\bar{W}(s^t)} \right)^{-\sigma} \frac{(1 - \phi)(1 - \alpha)V(s^t)}{\bar{W}(s^t)} Y(j, s^t), \quad i \in [0, 1], \quad (11)$$

$$Z^d(j, k, s^t) = \left(\frac{P(k, s^t)}{\bar{P}(s^t)} \right)^{-\theta} \frac{\phi V(s^t)}{\bar{P}(s^t)} Y(j, s^t), \quad k \in [0, 1], \quad (12)$$

where $\bar{W}(s^t) \equiv \left(\int_0^1 W(i, s^t)^{1-\sigma} di \right)^{\frac{1}{1-\sigma}}$ is a wage index and $V(s^t)$ is a unit cost function that is firm independent and is given by

$$V(s^t) = \tilde{\phi} \bar{P}(s^t)^\phi R^k(s^t)^{(1-\phi)\alpha} \bar{W}(s^t)^{(1-\phi)(1-\alpha)}, \quad (13)$$

with $\tilde{\phi} \equiv \phi^{-\phi} (1 - \phi)^{-(1-\phi)} \alpha^{-(1-\phi)\alpha} (1 - \alpha)^{-(1-\phi)(1-\alpha)}$.

The total demand for a type i labor skill is equal to the sum of all individual firms' demand, that is,

$$L^d(i, s^t) = \left(\frac{W(i, s^t)}{\bar{W}(s^t)} \right)^{-\sigma} L(s^t), \quad (14)$$

where $L(s^t) \equiv \frac{\int_0^1 \int_0^1 W(i, s^t) L(i, j, s^t) di dj}{\bar{W}(s^t)} = \frac{(1-\phi)(1-\alpha)V(s^t)}{\bar{W}(s^t)} \int_0^1 Y(j, s^t) dj$, with the second equality obtained from cost minimization.

Given the households' demand for consumption or investment goods and the firms' demand for intermediate inputs, we obtain the demand function for good j . In light of (6) and (12), it is given by

$$Y^d(j, s^t) = \left(\frac{P(j, s^t)}{\bar{P}(s^t)} \right)^{-\theta} Y(s^t), \quad (15)$$

where $Y(s^t) \equiv \int_0^1 X(i, s^t) di + \frac{\phi V(s^t)}{\bar{P}(s^t)} \int_0^1 Y^d(j, s^t) dj$. It follows that

$$Y(s^t) = \frac{X(s^t)}{1 - \phi V(s^t) G(s^t) / \bar{P}(s^t)}, \quad (16)$$

where $X(s^t) \equiv \int_0^1 X(i, s^t)$ and $G(s^t) \equiv \bar{P}(s^t)^\theta \int_0^1 P(j, s^t)^{-\theta} dj$. Note that $X(s^t)$ corresponds to aggregate value-added, or real GDP.

We are interested in the dynamic effects of a monetary policy shock on output and real wages. In this economy, monetary policy is conducted via a lump-sum transfer. Money stock grows at a rate $\mu(s^t)$. In particular, we have

$$\int_0^1 T(i, s^t) = M^s(s^t) - M^s(s^{t-1}), \quad M^s(s^t) = \mu(s^t) M^s(s^{t-1}), \quad (17)$$

and the money growth rate follows a stationary stochastic process given by

$$\ln \mu(s^t) = \rho \mu(s^{t-1}) + \varepsilon_t, \quad (18)$$

where $0 < \rho < 1$ and ε_t is a white noise process with a zero mean and a finite variance σ_ε^2 .

To generate real effects of monetary shocks, we assume that firms' pricing decisions and households' wage-setting decisions are staggered. Specifically, upon the realization of s^t in each period t , a fraction $1/N_p$ of firms sets new prices and a fraction $1/N_w$ of households sets new wages. Once set, a price (or a wage) remains effective for N_p (or N_w) periods.

Under staggered price contracts, if firm $j \in [0, 1]$ can set a new price in period t , it solves

$$\text{Max}_{P(j, s^t)} \sum_{\tau=t}^{t+N_p-1} \sum_{s^\tau} D(s^\tau | s^t) [P(j, s^t) - V(s^\tau)] Y^d(j, s^\tau), \quad (19)$$

where $V(s^\tau)$ is the unit cost function given by (13) and $Y^d(j, s^\tau)$ is the demand function for good j given by (15). Note that, given the constant-returns-to-scale technology, the unit cost is also the marginal cost. The solution to (19) yields an optimal pricing rule

$$P(j, s^t) = \frac{\theta}{\theta - 1} \frac{\sum_{\tau=t}^{t+N_p-1} \sum_{s^\tau} D(s^\tau | s^t) V(s^\tau) Y^d(j, s^\tau)}{\sum_{\tau=t}^{t+N_p-1} \sum_{s^\tau} D(s^\tau | s^t) Y^d(j, s^\tau)}. \quad (20)$$

This equation says that firm j 's optimal price is a constant markup over a weighted average of its marginal costs within the contract duration, with the weights given by normalized quantities demanded. If there is no staggering, that is, if $N_p = 1$, the optimal price is a markup over the current period marginal cost.

Under staggered wage contracts, if household i can set a new wage, it chooses $W(i, s^t)$, along with $C(i, s^t)$, $K(i, s^t)$, $B(i, s^{t+1})$, $M(i, s^t)$, to maximize utility (1) subject to the budget constraints (2)-(3), a borrowing constraint $B(i, s^t) \geq -\bar{B}$ for some large positive number \bar{B} , and the labor demand schedule (14). It takes prices set by firms and wages set by other households as given. The initial conditions $B(i, s^0)$, $M(i, s^{-1})$, and $K(s^{-1})$ are also taken as given. The first order conditions are

$$\frac{U_m(i, s^t)}{\bar{P}(s^t)} = \frac{U_c(i, s^t)}{\bar{P}(s^t)} - \beta \sum_{s^{t+1}} \pi(s^{t+1} | s^t) \frac{U_c(i, s^{t+1})}{\bar{P}(s^{t+1})}, \quad (21)$$

$$D(s^{t+1} | s^t) = \beta \pi(s^{t+1} | s^t) \frac{U_c(i, s^{t+1})}{U_c(i, s^t)} \frac{\bar{P}(s^t)}{\bar{P}(s^{t+1})}, \quad (22)$$

$$U_c(i, s^t) \left[1 + 2\psi \left(\frac{K(i, s^t)}{K(i, s^{t-1})} - 1 \right) \right] = \beta \sum_{s^{t+1}} \pi(s^{t+1} | s^t) U_c(i, s^{t+1}) \left\{ \frac{R^k(s^{t+1})}{P(s^{t+1})} + 1 - \delta + \psi \left(\left(\frac{K(i, s^{t+1})}{K(i, s^t)} \right)^2 - 1 \right) \right\}, \quad (23)$$

$$\begin{aligned}
& \sum_{\tau=t}^{t+N_w-1} \sum_{s^\tau} \beta^{\tau-t} \pi(s^\tau|s^t) U_L(i, s^\tau) \frac{\partial L^d(i, s^\tau)}{\partial W(i, s^t)} = \\
& \sum_{\tau=t}^{t+N_w-1} \sum_{s^\tau} \beta^{\tau-t} \pi(s^\tau|s^t) \frac{U_c(i, s^\tau)}{\bar{P}(s^\tau)} L^d(i, s^\tau) (1 - \sigma), \tag{24}
\end{aligned}$$

where $U_c(i, s^t)$, $U_m(i, s^t)$, and $U_L(i, s^t)$ denote the marginal utility of consumption, real money balances, and leisure, respectively, and $\pi(s^\tau|s^t) = \pi(s^\tau)/\pi(s^t)$ is the conditional probability of s^τ given s^t , for $\tau \geq t$.

Equations (21)-(23) are standard first order conditions with respect to money balances, bond holdings, and capital investment, respectively. Equation (24) corresponds to the wage-setting rule. The left-hand side of (24) is the expected present value of marginal utility gains resulting from an increase in wage and thus more leisure time within the contract duration, while the right-hand side is the expected present value of marginal utility losses because of unemployed hours and thus a lower wage income. The wage is set to balance the gains and the losses at the margin. Given the labor demand function (14), the wage setting rule (24) can be rewritten as

$$W(i, s^t) = \frac{\sigma}{\sigma - 1} \frac{\sum_{\tau=t}^{t+N_w-1} \sum_{s^\tau} \beta^{\tau-t} \pi(s^\tau|s^t) U_L(i, s^\tau) L^d(i, s^\tau)}{\sum_{\tau=t}^{t+N_w-1} \sum_{s^\tau} \beta^{\tau-t} \pi(s^\tau|s^t) [U_c(i, s^\tau)/\bar{P}(s^\tau)] L^d(i, s^\tau)}, \tag{25}$$

which says that the optimal wage is a constant “markup” over the ratio of average marginal utilities of leisure within the contract duration to average marginal utilities of income during the same periods, both weighted by normalized labor demand. In the case with $N_w = 1$, the optimal wage is simply a “markup” over the marginal rate of substitution between leisure and consumption.

An equilibrium in this economy consists of allocations $C(i, s^t)$, $M(i, s^t)$, $K(i, s^t)$, and $B(i, s^t)$ and wage $W(i, s^t)$ for household $i \in [0, 1]$; allocations $Z(j, s^t)$, $K(j, s^t)$, and $L(j, s^t)$ and price $P(j, s^t)$ for firm $j \in [0, 1]$; together with prices $D(s^{t+1}|s^t)$, $\bar{P}(s^t)$, and $\bar{W}(s^t)$ that satisfy the following conditions: (i) taking all wages and prices but its own as given, each firm’s allocations and price solve its profit maximization problem; (ii) taking all prices and wages but its own as given, each household’s allocations and wage solve its utility maximization problem; (iii) capital market, money market, and bond market all clear; (iv) monetary policy is as specified.

To compute an equilibrium, we first reduce the equilibrium conditions to four equations, including a pricing decision equation, a wage-setting equation, a capital Euler equation, and a money demand equation. The decision variables are current prices, current wages, aggregate

consumption, and aggregate capital stock. These variables are functions of the state variables that consist of lagged prices, lagged wages, the capital stock, and the money growth rate. We then log-linearize the equilibrium conditions around a deterministic steady state, and compute the linear decision rules using standard methods.⁴

3 The calibration

The parameters to be calibrated include the subjective discount factor β , the preference parameters b , ν , and η , the share ϕ of intermediate goods in production, the share α of capital income in value-added, the elasticity of substitution σ between labor skills and θ between goods, the capital depreciation rate δ , the adjustment cost parameter ψ , the duration of nominal contracts N_p and N_w , and the monetary policy parameters ρ and σ_e . The calibrated values are summarized in Table I.

Following the standard business cycle literature, we choose $\beta = 0.99$, $\alpha = 1/3$, and $\delta = 0.021$. Following Chari, et al. (1998), we set $\theta = 10$, corresponding to a steady state markup of 11%.

To assign values for b and ν , we use the implied money demand equation

$$\log\left(\frac{M(s^t)}{P(s^t)}\right) = -\frac{1}{1-\nu}\log\left(\frac{b}{1-b}\right) + \log(C(s^t)) - \frac{1}{1-\nu}\log\left(\frac{R(s^t)-1}{R(s^t)}\right),$$

where $R(s^t) = (\sum_{s^{t+1}} D(s^{t+1}|s^t))^{-1}$ is the gross nominal interest rate. A regression of consumption velocity on nominal interest rates implies that $b = 0.998$ and $\nu = -1.75$. The implied interest elasticity is 0.36, with a standard error of 0.04, similar to those obtained by Chari, et al. (2000) and Lucas (1988).

To calibrate σ , the elasticity of substitution between labor skills, we resort to the microstudies by Griffin (1992, 1996). Griffin uses disaggregated firm-level data and obtains estimates of σ values in the range between 2 and 6. We thus choose $\sigma = 4$ as a benchmark. Under this value of σ , a one percent rise in a household's nominal wage relative to the wage index implies a four percent fall in its employed hours relative to aggregate employment.

In what follows, we compare the implications of six alternative models on the dynamic responses of real output and real wages. These include a model with staggered prices, staggered wages, and intermediate goods (SPWI), which is presented in Section 2, and five special cases obtained by restricting the values of the parameters N_p , N_w , and ϕ . The five special cases are:

⁴Details of computation methods are available upon request.

(1) a model with staggered prices only (SP); (2) a model with staggered wages only (SW); (3) a model with staggered prices and staggered wages (SPW); (4) a model with staggered prices and intermediate goods (SPI); and (5) a model with staggered wages and intermediate goods (SWI). Table II displays the parameter restrictions in the models.

In light of the evidence presented in Taylor’s (2000) survey, nominal wage and price contracts typically last for one year. Thus, in the SPWI model, we set $N_p = 4$ and $N_w = 4$ so that, in each quarter, a fraction 1/4 of firms and households can adjust prices and wages, and once adjusted, a price (or a wage) remains effective for four quarters. To calibrate the value of ϕ , the share of intermediate goods in production, we rely on the study by Jorgenson, et al. (1987), who find that ϕ is no less than 0.5, and on Basu (1995), who argues that a reasonable value of ϕ should be between 0.8 and 0.9 when fixed costs are taken into consideration. Therefore, in the models with intermediate goods, we set $\phi = 0.7$.

In each model, we adjust the preference parameter η so that the average time allocated to market activity is 1/3, and we vary the capital adjustment cost parameter ψ so that, following a monetary shock, the model generates an impulse response of investment 2.3 times as large as that of real GDP, in accordance with the VAR evidence presented by Leeper, et al. (1996).

Finally, we set the serial correlation parameter ρ of money growth rate to 0.72 and the standard deviation of the innovation term in the money growth process σ_ε to 0.006, based on M2 data.⁵

4 Findings

In this section, we present the dynamic impulse responses of real GDP and real wages following a monetary shock. As we have noted, empirical studies suggest that the response of real GDP is strong and persistent while that of real wages is weakly procyclical. We thus evaluate the empirical performance of the six different models based on their predictions on these dimensions. To compute the impulse responses, we choose the date-zero value of the innovation term ε_t in the money growth process (18) so that the money stock rises by 1% one year after the shock, and we set $\varepsilon_t = 0$ for all $t \geq 1$.

⁵We have also experimented with M1 data in our calibration and simulation, and obtained similar results (not reported).

4.1 The Case without Intermediate Goods

To evaluate the models' empirical performance, we first look at the case without intermediate goods. The models we consider here include a staggered price model, a staggered wage model, and a model that combines both types of nominal rigidities. The impulse responses of real GDP and real wages in these three models are plotted in the top panels of Figures 1 and 2.

Figure 1 shows that the staggered price model (SP) does not generate real persistence while the staggered wage model (SW) does. This conclusion confirms the findings by Chari, et al. (2000) and Huang and Liu (1998). Figure 2 reveals that the real wage response is strongly procyclical in the SP model while strongly countercyclical in the SW model, neither of which seems to be supported by empirical evidence. The model with both staggered price and staggered wage contracts (SPW) generates real persistence that is greater than that in the SP model but smaller than that in the SW model. Meanwhile, the SPW model shares with the SW model the counter-factual prediction that the real wage response is countercyclical, although to a lesser degree.

The lack of persistence in the SP model is consistent with Chari, et al. (2000), despite the different labor market structures. In the SP model, the labor market is monopolistically competitive while in Chari, et al. (2000), it is perfectly competitive. Nominal wages are flexible in both models. The difference is that, in their model, the real wage clears the competitive labor market and is equal to the marginal rate of substitution (MRS) between leisure and consumption; while in the SP model here, nominal wages are set by monopolistically competitive households and the optimal wage decision rule implies that the real wage is a constant "markup" over the MRS. Since pricing decisions are staggered, real aggregate demand rises following an expansionary monetary shock. Those firms that cannot adjust prices face a higher demand for their products and thus have to increase their demand for labor. Since households take the labor demand schedule as given, if they do not change their wages, then they will have to supply more labor, increasing their marginal utility of leisure. Meanwhile, since households have higher real income and hence more consumption, the marginal utility of consumption falls. In consequence, the MRS between leisure and consumption rises sharply, so does the real wage. In other words, real wages are strongly procyclical. Facing a higher real wage and a higher capital rental rate, firms' marginal cost rises sharply and they will respond by setting a higher price whenever they have the chance to renew contracts. Therefore, prices adjust quickly and the response of real output is short-lived.

That the SW model can generate substantial real persistence is also found by Huang and Liu (1998), for the same reason. Here we further show that the SW model implies a strong and countercyclical real wage response to a monetary shock. This is so because, given that nominal wages decisions are staggered while pricing decisions are not, any rigidity in the price level has to be inherited from the nominal wage rigidity. The change in prices is faster than in the nominal wage index since the prices are a constant markup over the marginal cost, which, being composed of the wage index and the nominal rental rate on capital, changes more quickly than does the wage index.

When both types of nominal rigidities are combined, as in the SPW model, one should expect that the model produce a greater magnitude of real persistence but with no systematic relation between the responses of real wages and aggregate output following the shock. Yet, we find that the results are not as clear-cut as expected. While the SP model generates no real persistence and the SW model produces substantial persistence, the SPW model predicts an output persistence that lies somewhere in between. Perhaps more surprisingly, the SPW model shares with the SW model the counter-factual prediction that the real wage response is countercyclical. The reason underlying this result is that, under calibrated parameter values, the price level is less sticky than the wage index, although both pricing and wage-setting decisions are staggered. This is so because the marginal cost changes more quickly than does the wage index, given that nominal wages are sticky while the capital rental rate is not. In Section 4.3, we will show that the prediction of countercyclical real wages is a fairly robust feature of the SPW model.

4.2 The Case with Intermediate Goods

We now consider the case with intermediate goods used in production. Our models with intermediate goods build on Basu (1995) who shows that the input-output connections among firms introduce a real rigidity that allows sticky-price models to explain much larger output fluctuations. We examine the implications of the input-output structure on the responses of aggregate output and real wages in three models, one with staggered price contracts alone, one with staggered wage contracts alone, and the third combines both types of nominal rigidities. The impulse responses of real GDP and real wages are displayed in the lower panels of Figures 1 and 2.

Figure 1 shows that the staggered price model with intermediate goods (SPI) generates more output persistence than does the model without intermediate goods (SP); that the staggered wage model with or without intermediate goods has similar implications on the response of aggregate output; and that the model with both types of nominal rigidities and intermediate goods (SPWI) produces significantly more real persistence than the model without intermediate goods (SPW). Figure 2 shows that adding intermediate goods does not revert the counter-factual predictions of real wage responses in the models with staggered prices or staggered wages, while it does help the model with both types of nominal rigidities to produce the observed weakly procyclical response of real wages.

In the staggered price model, adding intermediate goods can generate more real output persistence. With intermediate goods used in production, the price level enters as an additional component in firms' marginal cost function, and the rigidity in the price level due to staggering contributes to dampening the response of marginal cost following the shock and hence increases the rigidity in firms' pricing decisions. Meanwhile, since firms who can adjust prices choose not to change their relative prices too much, the need for those firms who cannot adjust prices to raise their quantities produced and hence their demand for labor is not as strong as in the case without intermediate goods. Hence, the initial rise in real wages is partially dampened. Nonetheless, adding intermediate goods in a staggered price model does not alter the counter-factual prediction that the response of real wages is strongly procyclical: the initial response of real wages is lowered from 1.74 percent only to 1.72 percent. The strong real wage response is mainly attributable to the strong income effect on households' wage setting decisions: the rise in real income lowers the marginal utility of consumption so much that the households will raise their real wages accordingly, even though the rise in the demand for their skills is not as dramatic as in the case without intermediate goods.

Adding intermediate goods in the model with staggered wage contracts does not change the model's implications on the responses of aggregate output and real wages. Since pricing decisions are not staggered here, all firms set the same price in a symmetric equilibrium. Thus, the optimal pricing equation is identical with or without intermediate goods. This intuition becomes more transparent when we look at the optimal pricing decision rule, which is a special case of equation (20) and is given by

$$P(j, s^t) = \frac{\theta}{\theta - 1} \tilde{\phi} \bar{P}(s^t)^\phi R^k(s^t)^{(1-\phi)\alpha} \bar{W}(s^t)^{(1-\phi)(1-\alpha)}, \quad (26)$$

where we have plugged in the unit cost function from (13). With synchronized pricing decisions, $P(j) = \bar{P}$ for all j , and thus the pricing equation (26) reduces to

$$P(s^t) = \frac{\theta}{\theta - 1} \tilde{\phi} R^k(s^t)^\alpha \bar{W}(s^t)^{1-\alpha}, \quad (27)$$

which is formally identical (up to a constant) to the pricing equation in the model with staggered wage contracts but without intermediate goods. Thus the SWI model has similar predictions as the SW model, and they both predict substantial output persistence while strongly countercyclical real wages.

In the model with both staggered prices and staggered wages, adding intermediate goods helps generate substantially more output persistence. More importantly, it overturns the counter-factual response of real wages and makes the prediction on real wages in line with empirical evidence. Thus, the SPWI model is the only model that does well on both dimensions. When both the price level and the wage index are sticky, the main source of variations in marginal cost is the change in the capital rental rate. Since the share of the rental rate in the cost is now smaller, the response of marginal cost following the shock is also smaller, leading to greater price-level rigidity. Given the degree of nominal wage rigidity, real wages thus tend to rise following an expansionary monetary shock. Meanwhile, greater rigidity in the price level also implies larger and more persistent real effects of money.

4.3 Robustness of the Results

We now show that our results are robust for a wide range of key parameter values. We have established that a model with either sticky prices alone or sticky wages alone tends to produce counter-factual implications, especially on the response of real wages, and this is true with or without the presence of intermediate goods. Thus, we focus here on the implications of models with both types of nominal rigidities, that is, the SPW model and the SPWI model.

There are two key parameters driving the results in these models. One is σ , the elasticity of substitution between labor skills, and the other is ϕ , the share of intermediate goods in production. A greater value of σ tends to generate more rigidity in nominal wages. In making their wage-setting decisions, those households who can set new wages have to keep their wages in line with others in order to avoid excessive fluctuations in the employment of their labor skills. A greater elasticity of substitution between skills implies a larger change in the employment of a specific skill for a given change in relative wages. Thus those households who can renew contracts have a greater incentive not to excessively adjust their wages. On

the other hand, a larger value of ϕ contributes to more rigidity in prices because it implies a smaller share of capital rental rate in the marginal cost function, and given that both prices and nominal wages are sticky, a smaller variation in the marginal cost.

We confirm this intuition by plotting the sensitivity of the impulse responses with respect to the two parameters. Figure 3 shows that, in the absence of intermediate goods (i.e., the SPW model), a larger value of σ is associated with a greater degree of output persistence and meanwhile a greater fall in real wages following an expansionary monetary policy shock. The real wage response is countercyclical unless σ is sufficiently small (for example, when $\sigma = 2$). When the value of σ falls to 2, however, the model predicts little real persistence: the response of real GDP at the end of the initial duration of the pricing and wage contracts falls to only about 12% of its initial response. Therefore, the SPW model fails to generate plausible responses of both aggregate output and real wages following the shock.

Figure 4 shows that, when intermediate goods are used in production (i.e, the SPWI model), a larger share of intermediate goods leads to greater real persistence, holding σ at the calibrated value (i.e., $\sigma = 4$). More importantly, a larger value of ϕ implies greater rigidity in the price level and hence real wages tend to be acyclical or weakly procyclical. With the calibrated values $\phi = 0.7$ and $\sigma = 4$, the model predicts substantial output persistence and a weakly procyclical real wage response. Thus, adding intermediate goods in the SPW model helps overturn the prediction of countercyclical real wages while generating more real persistence. In this sense, it is necessary to combine all three types of rigidities, including sticky prices, sticky wages, and intermediate goods in order to generate empirically plausible responses of both aggregate output and real wages.

5 Conclusions

In this paper, we have explored the role of staggered price contracts, staggered wage contracts, and an input-output structure in transmitting monetary policy shocks. We have established that all three types of rigidities are necessary to account for the observed persistent movements in aggregate output and the weakly procyclical response of real wages following a monetary shock.

Several issues merit further investigation. In a dynamic general equilibrium model with nominal rigidities such as ours, shocks to technologies, fiscal policy, and money demand, for example, are likely to play an important role in generating the observed aggregate dynamics and

thus may have important implications on the conduct of monetary policy. Incorporating these shocks into the models will enable us to analyze the short-run tradeoff between inflation and real output and to assess the quantitative welfare effects of alternative monetary policy rules (e.g., Ireland (1996), Goodfriend and King (1997), and Clarida, et al. (1999)). We can also extend the model to an open economy and study issues such as international comovements. With nominal rigidities and intermediate goods, shocks (either real or monetary) can be transmitted across countries through the international input-output connections.⁶ Such an open-economy model will also be useful to assess the quantitative implications of alternative monetary policy rules such as interest rate targeting, inflation targeting, or exchange rate targeting.

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⁶The difficulties to account for the international comovements are summarized by, for example, Baxter (1995) and Backus, et al. (1995). More recently, Huang and Liu (2000) try to explain the comovements in a model with sticky prices and with vertical international trade.

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Table I.
Calibrated Parameter Values

| | |
|--|---|
| Preferences: | $b = 0.998, \quad \nu = -1.75$ |
| $U(C, M/\bar{P}, L) = \log [bC^\nu + (1 - b)(M/\bar{P})^\nu]^{1/\nu} + \eta \log(1 - L)$ | η adjusted |
| Technologies: $Y = Z^\phi K^{(1-\phi)\alpha} L^{(1-\phi)(1-\alpha)}$ | $\phi \in \{0.7, 0\}, \quad \alpha = 1/3$ |
| Labor composite: $L = \left[\int L(i)^{\frac{\sigma-1}{\sigma}} di \right]^{\frac{\sigma}{\sigma-1}}$ | $\sigma = 4$ |
| Goods composite: $Y = \left[\int Y(j)^{\frac{\theta-1}{\theta}} dj \right]^{\frac{\theta}{\theta-1}}$ | $\theta = 10$ |
| Capital accumulation: $K_t = I_t + (1 - \delta)K_{t-1}$, | $\delta = 0.021$ |
| Adjustment cost: $\psi(K_t - K_{t-1})^2/K_{t-1}$ | ψ adjusted |
| Money growth: $\log \mu(s^t) = \rho \log(\mu(s^{t-1})) + \varepsilon_t$ | $\rho = 0.72, \quad \sigma_\varepsilon = 0.006$ |
| Subjective discount factor | $\beta = 0.99$ |
| Contract duration (quarters) | $N_p \in \{4, 1\}, \quad N_w \in \{4, 1\}$ |

Table II.
Parameter restrictions in alternative models^a

| Parameters | SP | SW | SPW | SPI | SWI | SPWI |
|------------|----|----|-----|-----|-----|------|
| N_p | 4 | 1 | 4 | 4 | 1 | 4 |
| N_w | 1 | 4 | 4 | 1 | 4 | 4 |
| ϕ | 0 | 0 | 0 | 0.7 | 0.7 | 0.7 |

^aThe symbol ‘‘SP’’ stands for a model with staggered prices, ‘‘SW’’ for a model with staggered wages, ‘‘SPW’’ for a model with both staggered prices and staggered wages, and ‘‘SPI,’’ ‘‘SWI,’’ and ‘‘SPWI’’ are the corresponding models with intermediate goods.

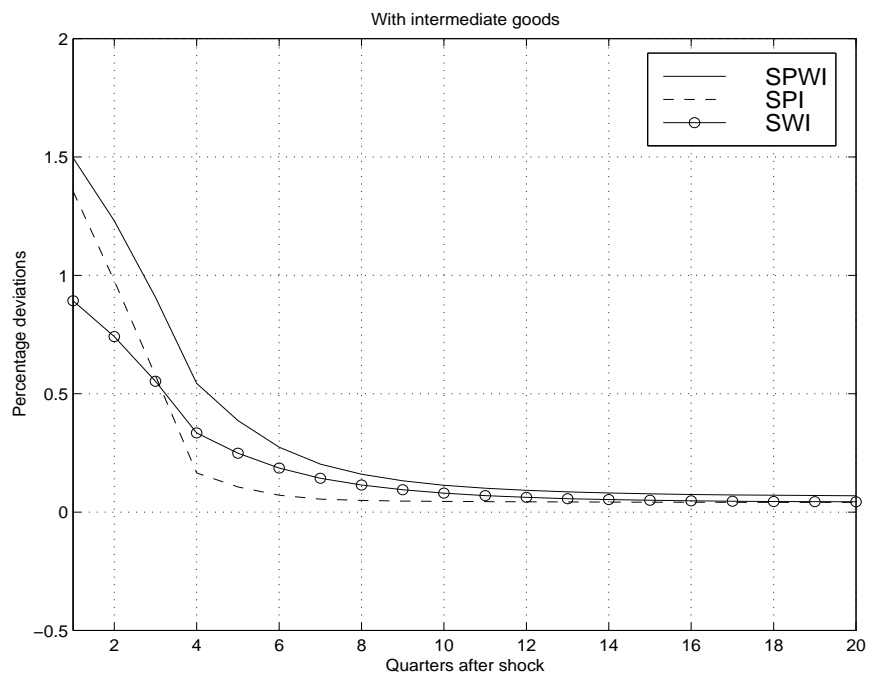
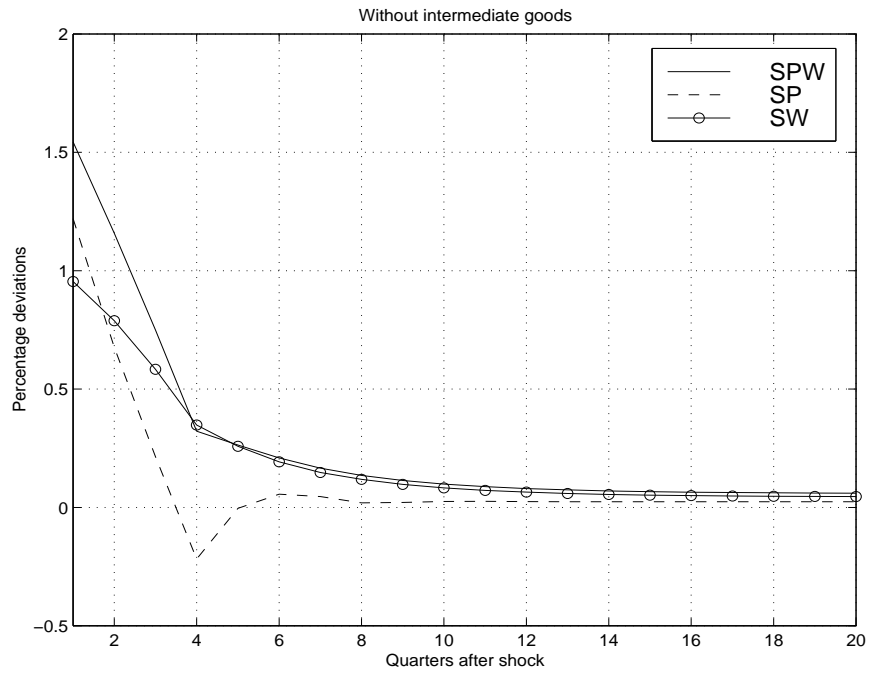


Figure 1:—The impulse response of real GDP in alternative models

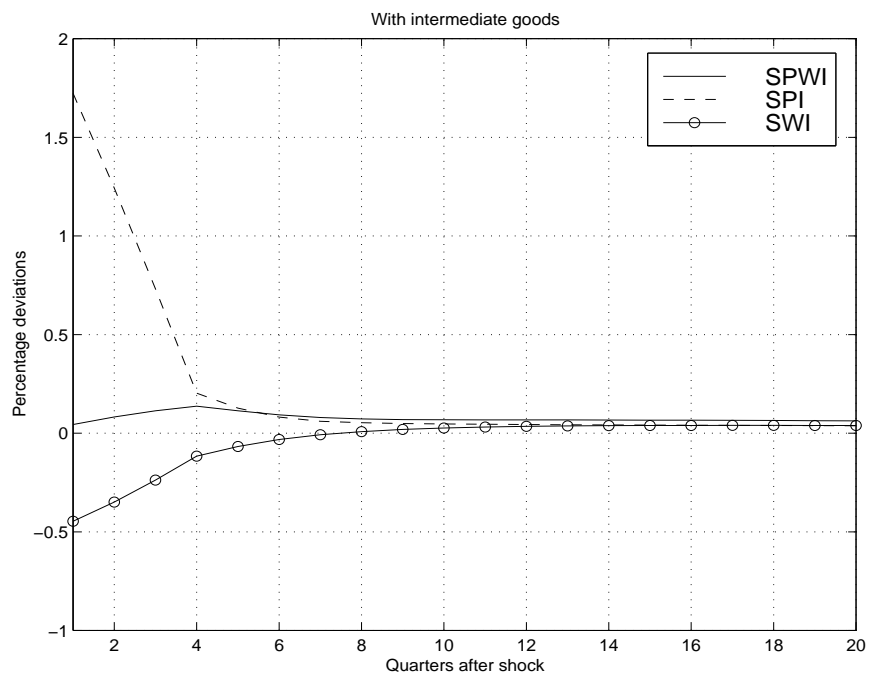
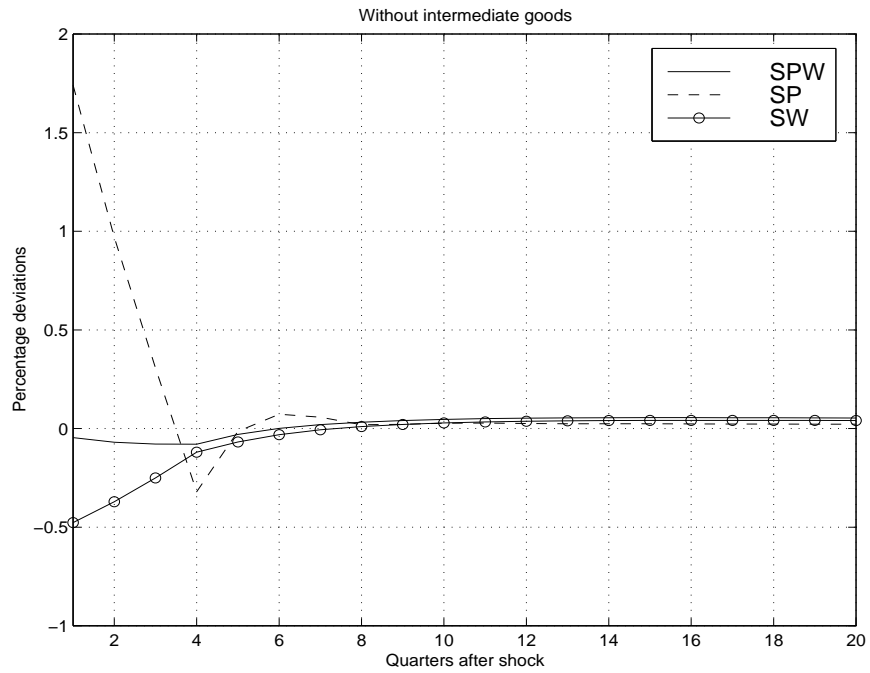


Figure 2:—The impulse response of real wages in alternative models

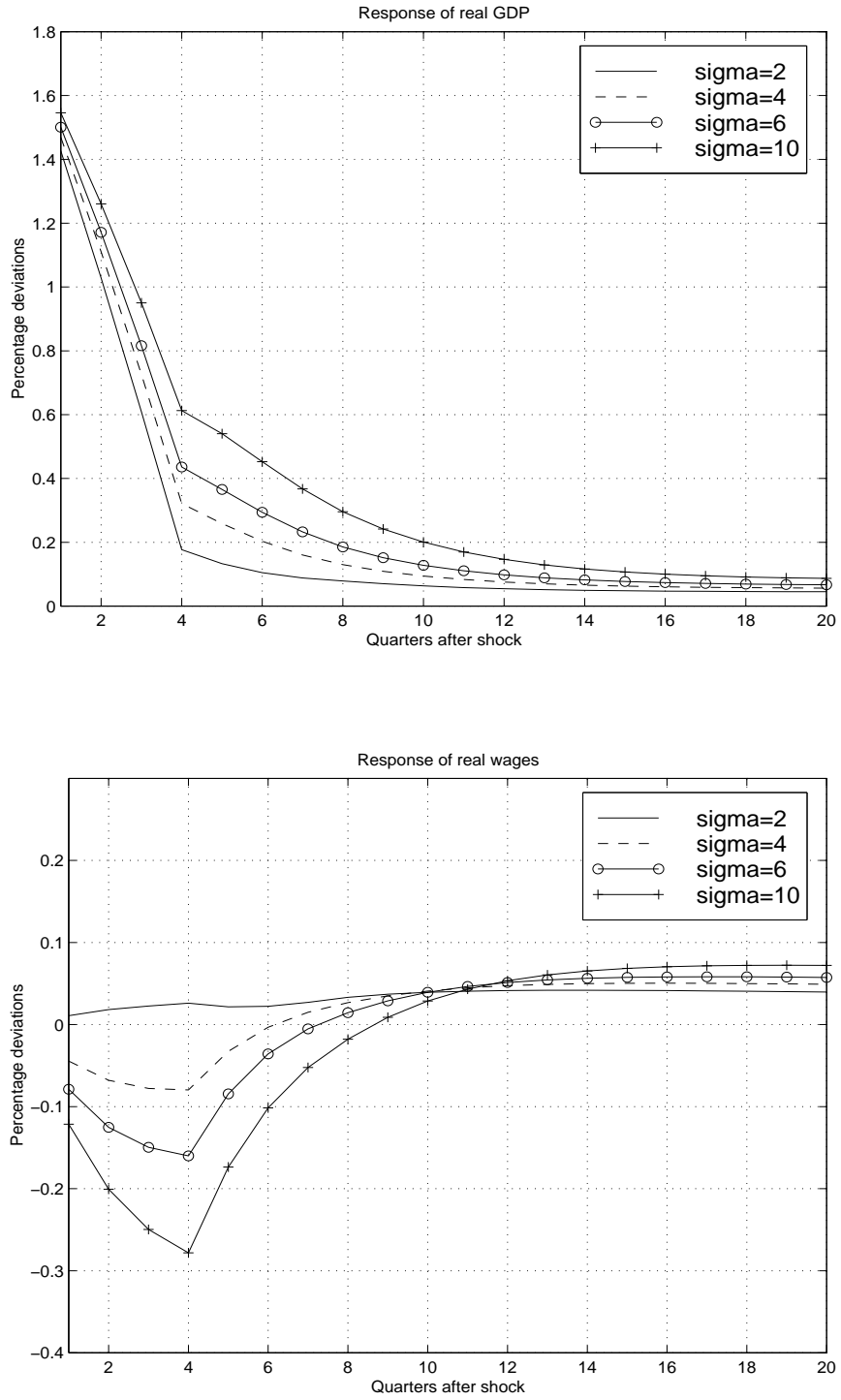


Figure 3:—The sensitivity of the impulse responses with respect to σ in the model with both sticky prices and sticky wages

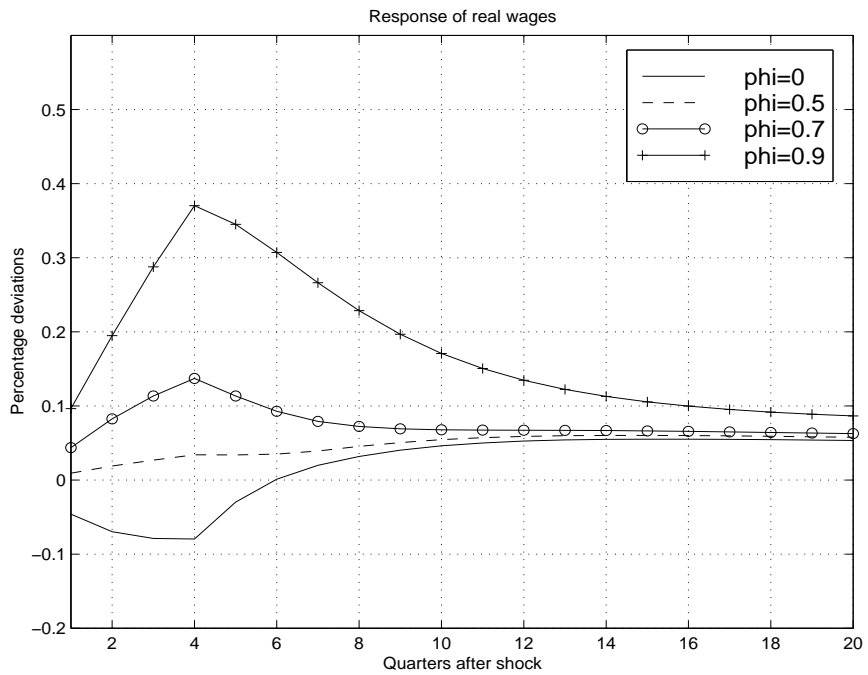
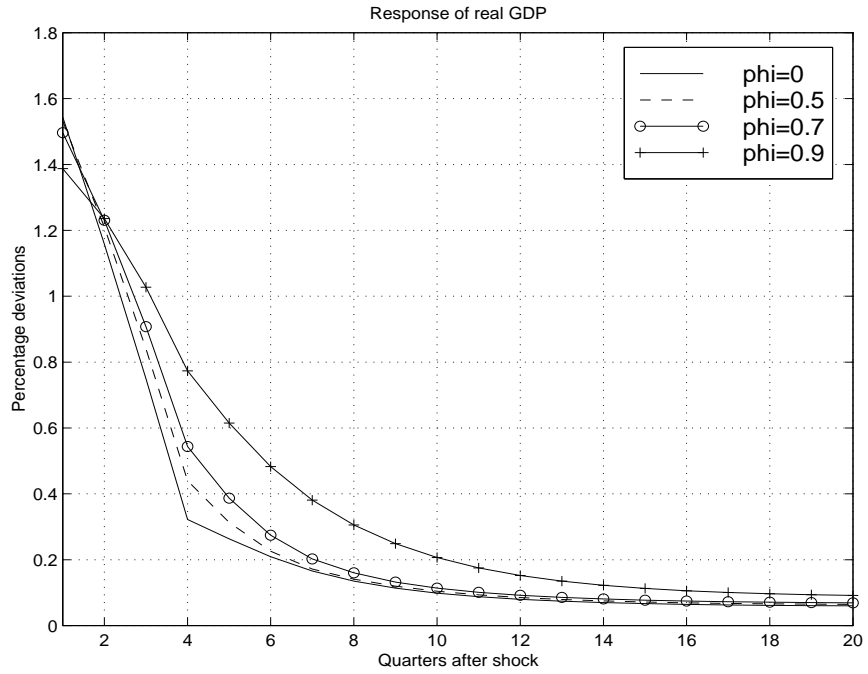


Figure 4:—The sensitivity of the impulse responses with respect to ϕ in the model with sticky prices, sticky wages, and intermediate goods, given $\sigma = 4$