

What Explains the Effects of Technology Shocks on Labor Market Dynamics?*

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Abstract

The sticky-price theory has proved fairly successful in explaining the dynamic effects of technology shocks on employment, at least under weak accommodation of monetary policy to the shocks. Yet, when we extend the analysis to a broader set of labor market variables, including employment as well as real wages and nominal wages, the sticky-price theory cannot claim victory: it fails to account for the observed wage dynamics following technology shocks unless one is willing to assume implausibly large degrees of monetary policy accommodation and large values of labor supply elasticity. We show that a model that allows for a role of nominal wage rigidity, coupled with a modest degree of price stickiness as some recent research suggests, provides a better account for the macroeconomic effects of technology shocks on the labor market.

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1 Introduction

A recent strand of literature proposes that an important criterion for evaluating competing business-cycle theories is to look at their predictions on the employment effects of technology shocks. The work by Susanto Basu, John Fernald and Miles Kimball (1998, 2004) (hereafter BFK) and Jordi Gali (1999) presents provocative evidence that positive technology shocks typically lead to a short-run *decline* in employment during the post World-War II period in the United States. This finding has stimulated a rapidly growing empirical literature that largely confirms the contractionary effects of technology improvements on employment.¹ It has also stimulated a lively intellectual debate on what theories may account for the evidence.

A popular view, primarily inspired by Gali’s (1999) influential work, is that nominal price rigidity helps explain the contractionary effects of technology improvements on employment: as prices are sticky, the rise in output, –in the absence of strong accommodation of monetary policy to the technology improvement, does not catch up with the rise in productivity, so that employment has to fall. This interpretation is also favored by, for example, Basu (1998), Gali and Rabanal (2004), and BFK (2004).²

Interestingly, almost a decade before the contributions of BFK (1998) and Gali (1999), Olivier Jean Blanchard and Danny Quah (1989) and Blanchard (1989) reached a similar conclusion. They find that “supply shocks” have a positive long-run effect on output and a positive short-run effect on unemployment. In an effort to explain why permanent supply shocks could lead to a short-run increase in unemployment, Blanchard and Quah (1989, p. 663) suggest that “nominal rigidities can explain why in response to a positive supply shock, say an increase in productivity, aggregate demand does not initially increase enough to match the increase in output needed to maintain unemployment.” In a similar vein, Blanchard (1989, p. 1158) argues that, “in the Keynesian model, increases in productivity . . . may well increase unemployment in the short run, if aggregate demand does not increase enough to maintain employment.”

¹For a detailed survey of this literature and a critical assessment of some alternative views and results, see, for example, Gali and Pau Rabanal (2004) and BFK (2004).

²There are models that can generate a decline in employment following technology improvements even if prices are perfectly flexible [e.g. Neville Francis and Valerie A. Ramey (2003); Jesper Lindé (2004)]. These models are not without their critics. Indeed, some have argued that this class of models tend to rely on implausible technology processes to generate reasonable employment dynamics [see the discussions in Gali and Rabanal (2004), and BFK (2004)]. Moreover, they typically fail to generate the size of the dynamic responses of hours and output to *non-technology* shocks close to those estimated in a VAR. Thus, it is difficult to fathom within this class of models a plausible explanation of the strong procyclical movements of employment observed in the U.S. data.

While we recognize the essential role of examining employment dynamics following technology shocks in assessing alternative business cycle theories, we argue in the present paper that looking more broadly at labor market adjustment in response to technology shocks, and not just at employment changes, can have far reaching implications for the identification of nominal frictions which are responsible for the effects of technology shocks on the economy. Specifically, we look at the adjustment of employment, nominal wages and real wages in response to technology shocks and then explore what type of frictions is most successful in explaining how these variables actually respond to technology improvements.

We begin with a short section summarizing the empirical evidence which motivates our paper (Section 2). This section establishes that, in the postwar U.S. economy, a positive technology shock has been followed by (i) a short-run decline in employment, (ii) a positive short-run rise and a permanent increase in real wages, and (iii) a weak (more or less constant) response of nominal wages. Basu (1998), Gali (1999) and Gali and Rabanal (2004) have shown that the predictions of a dynamic stochastic general equilibrium (DSGE) model with sticky prices are consistent with the first fact as long as monetary policy is not too accommodative for technology shocks. But, unlike these papers, our main goal is to account for all three key aspects of labor market adjustment in response to technology shocks.

We first look at the predictions of a standard sticky-price model (Section 3). Specifically, we consider a model with staggered price-setting in the spirit of Calvo (1983), which is a variant of Gali's (1999) model with predetermined prices. As in Gali (1999), our model allows, but does not require monetary policy to systematically respond to technology shocks.³ But unlike Gali (1999), we examine the sensitivity of the results to variations in the labor supply elasticity, a parameter that plays a key role in determining the equilibrium responses of employment and real wages following technology shocks. Our closed-form solution reveals that technology improvement consistently leads to a short-run decline in employment; and given the assumption that money supply

³For ease of comparison with previous work, especially with Gali (1999), we assume monetary policy takes the form of a simple money growth rule that potentially responds to technology shocks. This is not our literal interpretation of what the actual monetary policy practice has been. Under an alternative description of monetary policy, such as a Taylor rule, some authors find that a sticky price model is still able to generate a decline in employment in response to a positive technology shock (e.g., Basu (1998) and Gali and Rabanal (2004)); yet, some others show that, under a Taylor rule, employment may rise following a technology improvement (e.g., Michael Dotsey (1999) and Gali, J. David Lopez-Salido, and Javier Valles (2003)). We step aside from issues of the specific forms of monetary policy since we have a broader goal in mind: we would like to confront a sticky-price model with not only the employment dynamics, but also the dynamic adjustments of real wages and nominal wages. After all, a correctly specified Taylor rule should imply a money growth process that reflects weak monetary policy accommodation to technology shocks, as we find below using US data (see Section 3).

increases by less than one-for-one in face of a technology improvement, this result is not sensitive to variations in the labor supply elasticity or the accommodativeness of monetary policy. In this sense, Gali's (1999) finding that a sticky-price model predicts the correct patterns of employment adjustment following technology shocks is quite robust. Yet, to generate the observed rise in the real wage requires implausibly high degrees of monetary policy accommodation and implausibly large values of the labor supply elasticity. With low labor supply elasticity and weak monetary policy accommodation, which, as we argue below, are empirically plausible, the real wage tends to fall along with employment. Given that prices are sticky, the fall in the real wage implies that the nominal wage falls by even more, contradicting the empirical evidence that the real wage rises on impact and the nominal wage stays roughly constant.

The intuition for the adjustment of employment and the real wage in the sticky-price model is the following. Assume for the sake of simplicity a graphic representation of labor market adjustment to a positive technology shock in an economy with predetermined prices and a perfectly flexible nominal wage. In such a framework, firms' demand for labor is determined by their desire to meet the demand for their goods. With predetermined prices and a constant money supply, real money balances and aggregate demand are unchanged in the face of a positive technology shock. With an unchanged output and higher productivity of labor, firms reduce their demand for labor at any given real wage, so that the labor demand curve shifts to the left, leading to a fall in equilibrium employment and the real wage. In a more general environment where prices are partly flexible (for instance, under staggered price setting) or money supply increases to partly accommodate the shock, the shock may also trigger an income effect that shifts the labor supply curve to the left, putting an upward pressure on real wages, which tends to offset the fall in the real wage due to the inward shift of the labor demand curve. Thus, the real wage may rise or fall, depending on the degree of nominal price rigidity, the elasticity of labor supply, and thus the strength of the income effect. Further, the extent of monetary policy accommodation is also a key determinant of the equilibrium adjustments of employment and the real wage. Using US data on money aggregates (M1 or M2) and two alternative measures of technology shocks constructed by BFK (2004) and Gali and Rabanal (2004), we find that the estimates of the monetary policy accommodation parameter are not statistically significant during the postwar period, independent of which technology measure or broad money aggregate is used. With a value of the accommodation parameter close to its point estimates, the model predicts counter-factually sharp declines in the real wage following technology

improvements; meanwhile, since prices are sticky, the nominal wage falls by more than does the real wage.⁴

Given the empirical evidence that nominal wages respond weakly to technology shocks, it is natural to ask whether introducing nominal wage rigidity may help getting the labor market dynamics right. We find that, under fairly general conditions, it does (Section 4). In an extreme case with sticky nominal wages and flexible prices, the real wage rises following a technology improvement, while the nominal wage remains roughly constant, representing a step in the right direction compared to the sticky-price model. Nonetheless, a pure sticky-wage model does not predict the decline in employment: with flexible prices and sticky nominal wages, a technology improvement, absent of monetary policy accommodation, leads to a complete decline in the price level and a complete rise in aggregate output, so that employment stays constant; if money supply increases following the technology improvement, output rises by even more than does the productivity, so that employment also rises.

Fortunately, the failure of a pure sticky-wage model to generate the observed employment response to technology shocks can be amended by allowing for some price rigidity. Indeed, with both nominal wage and price rigidities, the model's predictions under calibrated parameter values are consistent with evidence: employment falls, the real wages rises, and the nominal wage responds weakly to technology improvements. More importantly, and unlike the pure sticky-price model, the predictions of the model that includes both types of nominal rigidities are not sensitive to changes in the key structural parameters. In particular, in the light of the micro evidence presented by Mark Bilal and Peter Klenow (2002) suggesting that prices are adjusted quite frequently, we also investigate whether our main findings hold if only a modest amount of nominal price rigidity is assumed. They do. Thus, a model with nominal wage rigidity, coupled with some modest price rigidity, proves to be more successful in explaining the labor market adjustment to technology shocks than does a pure sticky-price model.

⁴One way to prevent the real wage from declining following technology improvements is to introduce some type of real rigidity, such as efficiency wages (e.g., Michelle Alexopoulos (2004), Jean-Pierre Danthine and Andre Kurmann (2004)). Since this kind of real rigidity tends to generate weak responses of the real wage, the nominal wage has to adjust as much as does the price level. Unless prices are assumed to be predetermined, a technology improvement would lead to a systematic decline in the nominal wage, an implication not supported by empirical evidence (e.g., BFK (2004)).

2 Technology Shocks and Labor Market Dynamics: Some Evidence

Empirical studies on the effects of technology shocks on labor market dynamics fall into two broad categories. The first category, best exemplified by the work of Basu and Fernald (1997), Basu and Kimball (1997), and BFK (1998, 2004), uses direct measures of technology shocks that control for changes in non-technological components in measured Solow residual (Robert Solow, 1957).⁵ For instance, BFK (2004) construct a “purified” measure of aggregate technological change using annual industry data in the U.S. during the period from 1949 to 1996. They show that the level of the purified technology measure has a unit root, while there is no evidence of autocorrelation in technology growth rate. They use the purified series in a set of bivariate vector autoregressions (VARs) to estimate the dynamic responses of several variables to technology shocks. They find that, “when technology improves, total hours worked fall very sharply on impact” (BFK, 2004, p. 15). Their impulse-response plots suggest that the decline in total hours worked is about 0.6 percent on impact of a 1 percent positive shock to their technology measure (p. 53, Figure 3). A similar pattern holds for employment. Following the same shock, they find that the real wage rises (by about 0.55 percent on impact) and keeps rising for about 2 years before it settles down at a permanently higher steady state, whereas “the nominal wage stays flat” (p. 18 and p. 54, Figure 4).

The second category of evidence, in the spirit of the approach originally developed by Blanchard and Quah (1989), consists of studies that identify technology shocks by imposing long-run restrictions in a structural vector autoregression model. For instance, for the purpose of identification, Gali (1999) assumes that the technology shock is the only shock that affects labor productivity in the long run. Based on this identification assumption, Gali (1999) finds that a positive technology shock leads to a decline in hours worked and employment. Specifically, in his bivariate model with U.S. data, a 1 percent positive shock to identified technological change leads to a 0.4 percent decline in hours worked (Gali, 1999, pp. 261-262, Figures 2 and 3). The estimated effects of technology improvement on hours worked and employment are similar for several other OECD countries. Using a similar approach, Francis and Ramey (2003) identify technology shocks as those with permanent effects on real wages but no long-run effects on hours. They find that hours decline by 0.55 percent on impact and that real wages rise by 0.4 percent immediately after the shock.

⁵Such non-technological components include, for example, variations in unobserved capital utilization and labor efforts, non-constant returns to scale, imperfect competition, and aggregation effects.

As noted by Gali (1999, p. 259, Footnote 19), the decline in hours, or equivalently, the rise in unemployment in response to technology improvements have been found in a series of previous studies that also impose long-run restrictions to identify aggregate supply shocks. For example, Blanchard and Quah (1989) find that a 1 percent positive supply shock leads to an initial rise in unemployment of about 0.22 percent (p.663, Figure 6). Blanchard (1989) also finds that unemployment rises on impact of a positive productivity shock; and the same shock leads to a weak response of nominal wages (p.1159, figure 1b). Edward N. Gamber and Frederick L. Joutz (1993) study the responses of real wages and unemployment following a labor-demand shock (that can be interpreted as a productivity shock). Their finding about unemployment adjustment corroborates those of Blanchard and Quah (1989) and Blanchard (1989), with unemployment rising by about 0.17 percent on impact of a positive labor demand shock (p.1390, Figure 1). They also find that real wages are positively (and permanently) affected by the shock, with an impact effect of about 0.4 percent (p.1390, Figure 1).

In sum, empirical findings about the adjustments of employment, real wages, and nominal wages in response to technology shocks are remarkably consistent across studies, despite the use of different methodologies and sample periods. They all suggest that, in response to a positive technology shock, employment declines in the short-run, real wages rise on impact before reaching a permanently higher steady state, and nominal wages do not change much.

3 Labor-Market Dynamics in a Sticky Price Model

In this section, we present a stylized monetary business-cycle model with monopolistic competition in the goods market and sticky prices. We then examine the model's implied effects of technology shocks on employment and real wages. To simplify exposition, we focus on shocks to productivity and abstract from other sources of shocks (such as demand shocks) and from capital accumulation. We introduce stickiness of pricing decisions following Calvo (1983), so that each firm in each period faces a fixed probability of updating pricing decisions. Our main qualitative results do not hinge upon this particular way of introducing price-rigidity.

There is a large number of identical, infinitely-lived households. The representative household is endowed with one unit of time and derives utility from consumption, real money balances, and leisure time. The consumption good is a composite of a continuum of differentiated products produced by monopolistically competitive firms. Production of each type of differentiated good requires labor as the only input and is subject to a productivity shock.

3.1 The Representative Household

The representative household has preferences represented by the utility function

$$\mathbb{E} \sum_{t=0}^{\infty} \beta^t [\log C_t + \Phi \log \frac{M_t}{P_t} - V(N_t)], \quad (1)$$

where \mathbb{E} is an expectations operator, $\beta \in (0, 1)$ is a subjective discount factor, C_t denotes consumption, M_t/P_t denotes real money balances, and N_t denotes labor hours. In each period t , the household faces a budget constraint

$$P_t C_t + M_t + \mathbb{E}_t D_{t,t+1} B_{t+1} \leq W_t N_t + \Pi_t + M_{t-1} + B_t - T_t, \quad (2)$$

where B_{t+1} denotes the holdings of a one-period state-contingent nominal bond that matures in period $t + 1$ with a payoff of one unit of currency in the appropriate event, $D_{t,t+1}$ is the period- t cost of such bonds, W_t is the nominal wage rate, Π_t is a claim to all firms' profits, and T_t is a lump-sum tax. The consumption good is a composite of differentiated products given by

$$C_t = \left[\int_0^1 Y_t(j)^{\frac{\varepsilon_p - 1}{\varepsilon_p}} dj \right]^{\frac{\varepsilon_p}{\varepsilon_p - 1}}, \quad (3)$$

where $Y_t(j)$ denotes the output of good j and $\varepsilon_p > 1$ is the elasticity of substitution between the differentiated products. Solving the household's expenditure-minimization problem results in a demand schedule for good j given by

$$Y_t^d(j) = \left(\frac{P_t(j)}{P_t} \right)^{-\varepsilon_p} C_t, \quad (4)$$

where $P_t(j)$ denotes the price of good j and the consumer price index P_t is given by

$$P_t = \left[\int_0^1 P_t(j)^{1-\varepsilon_p} dj \right]^{\frac{1}{1-\varepsilon_p}}. \quad (5)$$

Solving the household's utility-maximization problem results in a labor supply equation, an intertemporal Euler equation, and a money demand equation, given respectively by

$$\frac{W_t}{P_t} = (-V'(N_t)) C_t, \quad (6)$$

$$D_{t,\tau} = \beta^{\tau-t} \frac{C_t}{C_\tau} \frac{P_t}{P_\tau}, \quad (7)$$

and

$$\Phi \frac{1}{M_t} + \beta \mathbb{E}_t \frac{1}{P_{t+1} C_{t+1}} = \frac{1}{P_t C_t}. \quad (8)$$

3.2 Firms and Optimal Price-Setting

The production function for good $j \in [0, 1]$ is given by

$$Y_t(j) = A_t N_t(j), \quad (9)$$

where A_t denotes a productivity shock, and $N_t(j)$ is the homogeneous labor used by firm j . The productivity shock follows random-walk process so that

$$A_t = A_{t-1} \exp(\varepsilon_t), \quad (10)$$

where ε_t is a mean-zero, iid normal process, with a finite variance σ_a^2 .

Firms are price-takers in the input markets and monopolistic competitors in the product markets. They set prices in a staggered fashion in the spirit of Calvo (1983). In particular, in period t , all firms receive an iid random signal that determines whether or not they can set a new price. The probability that firms can adjust prices is $1 - \alpha_p$. Thus, by the law of large numbers, a fraction $1 - \alpha_p$ of firms can adjust prices while the rest of the firms have to stay put.

If firm j can set a new price in period t , it chooses the new price $P_t(j)$ to maximize the expected present value of its profits

$$\mathbb{E}_t \sum_{\tau=t}^{\infty} \alpha_p^{\tau-t} D_{t,\tau} [P_t(j) - V_\tau] Y_\tau^d(j), \quad (11)$$

where $V_\tau = W_\tau/A_\tau$ is the unit production cost, and $Y_\tau^d(j)$ is the demand schedule for j 's output given by (4). Solving (11) gives the optimal pricing decision rule

$$P_t^*(j) = \mu_p \frac{\mathbb{E}_t \sum_{\tau=t}^{\infty} \alpha_p^{\tau-t} D_{t,\tau} V_\tau Y_\tau^d(j)}{\mathbb{E}_t \sum_{\tau=t}^{\infty} \alpha_p^{\tau-t} D_{t,\tau} Y_\tau^d(j)}, \quad (12)$$

where $\mu_p = \varepsilon_p/(\varepsilon_p - 1)$ measures the steady-state markup. The optimal price is thus a constant markup over a weighted average of the marginal costs in the future periods during which the price is expected to remain in effect.

Solving the cost-minimizing problem of firm j yields the demand for labor $N_t^d(j) = Y_t^d(j)/A_t$. The aggregate demand for labor is then given by

$$N_t^d = \frac{1}{A_t} \int_0^1 Y_t^d(j) dj = \frac{G_t C_t}{A_t}, \quad (13)$$

where the second equality follows from substituting the demand schedule (4) for the $Y_t^d(j)$ terms, and the variable $G_t = \int_0^1 [P_t(j)/P_t]^{-\varepsilon_p} dj$ measures price dispersion under staggered price setting. Thus, if the rise in aggregate demand cannot catch up with productivity improvement, the aggregate demand for labor falls.

The labor market clears in an equilibrium so that $N_t = N_t^d$ for all t . The bond market clearing implies that $B_t = 0$ for all t . The market for the composite good also clears in an equilibrium.

3.3 Monetary Policy

Following Gali (1999), we assume that the monetary authority is allowed, but not required to adjust the growth rate of money stock in response to changes in productivity shocks. Specifically, we assume

$$\log(M_t^s/M_{t-1}^s) = \gamma\varepsilon_t, \quad (14)$$

where $\gamma \neq 0$ implies systematic responses of monetary policy to technology shocks.

3.4 Equilibrium

Given the monetary policy described in (14), an *equilibrium* consists of allocations C_t , N_t , B_{t+1} , and M_t for the representative household; allocations $Y_t(j)$ and $N_t(j)$, and price $P_t(j)$ for producer $j \in [0, 1]$; together with prices $D_{t,t+1}$, \bar{P}_t , and wage W_t , that satisfy the following conditions: (i) taking the prices and the wage as given, the household's allocations solve its utility maximizing problem; (ii) taking the wage and all prices but its own as given, each producer's allocations and price solve its profit maximizing problem; and (iii) markets for bonds, money, labor, and the composite goods clear.

We focus on a symmetric equilibrium in which all firms who can adjust prices in a given period make identical pricing decisions. Thus, we do not have to keep track of the firm-specific index j and write the pricing decisions as P_t^* in place of $P_t^*(j)$.

3.5 Confronting the Labor-Market Dynamics: How Successful Is the Sticky-Price Model?

3.5.1 Theoretical possibility

We first examine the potential ability of the sticky-price model in generating the correct patterns in the observed labor market adjustments following technology shocks, and then, in the next subsection, we evaluate the model's performance along this dimension under empirically plausible values of the parameters. For this purpose, we consider small shocks so that the equilibrium conditions can be approximated by log-linearizing around a zero-inflation steady state. In this case, we can characterize the equilibrium dynamics by obtaining a closed-form solution.

Combining the pricing decisions (12), the price index relation (5), the intertemporal bond holding decision (7), and the labor supply equation (6) yields, to a first order approximation, the familiar Phillips curve relation

$$\pi_t = \beta\mathbf{E}_t\pi_{t+1} + \kappa_p(c_t - \bar{c}_t), \quad (15)$$

where lower-case variables denote the log-deviations of the upper-case variables from steady state, $\pi_t = p_t - p_{t-1}$ denotes the inflation rate, $\bar{c}_t = a_t$ is the natural rate of output. The parameter $\kappa_p = \lambda_p(1 + \eta)$ determines the response of real marginal cost to changes in output, where $\eta = V''(N)N/V'(N)$ is the inverse labor-supply elasticity and $\lambda_p = (1 - \beta\alpha_p)(1 - \alpha_p)/\alpha_p$. Note that κ increases with η , the inverse labor supply elasticity. A smaller labor supply elasticity implies a larger value of η and thus of κ_p , so that the marginal cost responds more to changes in aggregate demand, and there is less endogenous price rigidity. As we show below, labor supply elasticity plays an important role in determining the effect of technology shocks on labor market dynamics in the sticky-price model.

The log-linearized version of the intertemporal money demand decision (8) is given by

$$p_t + c_t = (1 - \beta)m_t + \beta\mathbf{E}_t(p_{t+1} + c_{t+1}). \quad (16)$$

Given that money supply follows a random-walk process as the technology shock, we can solve out the aggregate demand from (16) to obtain

$$p_t + c_t = (1 - \beta) \sum_{j=0}^{\infty} \beta^j \mathbf{E}_t m_{t+j} = m_t. \quad (17)$$

Note that, this seemingly static aggregate demand relation is an *equilibrium* outcome obtained under the assumptions of separable period-utility function, log-utilities in consumption and real money balances, and the random-walk property of money stocks inherited from the technology shock process under accommodative monetary policy described by (14).

To solve for the equilibrium dynamics, we rewrite the Phillips curve relation (15) in terms of the price level, and replace c_t using the aggregate demand relation (17), to obtain

$$\beta\mathbf{E}_t p_{t+1} - (1 + \beta + \kappa_p)p_t + p_{t-1} = -\kappa_p(\gamma - 1)a_t. \quad (18)$$

Solving this second-order difference equation in p_t , we obtain

$$p_t = \theta_p p_{t-1} + \theta_p \kappa_p (\gamma - 1) \sum_{i=0}^{\infty} (\theta_p \beta)^i \mathbf{E}_t a_{t+i},$$

where θ_p is the smaller root of the quadratic polynomial $\beta\theta^2 - (1 + \beta + \kappa_p)\theta + 1 = 0$. Using the random-walk property of a_t , we get

$$p_t = \theta_p p_{t-1} + (1 - \theta_p)(\gamma - 1)a_t. \quad (19)$$

Thus, the price level will fall on impact of a positive technology shock if and only if $\gamma < 1$. Given the solution for p_t , we can obtain the solution for c_t by using (17). It then follows from $n_t = c_t - a_t$ that the solution for employment is given by

$$n_t = \theta_p n_{t-1} + (\gamma - 1)\theta_p \varepsilon_t, \quad (20)$$

implying that a technology improvement leads to a fall in employment if and only if $\gamma < 1$, confirming Gali's (1999) results.

As a point of departure from Gali (1999), we also examine the dynamic response of real and nominal wages to technology shocks. From the labor supply equation, the real wage is given by $w_t - p_t = c_t + \eta n_t = (1 + \eta)n_t + a_t$. Since $a_t = \sum_j \varepsilon_{t-j}$ and, from (20), we have $n_t = (\gamma - 1)\theta_p \sum_j \theta_p^j \varepsilon_{t-j}$, it is reasonable to conjecture that the solution for real wages has an MA(∞) representation described by $w_t - p_t = \sum_j \omega_j \varepsilon_{t-j}$, where the limits of the sums run from 0 to ∞ . Using the method of undetermined coefficients, one can show that the initial response of real wages is given by

$$\omega_0 = 1 - \theta_p(1 + \eta)(1 - \gamma). \quad (21)$$

The impact effect on real wages is thus ambiguous, depending on parameter values. It follows that, the real wage falls on impact if monetary policy is not too accommodative to the technology shock (in the sense that γ is small). Specifically, the real wage falls if

$$\gamma < 1 - \frac{1}{\theta_p(1 + \eta)} \equiv \bar{\gamma}. \quad (22)$$

This equation reveals that, given the size of policy accommodation measured by $\gamma < 1$, a smaller labor supply elasticity (measured by $1/\eta$) or a greater magnitude of persistence in equilibrium employment (measured by θ_p) makes it more likely for the real wage to fall along with employment.

To illustrate the intuition, we plot in Figure 1 the labor market adjustment following a positive technology shock. The aggregate demand for labor is given by $N_t^d = G_t C_t / A_t$, as in (13), suggesting that the labor demand schedule is vertical. The labor supply schedule is upward-sloping (denoted by L^s), as suggested by the labor supply equation (6). In response to a positive technology shock, the stickiness in price-setting implies sluggishness in output adjustment as long as γ is small. Thus, for small γ , output adjustment cannot catch up with the technology improvement, leading to a fall in the demand for labor at any given real wage, so that the labor demand curve shifts to the left, and equilibrium real wage tends to fall along with employment. Since c_t rises, there is also an income effect on labor supply that tends to offset the fall in the real wage, rendering the net effect ambiguous. Specifically, the net effect on the real wage depends on the strength of the income effect (that depends negatively on the price stickiness measured by θ_p and positively on the degree of monetary policy accommodation measured by γ) relative to that of the substitution effect (that depends positively on the curvature coefficient of the labor supply curve η). For plausible parameter values, as we show below, the real wage indeed falls along with employment in the sticky-price model.

Under the same conditions that make the real wage and employment fall in response to a positive shock, the nominal wage falls by even more than that in the real wage, since the price level falls, as is clear from (19), where we have assumed that $\gamma < 1$ so that n_t falls. It is thus theoretically possible that the sticky-price model may fail to explain the rise in the real wage and the sluggishness in the adjustment in the nominal wage following technology shocks.

3.5.2 Empirical plausibility

We now examine the predictions of the sticky-price model on the labor-market variables under empirically plausible parameter values. We first consider a set of baseline calibrated parameters, and then examine the robustness of the results.

Since we have a quarterly model in mind, we set $\beta = 0.99$ so that the steady state annual real interest rate is 4 percent. We set the baseline value of α_p to 0.75 so that the average duration of the price contracts is four quarters. In a sensitivity analysis, we also consider smaller values of α_p (corresponding to more frequent price adjustments). We set $\varepsilon_p = 10$, corresponding to a steady state price-markup of 11 percent. The parameter η corresponds to the inverse labor supply elasticity. Most empirical studies suggest that this elasticity is small and lies well below one, so that η is above one. We set $\eta = 2$ as a benchmark value and also consider a range of η between 1 and 5, corresponding to a labor supply elasticity in the range between 0.2 and 1.⁶ For the purpose of illustration, we set $\gamma = 0$ as a benchmark. As we discuss below, this value seems empirically reasonable. In our sensitivity analysis, we allow γ to vary in the broad range between 0 and 1.

Figure 2 plots the impulse responses of the labor market variables following a positive technology shock under the calibrated parameters. Evidently, both real and nominal wages fall along with employment, and the fall in the nominal wage is greater than that of the real wage. The fall in employment is supported by empirical evidence, whereas the declines in the wages are not.

Figure 3 plots the impact effect of the shock on employment, as the policy parameter γ varies from 0 to 1, and the inverse labor supply elasticity η varies from 1 to 5. Apparently, the sticky-price model consistently predicts the fall in employment under all possible configurations of these parameters (which is perhaps not surprising in light the closed-form solution for n_t in (20)).

Figure 4 displays the impact effect of the shock on the real and nominal wages. Here, the results are not as clear-cut as in the case with employment. Consistent with our analytical solutions for the wage dynamics, the impact effect tends to be more negative if γ is small or η is large. Given the smallest value of η that we consider plausible (i.e., $\eta = 1$), the sticky-price model is able to generate a rise in the real wage if γ is large enough (above 0.3). But with large values of γ , the nominal

⁶The results are robust even when we extend the lower bound of η to 0.5 (not reported).

wage also rises along with the real wage, which is at odds with the evidence that the former does not adjust much while the latter rises significantly following technology shocks.

A natural question is then: How large is γ ? One way to answer this question is to examine the relation between money growth rate and appropriate measures of technology shocks. The money aggregate that we use is M2 for the United States, with a sample period from 1959 to 2003 (at monthly frequency), obtained from the FRED II database published by the St. Louis Federal Reserve Bank. We use two alternative measures of technology shocks. The first measure is constructed by Gali and Rabanal (2004), with a sample period from 1950 to 2002 (at quarterly frequency), and the second is the “purified” technology measure obtained by BFK (2004), from 1949 to 1996 (at annual frequency).⁷ Figure 5 presents scatter plots of M2 growth rate and the two alternative measures of technology shocks, with appropriate adjustments of data frequencies and sample periods. The plots suggest a weak correlation between the money growth rate and the technology measures, in other words, γ is likely to be small.

To obtain a formal estimate of γ , we run an OLS regression of the time series of M2 growth rate on the series of appropriately measured technology shocks. The regression equation that we use is the following:

$$\mu_t = (1 - \rho)\bar{\mu} + \rho\mu_{t-1} + \gamma\varepsilon_t, \quad (23)$$

where μ_t denotes the M2 growth rate, $\bar{\mu}$ is the mean money growth, and ε_t is the technology shock. Using Gali-Rabanal’s technology measure, the point estimate of γ is 0.08, with a standard error of 0.08 and a 95 percent confidence interval from -0.08 to 0.24 ; using BFK’s technology measure, the point estimate is 0.13, with a standard error of 0.33 and a 95 percent confidence interval from -0.53 to 0.79 . Thus, the estimates are not statistically different from zero.⁸

Going back to Figure 4, we see that, even if we use the higher point estimate of $\gamma = 0.13$, the responses of the wages are still negative for all values of η . Thus, although a pure sticky-price model is capable of generating a decline in employment following technology improvements, it in general fails to generate the rise in the real wage and the weak response of the nominal wage.

⁷We are grateful to Susanto Basu and Jordi Gali for kindly providing us with the data.

⁸We have also tried M1 data and obtained very similar results (not reported). Note that, in the scattered plot with BFK’s technology measure, there appears to be a slightly negative relation between M2 growth and the BFK technology measure, whereas the point estimate of γ using BFK’s measure is slightly positive. This difference arises since, in our regression, we have included the lagged money growth rate.

4 Does Introducing Nominal Wage Rigidity Help?

The failure of the sticky-price model to generate the observed responses of the wage rates, particularly of the nominal wage, suggests that the missing element might be nominal wage rigidity. Yet, it is far from clear that introducing nominal wage rigidity can also generate a substantial rise in the real wage while maintaining the fall in employment predicted correctly by the sticky-price model. We now investigate this possibility.

To introduce nominal wage rigidity, we assume that the labor market, like the goods market, is also monopolistically competitive. There is a continuum of households, each endowed with a differentiated labor skill indexed by $i \in [0, 1]$, with a utility function similar to (1) (except with all variables indexed by i). Production of goods requires input of a composite labor, and is subject to a productivity shock. The production function is the same as in (9), with the composite labor given by

$$N_t = \left(\int_0^1 N_t(i)^{\frac{\varepsilon_w - 1}{\varepsilon_w}} di \right)^{\frac{\varepsilon_w}{\varepsilon_w - 1}}, \quad (24)$$

where $\varepsilon_w > 1$ is the elasticity of substitution between differentiated skills. Cost-minimizing by firms implies that the demand for labor skill of type i is given by

$$N_t^d(i) = \left(\frac{W_t(i)}{W_t} \right)^{-\varepsilon_w} N_t, \quad (25)$$

where $W_t(i)$ is the nominal wage for type i labor skill, and W_t is the wage index that is related to individual wages by

$$W_t = \left(\int_0^1 W_t(i)^{1 - \varepsilon_w} di \right)^{\frac{1}{1 - \varepsilon_w}}. \quad (26)$$

In each period, each household receives an iid random signal that enables it to adjust its nominal wage with probability $1 - \alpha_w$, taking the demand schedule for labor skill (25) as given. It follows from the law of large numbers that, in each period, a fraction $1 - \alpha_w$ of all households can set new wages, while the rest have to stay put. The optimal wage decision rule is given by

$$W_t^*(i) = \mu_w \frac{\mathbf{E}_t \sum_{\tau=t}^{\infty} \alpha_w^{\tau-t} D_{t,\tau} MRS_{\tau}(i) N_{\tau}^d(i)}{\mathbf{E}_t \sum_{\tau=t}^{\infty} \alpha_w^{\tau-t} D_{t,\tau} N_{\tau}^d(i)}, \quad (27)$$

where $\mu_w = \varepsilon_w / (\varepsilon_w - 1)$ measures the steady-state wage markup, and $MRS = -V'(N)C$ denotes the marginal rate of substitution between leisure and consumption. The optimal wage is thus a constant markup over a weighted average of the MRS's in the future periods during which the wage is expected to remain in effect.

We focus again on log-linearized equilibrium conditions around a zero-inflation steady state. The log-linearized equilibrium conditions in the model with both sticky prices and sticky wages are

summarized as follows

$$\pi_t = \beta \mathbf{E}_t \pi_{t+1} + \lambda_p \tilde{\omega}_t, \quad (28)$$

$$\pi_{wt} = \beta \mathbf{E}_t \pi_{w,t+1} + \frac{\lambda_w}{1 + \eta \varepsilon_w} [(1 + \eta) \tilde{c}_t - \tilde{\omega}_t], \quad (29)$$

$$\tilde{\omega}_t = \tilde{\omega}_{t-1} + \pi_{wt} - \pi_t - \Delta a_t, \quad (30)$$

$$\pi_t + \Delta \tilde{c}_t = (\gamma - 1) \Delta a_t, \quad (31)$$

where $\pi_{wt} = w_t - w_{t-1}$ denotes the wage inflation rate, $\tilde{\omega}_t = w_t - p_t - a_t$ is the real wage “gap,” $\tilde{c}_t = c_t - a_t$ is the output gap, and $\lambda_w = (1 - \beta \alpha_w)(1 - \alpha_w)/\alpha_w$.

To examine the potential ability of the model with nominal wage rigidity in explaining the labor market dynamics, we consider various degrees of price rigidity. We begin with the extreme case where prices are perfectly flexible (i.e., $\alpha_p = 0$). In this case, the pricing decision is given by $p_t = w_t - a_t$, so that the real wage rises one-for-one with the technology shock. To obtain the equilibrium employment dynamics, we use the wage-Phillips curve relation (29), which can now be written as

$$\pi_{wt} = \beta \mathbf{E}_t \pi_{w,t+1} + \kappa_w (c_t - a_t). \quad (32)$$

where $\kappa_w = \lambda_w(1 + \eta)/(1 + \eta \varepsilon_w)$. Using the pricing decision equation $p_t = w_t - a_t$, this equation can be rewritten in terms of price inflation:

$$\pi_t + \Delta a_t = \beta \mathbf{E}_t (\pi_{t+1} + \Delta a_{t+1}) + \kappa_w (c_t - a_t).$$

Solving for the price level, we obtain

$$p_t = \theta_w p_{t-1} + (1 - \theta_w)(\gamma - 1)a_t - \theta_w \Delta a_t, \quad (33)$$

where θ_w is the smaller root of the quadratic polynomial $\beta \theta^2 - (1 + \beta + \kappa_w)\theta + 1 = 0$. Given the solution for p_t , we use the aggregate demand relation (17) to obtain c_t , and the production function to obtain n_t . The solution for employment is given by

$$n_t = \theta_w n_{t-1} + \theta_w \gamma \varepsilon_t. \quad (34)$$

Thus, with perfectly flexible prices and sticky nominal wages, the employment response to technology shocks is non-negative as long as $\gamma \geq 0$.

Since the real wage fully rises with the shock and the impact effect on the price level implied by (33) is $(1 - \theta_w)\gamma - 1$, the impact effect on the nominal wage is given by $(1 - \theta_w)\gamma$. As $\theta_w < 1$, the response of the nominal wage, as the response of employment, is non-negative as long $\gamma \geq 0$.

Thus, the pure sticky-wage model does not fare better than the pure sticky-price model in the sense that, although it delivers procyclical response of the real wage and weak response of the nominal wage, it fails to generate the fall in employment.

We now consider the more general case with some degree of price rigidity along with the nominal wage rigidity. In this case, the equilibrium dynamics are the solution to the system of equilibrium conditions (28)-(31). To solve the model, we use the calibrated parameter described in the previous section, and calibrate two additional parameters that are unique to nominal wage rigidity: we set $\alpha_w = 0.75$ so that the average duration of nominal wage contract is four quarters, as suggested by empirical evidence (e.g., John B. Taylor (1999)); and we set $\varepsilon_w = 4$, so that a 1 percent rise in relative nominal wages would result in a 4 percent fall in relative hours worked, in light of the microeconomic evidence presented by Peter Griffin (1992, 1996) (see also Kevin X.D. Huang and Zheng Liu (2002)). Again, we consider $\eta = 2$ and $\gamma = 0$ as a baseline calibration (the value of $\gamma = 0$ is in line with the regression results above), and examine the sensitivity of the results as η varies in the range between 1 and 5 and γ in the range between 0 and 1. Finally, in light of the evidence presented by Mark Bils and Peter Klenow (2002), we consider shorter durations of price contracts such as 2 quarters, as well as the standard calibration of 4 quarters.

Figure 6 and 7 plot the impulse responses of employment and wages, respectively, in the model with sticky nominal wages, with various degrees of price rigidity. In the extreme case with flexible prices, as we have shown analytically, employment does not change; with modest degree of price rigidity, for instance, when the average duration of price contracts is 2 quarters, employment would fall; increasing price rigidity to 4 quarters of contracts magnifies the fall in employment. The response of the real wage stays positive as we vary the degrees of price rigidity, although the initial response becomes more dampened as the length of the price contracts increases. Introducing price rigidity makes the response of nominal wages become negative, although the magnitude of the nominal wage response remains quite small relative to the changes in employment and the real wage, as is observed in the empirical studies.

In this sense, the model with nominal wage rigidity, along with some price rigidity, is more successful than the pure sticky-price model in explaining the labor market dynamics following technology shocks, and the required price rigidity is rather modest.

Now, how robust are these results if we consider a broader range of key parameter values? Figure 8 and 9 plot the impact effect on employment and on the wages, respectively, as η varies from 1 to 5 and γ from 0 to 1. For most of the parameter values, the model consistently predicts that employment falls, the real wage rises, and the nominal wage does not change much following technology shocks, just as observed in the empirical studies.

5 Conclusion

The implications on labor-market dynamics have often been used as a criterion to evaluate competing business cycle theories. A striking empirical result that technology improvement typically leads to a fall in employment has cast doubt on the ability of the standard RBC model to explain business cycle fluctuations. Many contemporary thinkers have argued on this ground that one should take sticky-price models more seriously as an explanation of business cycle fluctuations, since these models are capable of explaining the recessionary effect of technology improvement on employment.

In this paper, we show that a pure sticky-price model fails to explain a broader set of labor market dynamics: it predicts the wrong sign of the response of real wages and the wrong magnitude of the response of nominal wages. We propose that, an alternative model with nominal wage rigidity, coupled with some price rigidity, has a better chance of succeeding in explaining the broader set of labor market dynamics following technology shocks. Such a model is able to explain the fall in employment, the rise in real wages, and the weak response of nominal wages following technology shocks, as we observe in the data. These results obtain even with relatively short durations (such as 2 quarters instead of 4 quarters) of price contracts.

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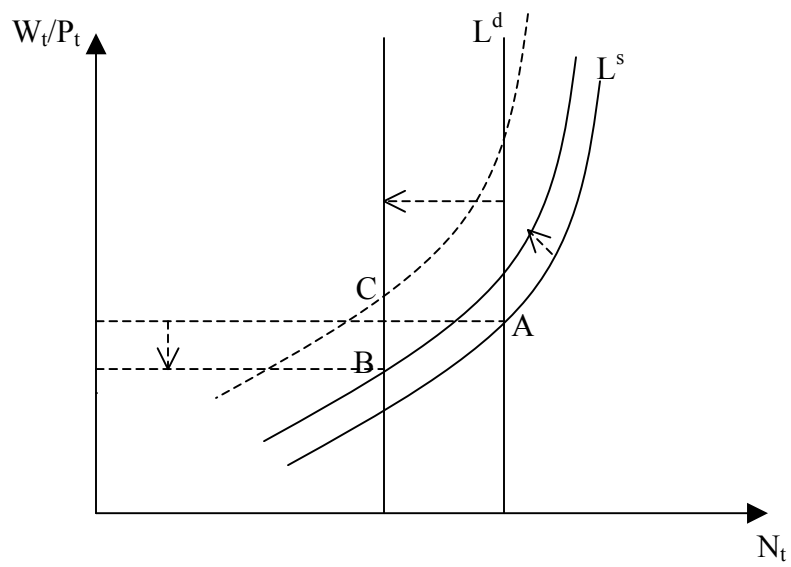


Figure 1. ---Labor market adjustments following a positive technology shock in the sticky-price model

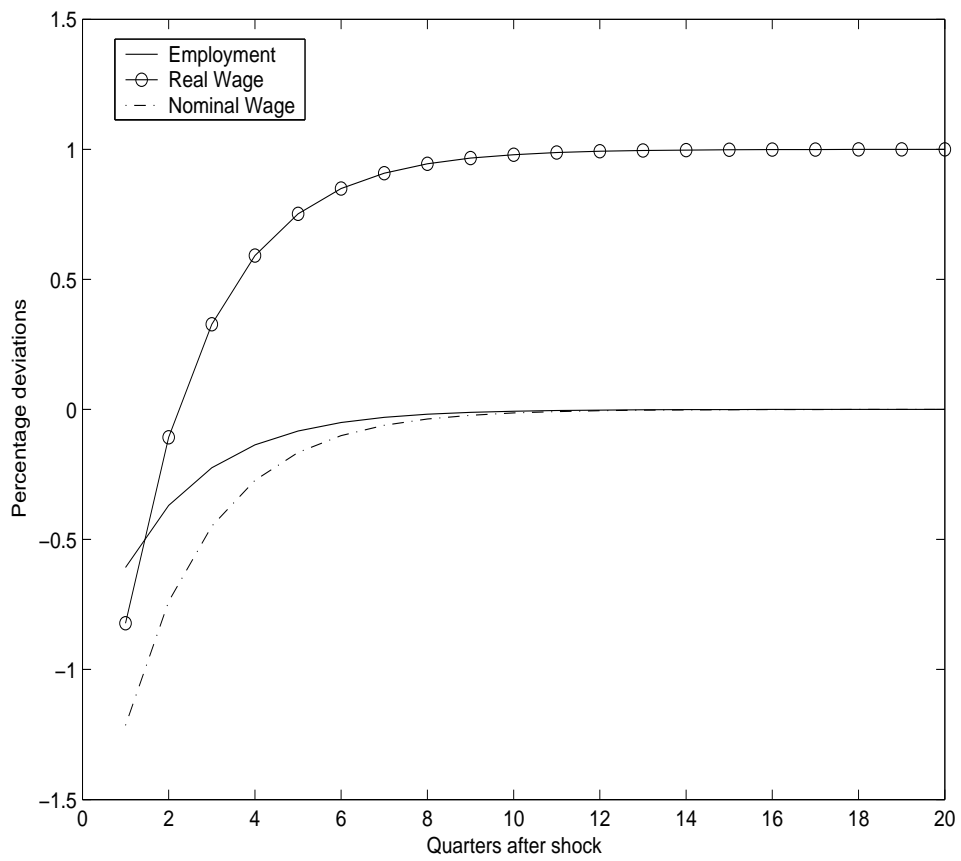


Figure 2:—Labor market responses to a technology shock in the sticky-price model.

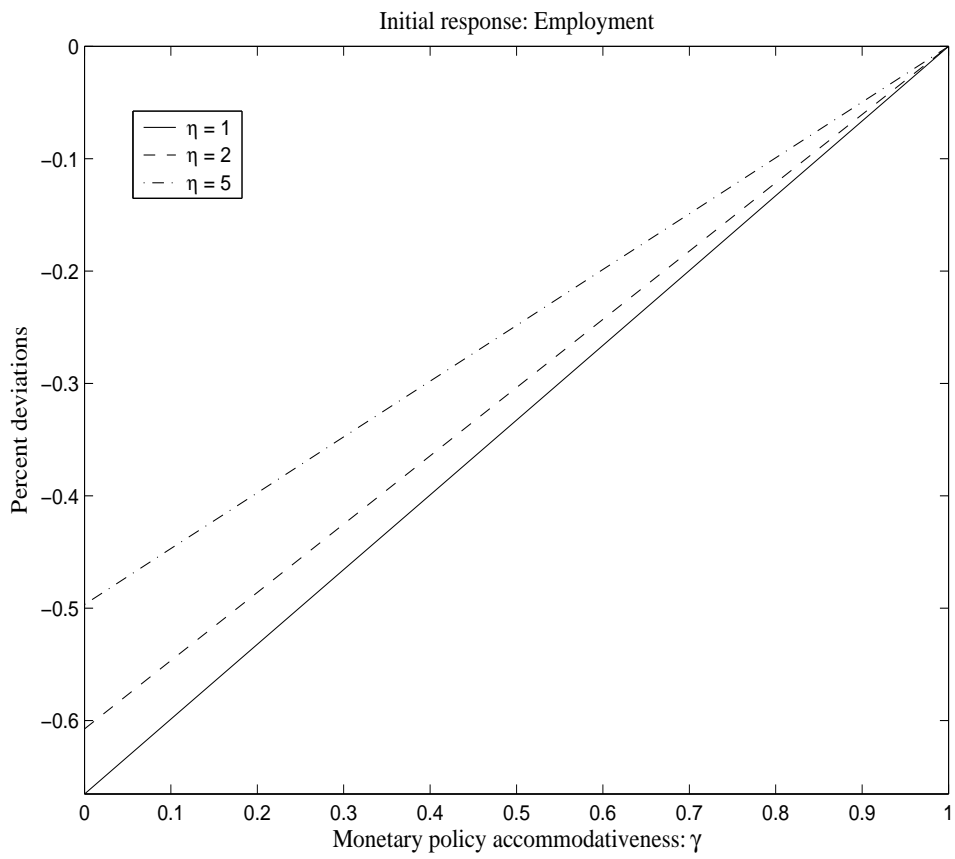


Figure 3:—Robustness of employment response in the sticky-price model.

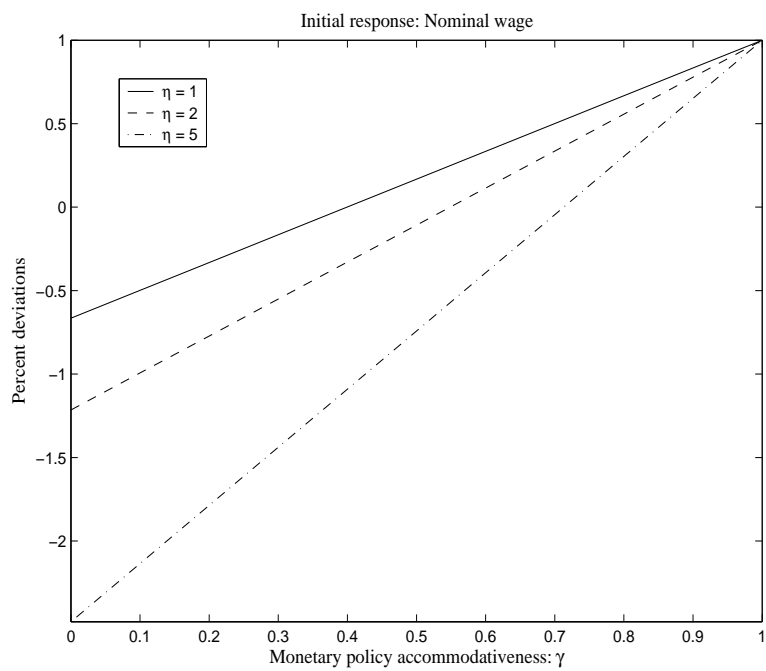
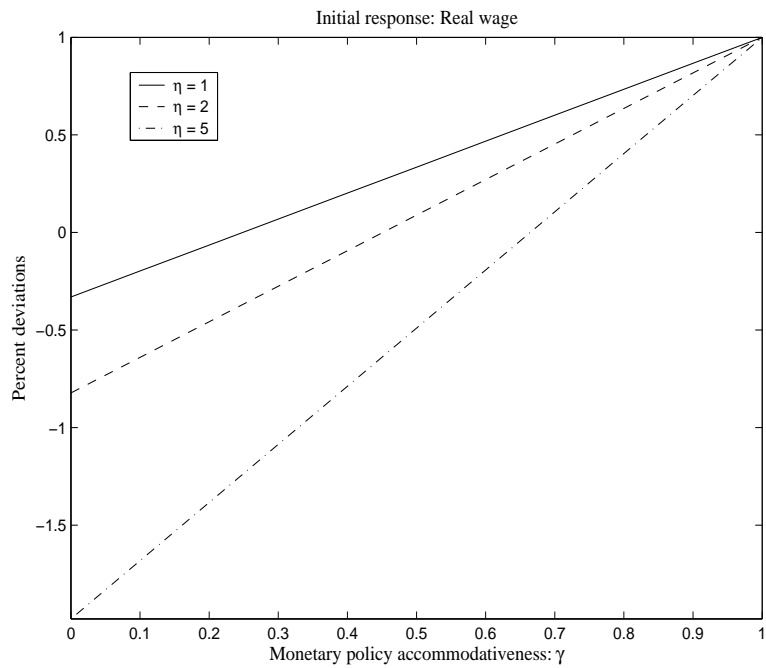


Figure 4:—Robustness of wage responses in the sticky-price model.

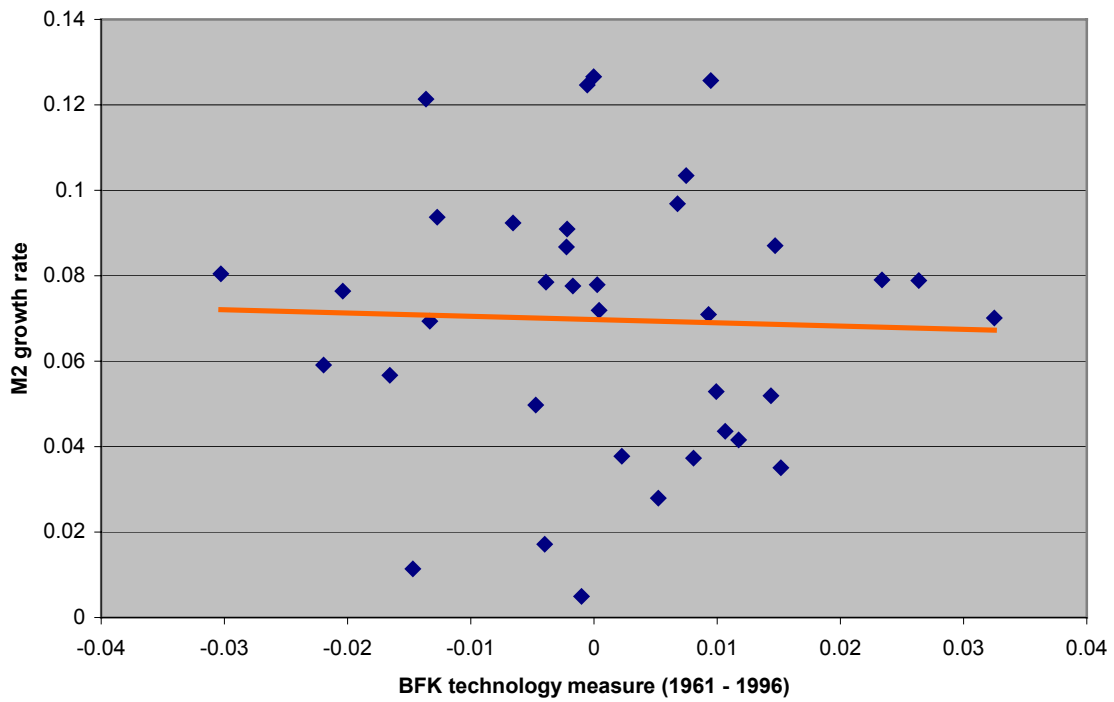
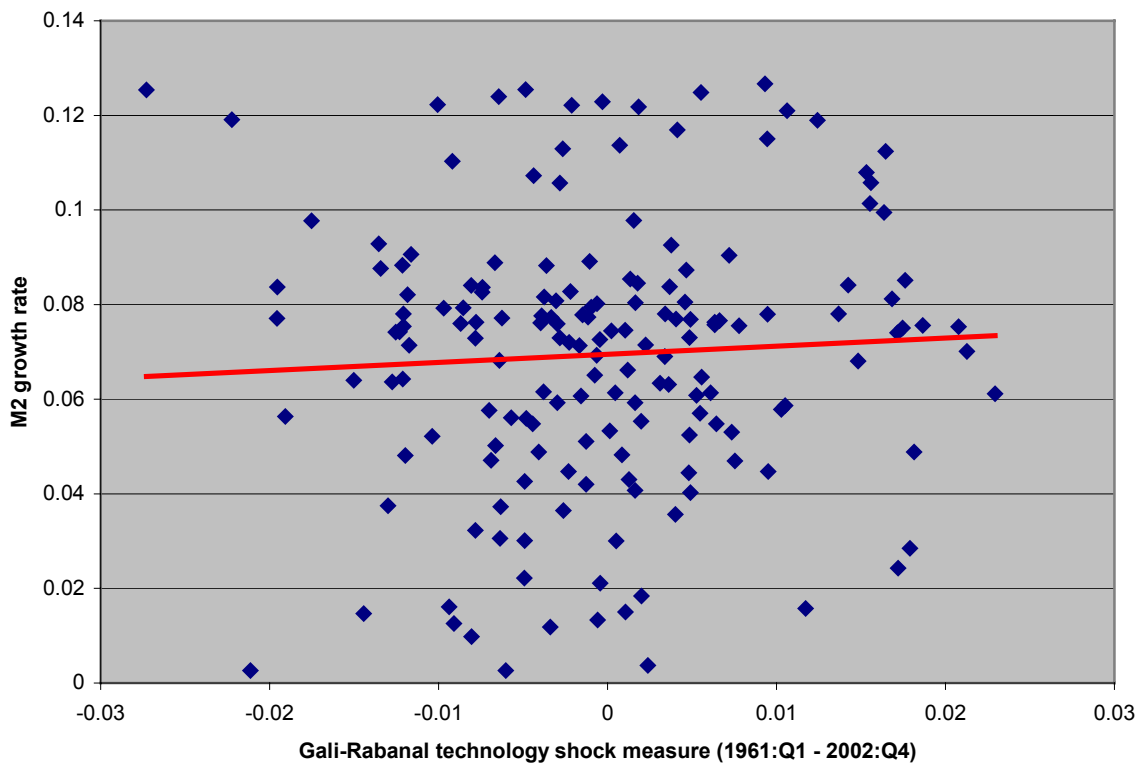


Figure 5. ---Monetary policy accommodation for technology shocks in the U.S.

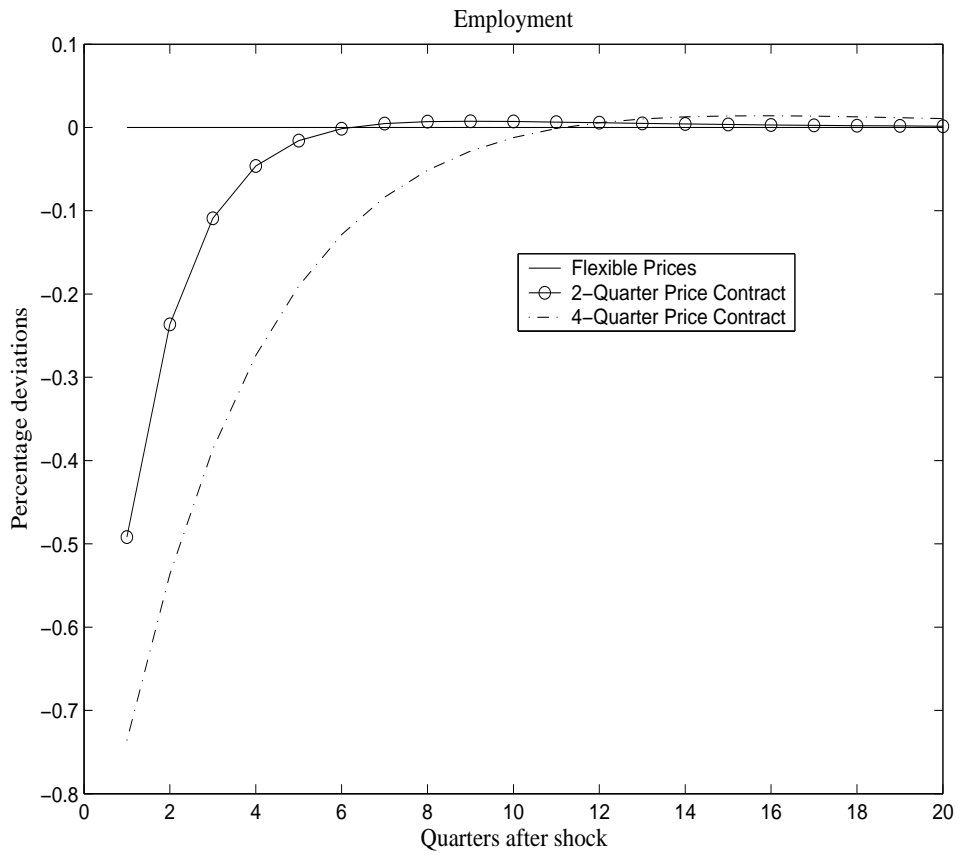


Figure 6:—Impulse responses of employment in the model with stick wages and prices:
Sensitivity to price stickiness.

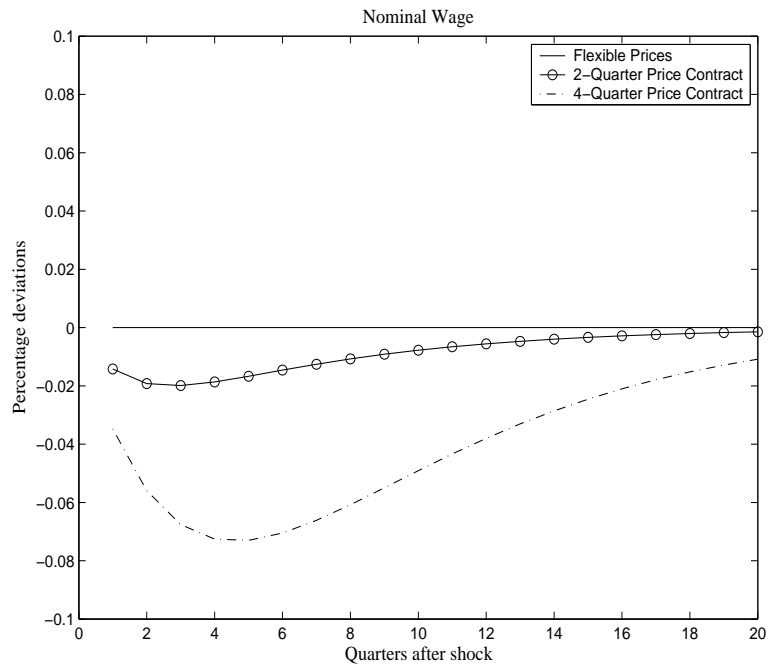
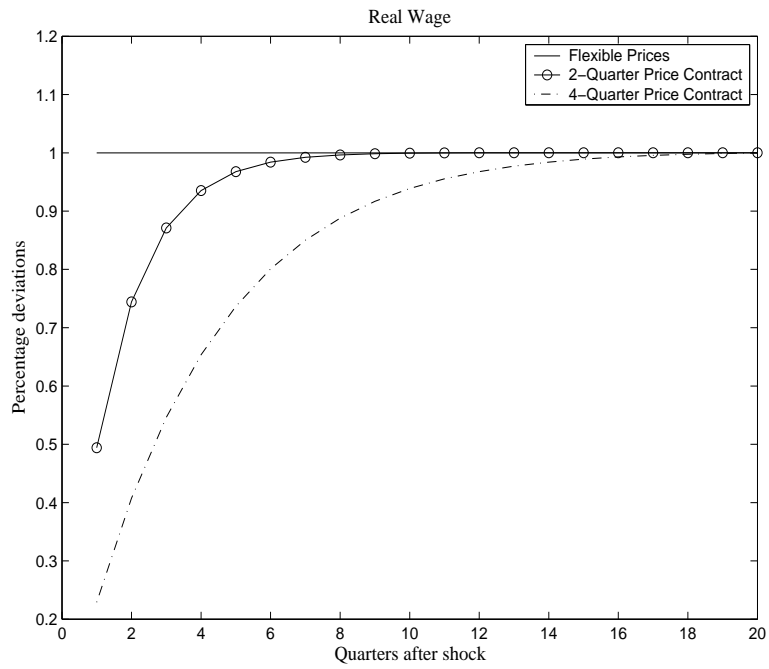


Figure 7:—Impulse responses of real and nominal wages in the model with stick wages and prices: Sensitivity to price stickiness

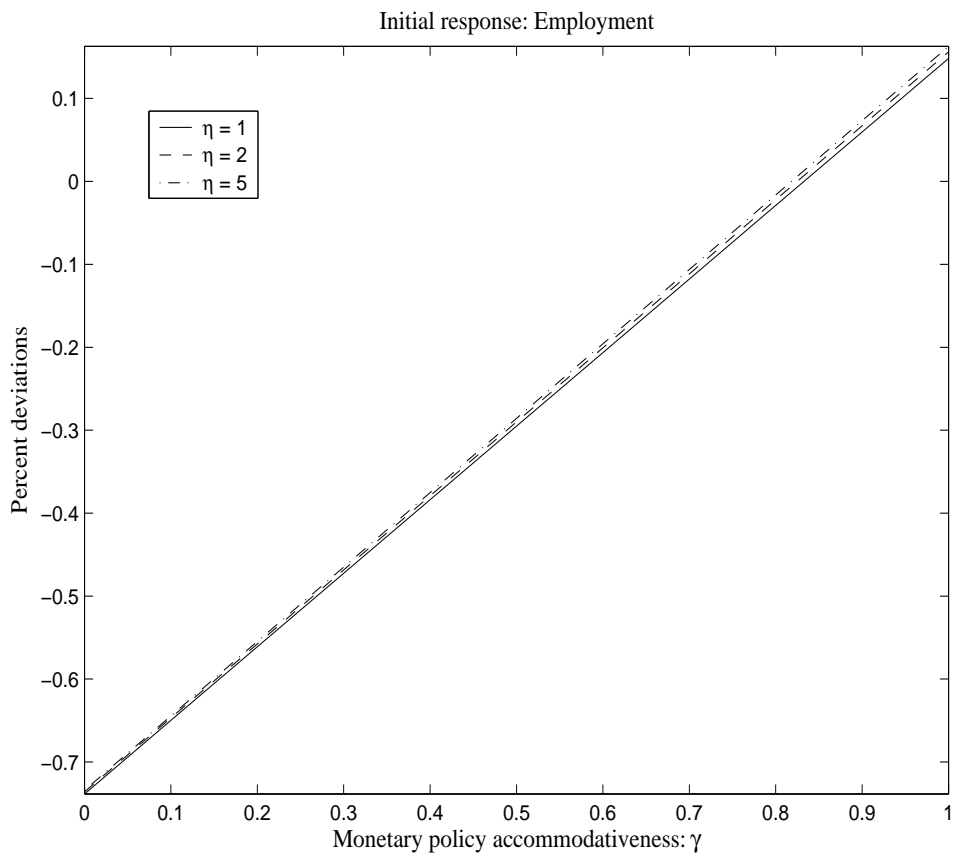


Figure 8:—Robustness of employment response in the model with sticky wages and prices.

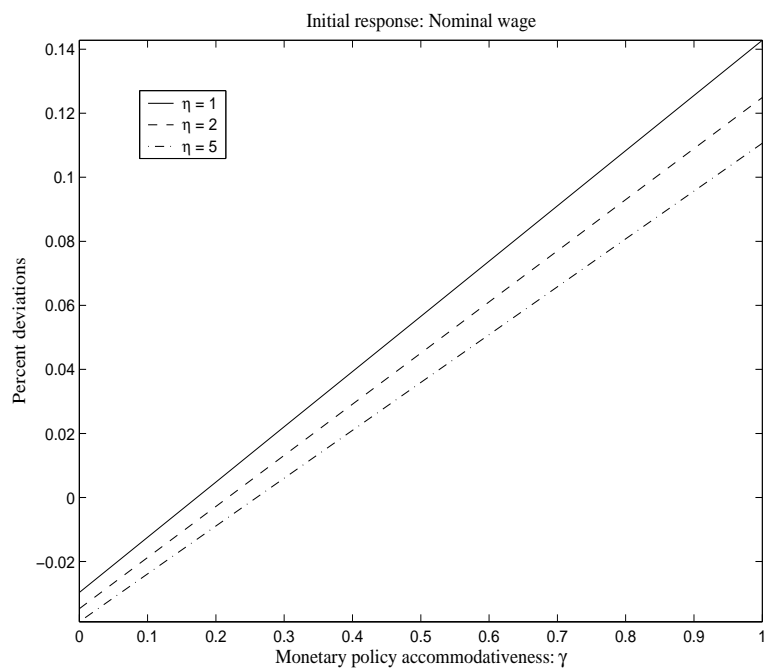
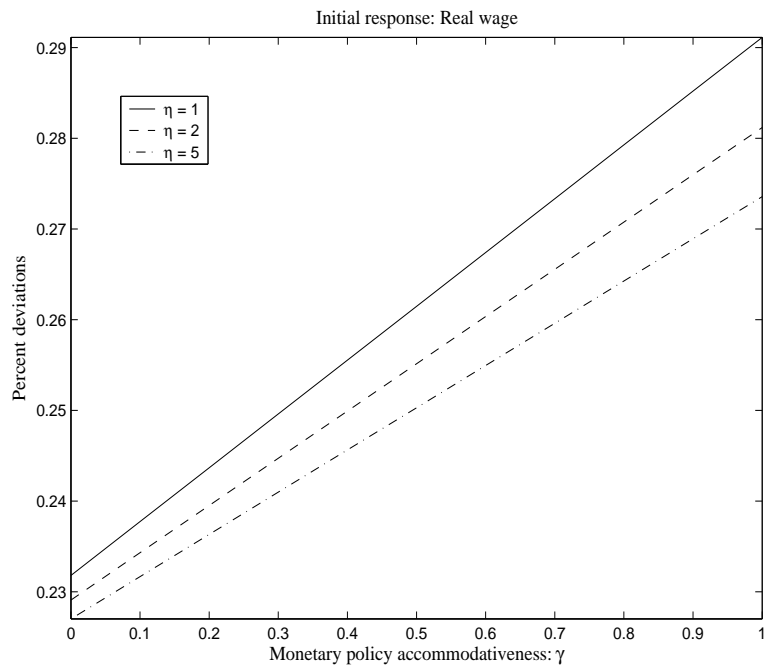


Figure 9:—Robustness of wage responses in the model with sticky wages and prices.