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Technology Shocks and Labor Market Dynamics: Some Evidence and Theory*

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Abstract

A positive technology shock may lead to a rise or a fall in per capita hours, depending on how hours enter the empirical VAR model. We provide evidence that, independent of how hours enter the VAR, a positive technology shock leads to a weak response in nominal wage inflation, a modest decline in price inflation, and a modest rise in the real wage on impact and a permanent rise in the long run. We then examine the abilities of several competing theories to account for the evidence. The model that stands out features sticky prices, sticky nominal wages, and habit formation. The same model also does well in accounting for the labor market evidence in the post-Volcker period.

JEL classification: E31, E32, E52

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1 Introduction

Understanding labor market dynamics has been an important goal for business cycle studies, at least since Dunlop (1938) and Tarshis (1939). While the historical debates have focused on the cyclical behavior of wages, a more recent strand of literature has focused on the cyclical behavior of employment or per capita hours, especially on their responses to permanent technology shocks.

A large body of empirical literature suggests that a permanent technology improvement leads to a *fall* in per capita hours. This result has been obtained from structural vector autoregression (SVAR) models, where a technology shock is identified as the only shock that affects labor productivity in the long run (e.g., Gali, 1999; Francis and Ramey, 2005).[1] A similar result has also been obtained with technology shocks measured by a "purified Solow residual" that controls for non-technological factors that may affect measured total factor productivity (e.g., Basu, Fernald, and Kimball, 2004; henceforth BFK). Yet another line of research argues that a positive technology shock triggers a *rise*, not a fall, in per capita hours, even when the technology shocks are identified using the same long-run restrictions as in Gali (1999) (e.g., Christiano, Eichenbaum and Vigfusson, 2004; henceforth CEV). The difference in conclusions arises from the different treatments of hours in the SVAR: whether hours rise or fall following a positive technology shock depends on whether hours enter the SVAR in log-levels or in log-differences.[2]

The lack of consensus in the empirical findings renders it difficult to assess alternative macroeconomic models based solely upon the employment effects of technology shocks. If a technology improvement indeed leads to a fall in hours, then such evidence would cast doubts on the empirical relevance of the standard real business cycle (RBC) theory, which predicts that hours should be procyclical. Some authors interpret this evidence as favoring a theory with nominal rigidities — and in particular, with sticky prices— along with a weakly accommodative monetary policy (e.g., Gali, 1999; BFK, 2004). Some other authors argue that the same evidence can be consistent with predictions of an RBC model that incorporates habit formation (e.g., Francis and Ramey, 2005).[3] If, on the other hand, a positive technology shock indeed leads to a rise in hours, then the standard RBC model would do just fine; and further, as we show in the current paper, so would a pure sticky-wage model.

[1]The approach to identifying technology shocks based on such long-run restrictions takes its root in Blanchard and Quah (1989) and Shapiro and Watson (1988).

[2]An interesting recent contribution to this debate is made by Fernald (2005), who shows that if one allows for statistically and economically plausible trend breaks in labor productivity, then hours worked would fall on impact of a positive technology shock, regardless of whether hours are measured in differences or in levels. For a survey of the recent SVAR literature, see, for example, Gali and Rabanal (2004). See also Chari, Kehoe, and McGrattan (2005) and Christiano, Eichenbaum, and Vigfusson (2006) for an interesting exchange on some general issues concerning the SVAR approach.

[3]For implications of incorporating habit formation in RBC models, see also Jermann (1998), Lettau and Uhlig (2000), and Boldrin, Christiano and Fisher (2001), among others.

The present paper proposes a way out of this dilemma. First, we go a step further in exploring the empirical evidence —from a broader perspective of the labor market. In particular, we examine the effects of technology shocks not only on hours but also on wages and prices. We present in Section 2 a four-variable SVAR model that includes the growth rate of average labor productivity, per capita hours, nominal wage inflation, and price inflation. In our SVAR specifications, we allow hours to enter in either log-differences or log-levels; and in doing so, we do not take a stand on which empirical specification better captures reality.

Some empirical regularities emerge from the SVAR model. Following a permanent technology improvement, (i) hours may rise or fall, depending on how hours enter the SVAR model; (ii) wage inflation responds weakly and not systematically; (iii) price inflation falls modestly; and (iv) real wages rise modestly on impact and continue rising until reaching a permanently higher level. The first finding confirms what others have found in the literature. The rest of the findings do not depend on how hours are modeled. Aside from our own SVAR evidence, we find corroborating evidence from the work of BFK (2004), who obtain similar empirical regularities in wages and prices based on an independent measure of technology shocks. We argue that a reasonable business cycle model should be able to account for the dynamic adjustments of wages and prices as we document here.

To help understand what drives these observed labor market dynamics following technology shocks, we examine in Section 3 a simple theoretical framework, much in the spirit of Gali (1999). This framework features monopolistic competition in both the labor market and the goods market (e.g., Blanchard and Kiyotaki, 1987). It captures interactions between nominal rigidities (in the forms of sticky prices and nominal wages) and monetary policy accommodation. In this simple illustrative model, monetary policy is described by a money growth rule that allows, but does not require, monetary policy to respond systematically to technology shocks.[4]

With the help of analytical solutions (and some numerical solutions), we show that a pure sticky-price model tends to generate a short-run decline in both the real and nominal wages following a positive technology shock. To understand this result, imagine an economy where prices are predetermined, wages are flexible, and money supply stays constant (i.e., no accommodation). Following a positive technology shock, the price level does not respond in the impact period, nor does the money supply. Hence, real aggregate demand and aggregate consumption do not change. Since the demand for labor is dictated by firms' need to meet the demand for goods, higher productivity and unchanged demand for goods imply a fall in employment. As such, the

[4]The model with sticky prices and sticky nominal wages has become an important theoretical workhorse in the recent dynamic stochastic general equilibrium (DSGE) literature. For example, it has been used to study effects of monetary policy shocks or aggregate demand shocks (e.g., Huang and Liu, 2002; Huang, Liu, and Phaneuf, 2004; Christiano, Eichenbaum, and Evans, 2005). It has also been used to examine optimal monetary policy (e.g., Erceg, Henderson, and Levin, 2000).

marginal disutility of working falls, so does the real wage, since the real wage is a constant "markup" over the marginal rate of substitution (MRS) between leisure and consumption, and the marginal utility of consumption remains unchanged. Since prices are sticky, the decline in the real wage is accompanied by a decline in the nominal wage. Allowing for partial adjustments in prices (such as staggered price setting) and partial monetary-policy accommodation for technology shocks does not change the qualitative results. These patterns of adjustments in the real and nominal wages in a sticky-price model do not seem to be consistent with our evidence.

A model with sticky nominal wages, on the other hand, does generate a weak (and more realistic) response of nominal wage inflation. However, if price adjustments are flexible, the sticky-wage model implies a sharp decline in price inflation and a sharp rise in the real wage, which are not supported by evidence. Further, as the price level falls, aggregate output rises. This rise in output can exceed the rise in productivity, and therefore hours can rise (as in an RBC model) provided that monetary policy is sufficiently accommodative for technology shocks. We conclude Section 3 by showing that a model that features both nominal wage and price rigidities is more promising in generating plausible dynamics in hours, wages, and prices following technology shocks.

In Section 4, we provide a formal quantitative evaluation of several macroeconomic models, including those discussed in Section 3, in terms of their ability to account for our evidence. For this purpose, we generalize the simple framework presented in Section 3 along two dimensions, although the basic intuition carries through in the more general framework. First, we replace the simple money growth rule by a Taylor rule. Second, we incorporate habit formation in preferences.

By incorporating habit formation in our model with nominal rigidities, we are able to evaluate the quantitative relevance of the sticky-price mechanism favored by Gali (1999) and BFK (2004) versus the habit-formation mechanism proposed by Francis and Ramey (2005) in accounting for a broad set of labor-market dynamics following technology shocks. When we confront the theoretical impulse responses obtained from either of these models against the VAR-based estimates, we find some aspects of the models' predictions inconsistent with our evidence. The model with habit formation but without nominal rigidities does generate a short-run decline in hours, as found by Francis and Ramey (2005); but it fails to generate the observed responses of wages and prices. The sticky-price model, with or without habit formation, does not fare better. While it does generate a fall in hours under calibrated parameters, it has trouble explaining the dynamic adjustments in the real and nominal wages. Through the mechanisms discussed above, the sticky-price model generates a sharp decline in both the real and nominal wages on impact of a positive technology shock. In contrast, in the data, the real wage rises modestly on impact of the shock, and the nominal wage does not adjust systematically.[5]

[5]One way to prevent the real wage from declining following technology improvements is to introduce some type of real rigidity, such as efficiency wages. Since this kind of real rigidity tends to generate weak responses of the real wage, the nominal wage has to adjust as much as the price level does. Unless prices are assumed to be extremely sticky,

Given that nominal wages respond weakly to technology shocks in the data, it is natural to examine whether or not introducing nominal wage rigidity would help to account for the observed labor market dynamics. We find that, under fairly general conditions, it does. In an extreme case with sticky nominal wages and flexible prices, the real wage rises following a technology improvement, while the nominal wage stays roughly constant, representing a step in the right direction. Unlike the sticky-price model, the sticky-wage model predicts a rise in hours in the presence of partial policy accommodation, consistent with the SVAR evidence when hours enter in levels. But, as in the simpler model with a money growth rule, a problem with the pure sticky-wage model lies in the adjustment of the real wage: it rises sharply immediately after the shock. Another problem is that wage inflation rises slightly in the pure sticky-wage model, whereas it declines slightly (although statistically insignificantly) in the data. Introducing habit formation improves the sticky-wage model's fit with respect to the adjustment of wage inflation; but with or without habit formation, the model consistently predicts a sharp rise in the real wage and a sharp decline in price inflation, which are at odds with evidence.

Combining nominal wage rigidity with price rigidity leads to an improvement in the model's quantitative predictions along several dimensions. It helps bring the responses of hours and the real wage closer to the data, although the response of the real wage in the model is somewhat too strong. Further, although the model predicts a weak response of wage inflation, the response is slightly positive, which is somewhat different from the evidence. These flaws can be alleviated when we incorporate habit formation. The hybrid model with sticky prices, sticky wages, and habit formation predicts that hours decline modestly in the short run; the real wage rises modestly on impact and continues to rise thereafter until reaching a new, permanently higher steady-state level; and nominal wage inflation declines slightly following the shock, and the decline is much weaker than that in price inflation, just as in the data. Quantitatively, with monetary policy described by a Taylor rule, the theoretical responses of the labor market variables in our preferred model with sticky prices, sticky nominal wages, and habit formation lie mostly within the confidence bands of the VAR-based estimates for the postwar sample. Further, with appropriately calibrated monetary policy rules, the model also does well in accounting for the VAR evidence for the Volcker-Greenspan period in the U.S. economy.

2 Technology Shocks and the Labor Market Dynamics: Some Evidence

A large body of empirical literature that studies the effects of technology shocks on labor market dynamics focuses on employment or per capita hours. We approach this empirical issue from a

a technology improvement would lead to a systematic decline in the nominal wage, an implication not supported by our empirical evidence.

broader perspective of the labor market. In particular, we study the adjustments of employment, real wages, nominal wages, and prices following technology shocks, not just of employment. For this purpose, we estimate a four-variable SVAR model which includes the log-difference of labor productivity, the log-difference (Gali) or the log-level (CEV) of per capita hours, the log-difference of nominal wages, and the log-difference of nominal prices. The sample period of our data covers 1949:Q2 - 2003:Q4.[6]

In our estimations, we adopt the same long-run restrictions to identify technology shocks as in Gali (1999) or CEV (2004). We estimate both a model with hours in log-differences (i.e., the difference specification) and one with hours in log-levels (i.e., the level specification). We do this for two reasons. First, we try to avoid taking a stand on which measure of hours should enter the SVAR models. Second, and more important, we would like to examine whether or not the responses of other labor-market variables such as wages and prices are sensitive to changes in the SVAR specifications. And they are not.

Figure 1 presents the impulse responses of the labor-market variables following a positive technology shock in the SVAR model with the difference specification. The figure shows both the point estimates (the solid lines) and their 95% confidence bands (the shaded areas).[7] The figure shows that, following the shock, hours decline persistently, with an initial response of -0.4% and a peak response of about -0.6% in the third quarter. After the third quarter, hours return gradually to the pre-shock level. This result is not surprising, since we use the same difference specification as in Gali (1999), who also obtains a short-run decline in hours. What is new here is our results about the responses of wages and prices. In particular, nominal wage inflation and price inflation both decline following the shock, and the decline in price inflation is much larger (and statistically significant) than in nominal wage inflation (which is insignificantly different from zero). According to the point estimates, price inflation declines on impact about 3 times as much as does nominal wage inflation. As the price level falls more than does the nominal wage, the real wage rises modestly (and significantly) on impact of the shock, and continues rising until reaching a permanently higher steady state level.

Figure 2 presents the impulse responses of the same set of variables and their 95% confidence bands in the SVAR with the level specification. Here, hours fall slightly on impact of a positive

[6]Our data are taken from the Haver Analytics Economics Database. The variables are measured as follows. Our output series is the output in the non-farm business sector (with a mnemonic "LXNFO" in Haver). Our total hours series is the hours in non-farm business sector (LXNFH). Our nominal wage series is the compensation per hour in the non-farm business sector (LXNFC). Our nominal price series is the consumer price index (urban, all items) (PCU). We divide output by total hours to obtain labor productivity. We divide total hours by civilian non-institutional population 16 years and over (LNN) to obtain per capita hours. We have also tried to use the deflator for non-farm business output or the GDP deflator instead of the CPI and obtained similar results.

[7]We follow the same procedure as in CEV (2004) to estimate the impulse responses and the 95% confidence bands. We are grateful to Rob Vigfusson for providing us with their Matlab codes.

technology shock (almost no change), and then turn into positive and rise persistently. This pattern of hours adjustment is similar to that obtained by CEV (2004).[8] Although the response of hours looks different here from that under the difference specification, the responses of wages and prices are remarkably similar, although the real-wage response is less precisely estimated. Specifically, similar to those under the difference specification, the decline in the nominal wage is less pronounced than that in the price level; the response of price inflation is significant but that of nominal wage inflation is not; and the real wage rises modestly on impact, and continues rising thereafter.

The responses of wages and prices to technology shocks are not only robust across SVAR specifications in hours, they are also broadly consistent with the evidence produced by BFK (2004), who use an independent measure of technology shocks. In particular, they construct a purified technology shock series by controlling for changes in non-technological components in measured Solow residual (Solow, 1957) based on annual industry-level data in the U.S. during the period from 1949 to 1996.[9] They then examine the dynamic responses of a set of variables to their technology shocks by estimating a set of bivariate vector autoregressions. They find that a positive technology shock is followed by a short-run decline in total hours and employment (BFK, 2004, Figure 3, p. 53). The reported responses of wages and prices are particularly interesting. The price level falls modestly within the first two years, and then remains at a permanently lower steady state. The estimated response of the price level is statistically significant at a conventional confidence level (BFK, 2004, Figure 4, p.54). In contrast, the nominal wage basically "stays flat" and the estimated responses are statistically insignificant (BFK, 2004, Figure 4, p.54). The real wage, on the other hand, rises modestly on impact and keeps rising for about 2 years before it settles down at a permanently higher steady state (BFK, 2004, Figure 4, p.54). These findings based on independent measures of technology shocks lend further credence to our empirical results based on our SVAR models.

To summarize, we have shown that a positive technology shock can lead to a rise or a fall in per capita hours, depending on whether hours enter the SVAR in levels or in differences. But regardless of whether one uses the level specification, the difference specification, or some direct measures of technology shocks, the same set of results about the responses of wages and prices seems to emerge: following a positive technology shock, the nominal wage does not respond much; the price level declines modestly; the real wage rises modestly on impact and continues rising until reaching a permanently higher steady state.

[8]The response of hours here, although positive, is not significant. CEV (2004) obtain a similar finding in a six-variable SVAR (see their Figure 4). The magnitude of hours response here is also similar to that obtained by CEV (2004).

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

3 Nominal Rigidities and Technology Shocks: Some Intuition

In this section, we present a monetary business cycle model with sticky prices and nominal wages. Recent literature shows that price and nominal-wage rigidities play an important role in transmitting aggregate demand shocks such as monetary policy shocks (e.g., Huang, Liu, and Phaneuf, 2004; Christiano, Eichenbaum, and Evans, 2005). We study here the role of nominal rigidities in propagating technology shocks. As shown by Gali (1999) and others, models with nominal rigidities are also promising in explaining the observed employment dynamics following technology shocks. We examine the model's implications on a broader set of labor-market dynamics, including wages and prices, in addition to employment. For ease of exposition, we abstract here from real rigidities such as habit formation and focus on a simple money growth rule in the spirit of Gali (1999). We relax these assumptions in Section 4, where we evaluate the model's quantitative implications in light of the evidence presented in Section 2.

3.1 The Model Economy

The economy is populated by a large number of households, each endowed with a differentiated labor skill indexed by $i \in [0, 1]$; and a large number of firms, each producing a differentiated product indexed by $j \in [0, 1]$. There is also a monetary authority that conducts monetary policy. The households each derives utility from consumption, real money balances, and leisure time. The consumption good is a composite of the differentiated products. Production of each type of differentiated good requires a composite of labor skills as input and is subject to a productivity shock.

Denote by N_t a composite of differentiated labor skills $N_t(i)$ for $i \in [0, 1]$ such that $N_t = \left[\int_0^1 N_t(i)^{(\varepsilon_w-1)/\varepsilon_w} di\right]^{\varepsilon_w/(\varepsilon_w-1)}$, and by Y_t a composite of differentiated goods $Y_t(j)$ for $j \in [0, 1]$ so that $Y_t = \left[\int_0^1 Y_t(j)^{(\varepsilon_p-1)/\varepsilon_p} dj\right]^{\varepsilon_p/(\varepsilon_p-1)}$, where $\varepsilon_w \in (1, \infty)$ and $\varepsilon_p \in (1, \infty)$ are the elasticity of substitution between the skills and between the goods, respectively. The composite skill and the composite good are both produced in an aggregation sector that is perfectly competitive. The demand functions for labor skill i and for good j resulting from the optimizing behavior in the aggregation sector are given by

$$N_t^d(i) = \left[\frac{W_t(i)}{W_t}\right]^{-\varepsilon_w} N_t, \quad Y_t^d(j) = \left[\frac{P_t(j)}{P_t}\right]^{-\varepsilon_p} Y_t, \tag{1}$$

where the wage rate W_t of the composite skill is related to the wage rates $\{W_t(i)\}_{i\in[0,1]}$ of the differentiated skills by $W_t = \left[\int_0^1 W_t(i)^{1-\varepsilon_w} di\right]^{1/(1-\varepsilon_w)}$, and the price P_t of the composite good is related to the prices $\{P_t(j)\}_{j\in[0,1]}$ of the differentiated goods by $P_t = \left[\int_0^1 P_t(j)^{1-\varepsilon_p} dj\right]^{1/(1-\varepsilon_p)}$.

Household $i \in [0, 1]$ has a utility function

$$\mathrm{E}\sum_{t=0}^{\infty} \beta^t \left[\log(C_t(i)) + \Phi \log\left(\frac{M_t(i)}{P_t}\right) - V(N_t^d(i))\right], \tag{2}$$

where E is an expectations operator, $\beta \in (0,1)$ is a subjective discount factor, $C_t(i)$ denotes consumption, $M_t(i)/P_t$ denotes real money balances, and $N_t(i)$ denotes hours worked. The household faces a budget constraint

$$P_t C_t(i) + M_t(i) + \mathrm{E}_t D_{t,t+1} B_{t+1}(i) \leq W_t(i) N_t^d(i) + \Pi_t(i) + M_{t-1}(i) + B_t(i) + T_t(i), \tag{3}$$

where $B_{t+1}(i)$ denotes the household's holdings of a one-period state-contingent nominal bond that pays off one dollar in period $t+1$ if a particular event is realized, $D_{t,t+1}$ is the period-t price of such a bond divided by the probability of the appropriate state, $W_t(i)$ is a nominal wage rate for i's labor skill, $N_t^d(i)$ is the demand schedule for i's labor given by (1), $\Pi_t(i)$ is the household's claim to firms' profits, and $T_t(i)$ is a lump-sum transfer from the monetary authority.

Each household maximizes (2) subject to (3) and a borrowing constraint $B_{t+1}(i) \geq -\underline{B}$, for some large positive number $\underline{B}$. The initial conditions on bonds and money are given. Households are price takers in the goods market and monopolistic competitors in the labor market, where they set nominal wages, taking the demand schedule in (1) as given. Wage-setting decisions are staggered in the spirit of Calvo (1983). In particular, in period t, all households receive an iid random signal that determines whether or not they can set a new wage rate. The probability that a household can set a new wage rate is $1-\alpha_w$. By the law of large numbers, a fraction $1-\alpha_w$ of all households can set new wages in a given period. At date t, if a household i can set a new wage, then the optimal choice of its nominal wage is given by

$$W_t^*(i) = \mu_w \frac{\mathrm{E}_t \sum_{\tau=t}^{\infty} \alpha_w^{\tau-t} D_{t,\tau} MRS_\tau(i) N_\tau^d(i)}{\mathrm{E}_t \sum_{\tau=t}^{\infty} \alpha_w^{\tau-t} D_{t,\tau} N_\tau^d(i)}, \tag{4}$$

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

The production of a type-j good requires the composite labor as input, with a constant-returns production function described by

$$Y_t(j) = A_t N_t(j), \tag{5}$$

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

$$A_t = A_{t-1} \exp(\varepsilon_t), \tag{6}$$

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, where they set prices for their differentiated products, taking the demand schedules in (1) as given. Similar to households' wage-setting decisions, firms price-setting decisions are staggered in the spirit of Calvo (1983), with the probability for each firm to set a new price given by $1-\alpha_p$. A firm j that can set a new price in period t chooses a price $P_t(j)$ to maximize an expected present value of its profits

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

where $V_\tau = W_\tau / A_\tau$ is the unit production cost, and $Y_\tau^d(j)$ is the demand schedule described in (1). Solving the profit maximizing problem results in an optimal pricing decision rule

$$P_t^*(j) = \mu_p \frac{\mathrm{E}_t \sum_{\tau=t}^{\infty} \alpha_p^{\tau-t} D_{t,\tau} V_\tau Y_\tau^d(j)}{\mathrm{E}_t \sum_{\tau=t}^{\infty} \alpha_p^{\tau-t} D_{t,\tau} Y_\tau^d(j)}, \tag{7}$$

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

Regardless of whether or not they can set new prices, all firms solve their cost-minimizing problems, taking the input price (i.e., the wage rate) as given. The solution to firms' cost-minimizing problems yields aggregate demand for the composite labor

$$N_t^d = \frac{1}{A_t} \int_0^1 Y_t^d(j) dj = \frac{G_t Y_t}{A_t}, \tag{8}$$

where $G_t = \int_0^1 [P_t(j)/P_t]^{-\varepsilon_p} dj$ measures price dispersion. Thus, to a first-order approximation, if the rise in aggregate demand cannot catch up with productivity improvement, demand for labor would fall.

We close the model by specifying a monetary policy. Monetary policy is conducted via lump-sum transfers so that $\int_0^1 T_t(i) di = M_t^s - M_{t-1}^s$, where M_t^s denotes aggregate money stock. Following Gali (1999), we assume that the monetary authority follows a money-growth rule, under which it may adjust the growth rate of money stock in response to changes in productivity shocks. Specifically, we have

$$\mu_t = (1-\rho)\bar{\mu} + \rho \mu_{t-1} + \gamma \varepsilon_t, \tag{9}$$

where $\mu_t = \log(M_t^s / M_{t-1}^s)$ denotes the growth rate of money supply, and $\gamma \neq 0$ implies systematic responses of monetary policy to technology shocks.

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

To simplify analysis, we assume the existence of some implicit financial arrangements that enables households to pool their idiosyncratic income risks that may arise from staggered wage setting (e.g., Rotemberg and Woodford 1997).[10] Under such financial arrangements, equilibrium consumption and holdings of real money balances would be identical across households even though wages and hours worked may differ. It follows that the market clearing condition for the composite good is given by $C_t = Y_t$; and the market clearing condition for the composite labor, in light of (8), is given by $N_t = G_t C_t / A_t$.

3.2 Sticky Prices and the Labor Market Dynamics

We now examine labor market dynamics in a model with sticky prices, that is, the special case of the model with staggered price setting (i.e., $\alpha_p > 0$) and flexible wage setting (i.e., $\alpha_w = 0$). We study the model's implied dynamic adjustments of employment, the real wage, nominal wage inflation, and price inflation following a technology shock. We consider small shocks so that the equilibrium conditions can be approximated by log-linearizing around a zero-inflation steady state.[11] We first characterize the equilibrium dynamics based on a closed-form solution under some simplifying assumptions. We then compute the impulse responses of labor market variables following technology shocks under more general parameter values calibrated to the U.S. data.

3.2.1 Some Analytical Solutions and Intuitions

The equilibrium variables can be solved by combining three equilibrium conditions. The first condition is the optimal pricing decision, the log-linearized version of which gives rise to a Phillips-curve relation

$$\pi_t = \beta \mathrm{E}_t \pi_{t+1} + \kappa_p \tilde{c}_t, \tag{10}$$

where $\pi_t = \log(P_t/P_{t-1})$ denotes the inflation rate, $\tilde{c}_t = \log(C_t/A_t)$ denotes output gap, that is, deviation of equilibrium output (or consumption) from its natural-rate level. The parameter $\kappa_p = \lambda_p(1+\eta)$ determines the response of price inflation to changes in output gap, where $\eta = V''(N)N/V'(N)$ is the inverse intertemporal elasticity of labor hours and $\lambda_p = (1-\beta\alpha_p)(1-\alpha_p)/\alpha_p$ is the elasticity of pricing decisions with respect to real marginal cost.

The second condition that we need to solve the equilibrium system is the money demand equation. For analytical convenience, we set $\rho = 0$ (and we relax this assumption when we compute the model's impulse responses), so that $m_t = \gamma a_t$. The log-linearized money demand relation can then be written as

$$p_t + c_t = m_t. \tag{11}$$

[10] The existence of such implicit financial arrangements is sufficient, but not necessary to insure the households against idiosyncratic income risks in the presence of staggered wage setting. As shown by Huang, Liu, and Phaneuf (2004), we can interpret the model as one with a representative household, consisting of a large number of workers with different skills, and obtain identical wage and price dynamics as in the baseline model presented here.

[11] Allowing for positive steady-state inflation does not change the qualitative results (not reported).

Note that, this apparently static aggregate demand relation is not an *ad hoc* assumption, but rather an *equilibrium* outcome. It is 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.

The third condition that we need to close the model is the monetary policy rule described by (9), which, under the assumption that $\rho = 0$, is reduced to $m_t = \gamma a_t$. It is straightforward to show that equilibrium inflation dynamics are given by

$$\pi_t = \theta_p \pi_{t-1} + (1 - \theta_p)(\gamma - 1)\varepsilon_t. \tag{12}$$

where $\theta_p \in (0, 1)$ is the smaller root of the quadratic polynomial $\beta\theta^2 - (1 + \beta + \kappa_p)\theta + 1 = 0$. Thus, inflation falls on impact of a positive technology shock if and only if $\gamma < 1$. A larger θ_p implies more persistence in the inflation dynamics, and thus a smaller response of inflation to technology shocks.

Given the solution for π_t, we can obtain the solution for output gap $\tilde{c}_t$ using the Phillips-curve relation (10), and also for employment using $n_t = c_t - a_t = \tilde{c}_t$. In particular, the employment dynamics are described by

$$n_t = \theta_p n_{t-1} + (\gamma - 1)\theta_p \varepsilon_t. \tag{13}$$

Therefore, a technology improvement can lead to a fall in employment if and only if $\gamma < 1$, which is consistent with the finding by Gali (1999), who assumes that $\gamma = 0$. Further, for a larger value of θ_p, employment becomes more persistent and, for any given $\gamma \neq 1$, more responsive to the shock.

We now consider the responses of the real and nominal wages to technology shocks. The real-wage gap (defined as the deviations of the equilibrium real wage from its natural-rate level) is given by $\tilde{\omega}_t = (1 + \eta)n_t$. Given the solution for n_t, we obtain the solution for the real-wage gap

$$\tilde{\omega}_t = \theta_p \tilde{\omega}_{t-1} + (1 + \eta)(\gamma - 1)\theta_p \varepsilon_t.$$

It follows that the initial response of the real wage to a one-percent permanent technology shock (i.e., $a_t = 1$ for all $t \geq 0$) is given by

$$\omega_0 = 1 - \theta_p(1 + \eta)(1 - \gamma). \tag{14}$$

The impact effect of the shock on the real wage is thus ambiguous, depending on parameter values. The real wage would fall if monetary policy accommodation is weak (i.e., if γ is small). Specifically, the real wage falls if and only if

$$\gamma < 1 - \frac{1}{\theta_p(1 + \eta)} \equiv \bar{\gamma}. \tag{15}$$

This equation reveals that, given the size of policy accommodation measured by $\gamma < 1$, 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.

How could the real wage fall in response to a positive technology shock? To illustrate the intuition, consider an extreme case with predetermined prices and no monetary-policy accommodation (i.e., $\gamma = 0$). This is the case presented in Gali (1999). Following a positive technology shock, the price level stays unchanged, so does the money stock. It follows from the money-demand relation that aggregate consumption and output do not change in the impact period of the shock. Thus, as productivity improves, employment falls. With flexible nominal wages, the real wage is a constant markup over the marginal rate of substitution between leisure and consumption (see (4) with $\alpha_w = 0$). The fall in hours worked leads to a fall in the marginal disutility of working, while the marginal utility of consumption does not change since consumption does not respond to the shock in the impact period. It follows that the real wage falls along with hours worked.

In the more general case with partial price adjustment (such as staggered price setting) and potential monetary-policy accommodation (i.e., $\gamma \geq 0$), similar intuition applies. A difference is that, as the price level falls partially and the money supply rises partially, consumption increases partially following the shock. As the marginal utility of consumption falls, the real wage falls by less or may even rise, depending upon whether the fall in the marginal utility of consumption dominates the fall in the marginal disutility of working associated with the decline in hours.

In general, whether or not the equilibrium real wage falls or rises following a positive technology shock depends on parameter values. For plausible parameter values, as we show below, the real wage indeed falls along with employment in the sticky-price model. As the price level falls following technology improvements, a short-run decline in the real wage implies an even stronger short-run decline in the nominal wage. While the short-run declines in employment and inflation may be supported by some evidence, the declines in the real and nominal wages are not.

3.2.2 Some Suggestive Calculations

We now present some suggestive calculations of the labor-market responses following a technology shock in the sticky-price model based on empirically plausible values of parameters. We first consider a set of baseline calibrated parameters, and then examine the robustness of the results.

The parameters to be calibrated include β, the subjective discount factor; α_p, the Calvo probability of price non-adjustment; ε_p, the elasticity of substitution between differentiated products; η, the inverse intertemporal elasticity of hours; and the monetary policy parameters ρ and γ. The calibrated parameters are summarized in Table 1.

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 $\alpha_p = 0.75$ so that the average duration of the price contracts is 4 quarters. The parameter ε_p determines the steady-state markup of prices over marginal cost, with the markup given by $\mu_p = \varepsilon_p/(\varepsilon_p - 1)$. Recent studies by Basu and Fernald (2002) suggest that the value-added markup is about 1.05 when factor utilization rates are controlled for; while without correction factor utilization, it is higher at about 1.12. Some other studies suggest an even higher value-added markup of about 1.2 (with no corrections for factor utilization) (e.g., Rotemberg and Woodford, 1997). Since we do not focus on variations in factor utilization, in light of these studies, we set $\varepsilon_p = 10$ so that $\mu_p = 1.1$. The parameter η corresponds to the inverse intertemporal elasticity of hours. Most empirical studies suggest that this elasticity is small. We set $\eta = 5$ as a benchmark value, corresponding to an intertemporal hours elasticity of 0.2, which is consistent with micro-evidence (e.g., Pencavel, 1986).

The parameter γ measures the extent of monetary-policy accommodation. To gauge a value of γ, it is informative to examine the relation between the growth rate of a measure of U.S. money aggregates and an appropriate measure of technology shocks. Without loss of generality, we use M2 as a measure of U.S. money aggregate, with a sample period from 1959 to 2003 (at monthly frequency). This series is 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 our own technology shock series constructed from the four-variable SVAR under the difference specification, which has a sample period from 1949 to 2003 (at quarterly frequency). The second measure of technology shock that we use is the "purified" technology measure constructed by BFK (2004), which has a sample period from 1949 to 1996 (at annual frequency). Figure 3 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 M2 growth rates on the technology shock series. In particular, we estimate the monetary policy rule specified in (9), which, for ease of reference, is rewritten here:

$$\mu_t = (1 - \rho)\bar{\mu} + \rho\mu_{t-1} + \gamma\varepsilon_t. \tag{16}$$

Using our technology measure, the point estimates are $\hat{\rho} = 0.62(0.06)$ and $\hat{\gamma} = 0.14(0.05)$, where the numbers in parentheses are standard errors. Using the BFK measure produces point estimates of $\hat{\rho} = 0.60(0.14)$ and $\hat{\gamma} = 0.13(0.33)$. The 95 percent confidence interval for $\hat{\gamma}$ is 0.04 to 0.23 with our measure, and -0.53 to 0.79 with the BFK measure. It appears that the estimates for γ are small and may even be statistically insignificant.[12] In light of these estimates, we set $\rho = 0.62$ and $\gamma = 0.14$ as our benchmark policy parameters. In a sensitivity analysis, we consider other values of γ in the range between 0 and 1.

[12] We have also used two other measures of technology shocks, one constructed from our SVAR under the level specification and the other constructed by Gali and Rabanal (2004), and we have obtained similar results. Specifically, using the technology shock series from our level specification, we obtain estimates of $\hat{\rho} = 0.62(0.06)$ and $\hat{\gamma} = 0.14(0.05)$, which appear identical to the estimates obtained under the difference specification. Using the Gali-Rabanal series, we obtain $\hat{\rho} = 0.61(0.06)$ and $\hat{\gamma} = 0.10(0.05)$. We are grateful to Susanto Basu and Jordi Gali for providing us with their data.

Figure 4 plots the impulse responses of the labor market variables following a positive technology shock under the calibrated parameters. The figure shows that, following a positive technology shock, the sticky-price model (solid lines) predicts that both the real wage and nominal wage inflation fall, as do hours and price inflation. The fall in nominal wage inflation is greater than that of the real wage, and is much sharper than is the fall in price inflation. There may be some empirical support for the decline in hours and price inflation, but the patterns of adjustments in the real and nominal wages are at odds with the evidence presented in Section 2.

3.2.3 The Role of Policy Accommodation

Here, we consider variations in the value of γ to examine the extent to which the sticky-price model's implications depend on monetary policy accommodation. Figure 5 plots the *impact* effect of a positive technology shock on hours, the real wage, nominal wage inflation, and price inflation as γ varies from 0 to 1 (i.e., from no accommodation to "perfect" accommodation). For small values of γ, the sticky-price model (the solid lines) suggests that hours and the real wage both decline on impact of the shock; as γ becomes larger, their responses both become less negative, and can turn into positive for large enough values of γ. Similar patterns hold for nominal wage inflation and price inflation. Under sufficiently accommodative monetary policy, nominal wage inflation and price inflation tend to rise because the increase in money supply in response to the technology shock represents an expansionary aggregate demand shift. While the technology improvement tends to drive prices down, the expansion in aggregate demand tends to drive prices up. With sufficient policy accommodation, the demand effect dominates, so that nominal wages and prices would rise.

As we have emphasized, the predicted rise (or fall) in employment in itself cannot be viewed as evidence against the model, because of the uncertainty of the empirical evidence along this dimension. Yet, the sticky-price model's predicted behaviors of wages and prices as displayed in the figure are not supported by evidence, regardless of the degree of policy accommodation. For small values of γ, as in our benchmark economy, the sticky-price model predicts incorrectly that the real wage falls and the nominal wage falls by even more; for large values of γ, the model incorrectly predicts that the price level *rises* and the responses of the nominal wage are larger than those of the price level. These results suggest that a sticky-price model may have some difficulties in accounting for the observed responses of labor market variables to technology shocks.

3.3 Nominal Wage Rigidity and Labor Market Dynamics

One aspect that the sticky-price model does not do well lies in the inertial adjustments in nominal wage inflation. This observation suggests that a missing element might be nominal wage rigidity. We now investigate this possibility.

We first consider a pure sticky-wage model, in which prices are flexible (i.e., $\alpha_p = 0$) and nominal wage decisions are staggered (i.e., $\alpha_w > 0$). The pricing decision is then given by $p_t = w_t - a_t$, so that the real wage rises one-for-one with productivity. To help inspect the model's mechanism, we make a simplifying assumption that the monetary authority follows the money growth rule (9) and that $\rho = 0$, although our main results do not hinge upon these assumptions, as we show below.

With sticky nominal wages and flexible prices, optimal wage-setting decisions give rise to a wage-Phillips curve relation

$$\pi_{wt} = \beta \mathrm{E}_t \pi_{w,t+1} + \kappa_w \tilde{c}_t, \tag{17}$$

where $\pi_{wt} = \log(W_t/W_{t-1})$ denotes the nominal-wage inflation, $\kappa_w = \lambda_w(1+\eta)/(1+\eta\varepsilon_w)$ is a parameter that determines the elasticity of wage inflation with respect to output gap, and $\lambda_w = (1-\beta\alpha_w)(1-\alpha_w)/\alpha_w$ is a parameter that measures the responsiveness of wage-setting decisions to the marginal rate of substitution between leisure and consumption. Using the pricing decision equation $p_t = w_t - a_t$, this equation can be rewritten in terms of price inflation:

$$\pi_t + \Delta a_t = \beta \mathrm{E}_t(\pi_{t+1} + \Delta a_{t+1}) + \kappa_w \tilde{c}_t.$$

Solving for price inflation, we obtain

$$\pi_t = \theta_w \pi_{t-1} + (1-\theta_w)(\gamma - 1)\Delta a_t - \theta_w(\Delta a_t - \Delta a_{t-1}), \tag{18}$$

where $\theta_w \in (0,1)$ is the smaller root of the quadratic polynomial $\beta\theta^2 - (1+\beta+\kappa_w)\theta + 1 = 0$. Given the solution for π_t, we use the aggregate demand relation (11) to obtain c_t, and the production function to obtain n_t. The solution for employment is given by

$$n_t = \theta_w n_{t-1} + \theta_w \gamma \varepsilon_t. \tag{19}$$

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 rises one-for-one with productivity and the impact effect on price inflation implied by (18) is $(1-\theta_w)\gamma - 1$, the impact effect on the nominal wage is given by $(1-\theta_w)\gamma$. Since $\theta_w < 1$, the response of the nominal wage, as is that of employment, is non-negative provided that $\gamma \geq 0$. Further, if γ is small, the response of the nominal wage is likely weak.

The predicted responses of employment, price inflation, and nominal wage inflation in the sticky-wage model do not seem to be contradicted by evidence. Yet, the response of the real wage seems too strong in the model. This result occurs because price adjustments are perfectly flexible.

We now consider the more general case with some price rigidity along with nominal wage rigidity. In this case, the equilibrium dynamics are solutions to the following system of equations:

$$\pi_t = \beta \mathrm{E}_t \pi_{t+1} + \lambda_p \tilde{\omega}_t, \tag{20}$$

$$\pi_{wt} = \beta \mathrm{E}_t \pi_{w,t+1} + \frac{\lambda_w}{1+\eta\varepsilon_w}[(1+\eta)\tilde{c}_t - \tilde{\omega}_t], \tag{21}$$

$$\tilde{\omega}_t = \tilde{\omega}_{t-1} + \pi_{wt} - \pi_t - \Delta a_t, \tag{22}$$

$$(1-\beta)(\tilde{c}_t - \tilde{m}_t) = \beta \mathrm{E}_t(\pi_{t+1} + \Delta \tilde{c}_{t+1}), \tag{23}$$

$$\Delta \tilde{m}_t = \mu_t - \pi_t - \Delta a_t. \tag{24}$$

In these expressions, $\tilde{\omega}_t = w_t - p_t - a_t$ is a real-wage gap and $\tilde{m}_t = m_t - p_t - a_t$ is a real-balance gap. Equations (20) and (21) are derived from optimal price- and wage-setting decisions. Equation (22) describes the law of motion of the real-wage gap. Equation (23) is derived from the money demand relation. Finally, (24) describes the law of motion of the real-balance gap.

With both sticky prices and nominal wages, we are not able to characterize equilibrium dynamics based on closed-form solutions. To solve the model numerically, we use the calibrated parameters described in the previous section. In addition, we calibrate two new 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., Taylor, 1999a); and we set $\varepsilon_w = 6$, so that a 1 percent rise in relative nominal wages would result in a 6 percent fall in relative hours worked, in light of the microeconomic evidence presented by Griffin (1992, 1996) (see also Huang and Liu, 2002). We consider the money growth rule (9) with $\rho = 0.62$ and $\gamma = 0.14$.

Figure 4 presents the impulse responses of employment, wages and prices in the model. When nominal wages are sticky and prices are flexible (dashed lines), as we have just discussed, hours rise on impact. When both wages and prices are sticky (dash-and-dotted lines), hours decline modestly in the short run. The response of the real wage is positive in the sticky-wage model, regardless of whether prices are sticky or not, although the initial response of the real wage becomes more modest and therefore more in line with empirical evidence when prices are sticky. The response of price inflation is negative, with or without price rigidity; but the price inflation responds more modestly if pricing decisions are staggered. The response of wage inflation remains weak relative to the adjustments of other labor-market variables, although the initial response of wage inflation is slightly positive in the model, whereas it is slightly negative (although insignificantly so) in the data. These results are broadly consistent with our empirical evidence documented in Section 2. Further, as shown in Figure 5, the qualitative patterns of labor-market adjustments in the model with nominal wage rigidity (with or without price rigidity) are not sensitive to variations in the degree of monetary-policy accommodation. In this sense, the model with nominal wage rigidity, along with some price rigidity, is more promising than the pure sticky-price model or the pure sticky-wage model in explaining the labor market dynamics following technology shocks.

4 Confronting the Labor Market Dynamics: Some Quantitative Results

We have thus far explored the role of two sources of nominal rigidities, –sticky prices and sticky nominal wages– in explaining the observed labor market dynamics following technology shocks. Our analysis suggests that both types of nominal rigidities are potentially important for obtaining realistic labor market dynamics. We now examine the *quantitative* performance of several competing models that emphasize different sources of nominal and real rigidities. In particular, we compare the models' theoretical impulse responses of labor-market variables following technology shocks with the VAR-based estimates.

4.1 The General Framework

For our quantitative experiments, we generalize the model with sticky prices and nominal wages presented in Section 3 by incorporating two additional elements emphasized in the recent literature: (i) habit formation in preferences and (ii) a monetary policy rule characterized by a Taylor rule.

To introduce habit formation, we assume that the household's utility function takes the form

$$\mathrm{E}\sum_{t=0}^{\infty}\beta^t\left[\log(C_t - b\bar{C}_{t-1}) + \Phi\log\left(\frac{M_t}{P_t}\right) - V(N_t^d(i))\right], \tag{25}$$

where C_t denotes individual consumption in period t, $\bar{C}_{t-1}$ denotes aggregate consumption in period $t-1$, and $b \in [0,1]$ is a parameter that measures the relative importance of habit.[13] The preference representation here features "catching up with the Jones" in the spirit of Campbell and Cochrane (1999).[14] To the extent that habit formation helps dampen output adjustments, it has been viewed as an important source of real rigidities in generating plausible output dynamics following monetary policy shocks in a DSGE model with nominal rigidities (e.g., Christiano, Eichenbaum, and Evans, 2005). It has also been considered promising in explaining the dynamic responses of employment following technology shocks in a model without nominal rigidities, such as a real business cycle model (e.g., Francis and Ramey, 2005). For our purpose, allowing for habit formation enables us to explore interactions between habit formation and various sources of nominal rigidities and thereby to evaluate the quantitative relevance of the sticky-price mechanism emphasized by Gali (1999) and BFK (2004) versus the habit-formation mechanism proposed by Francis and Ramey (2005) in accounting for a broad set of labor-market dynamics following technology shocks.

[13] We have left out the household index on consumption and real money balances to save notation. This is innocuous since we have assumed the existence of some implicit financial arrangements to ensure that all households attain the same consumption and real balances, regardless of their wage incomes.

[14] Alternatively, one could postulate internal habit formation by replacing past aggregate consumption by past individual consumption. Our quantitative results are not sensitive to this alternative formulation. We are grateful to an anonymous referee for suggesting that we incorporate habit formation in our model.

Recent literature suggests that U.S. monetary policy can be described by a Taylor rule, under which nominal interest rate is adjusted to respond to other "fundamental variables" such as the inflation rate and output. There is also an interesting debate in the literature about whether technology shocks drive hours up or down in a sticky-price model under a Taylor rule (e.g., Basu, 1998, Dotsey, 1999, and Gali and Rabanal, 2004). We consider a Taylor rule of the form

$$i_t = \rho_i i_{t-1} + (1 - \rho_i)[\phi_\pi \pi_t + \phi_y g_{yt}], \tag{26}$$

where $i_t = \ln[(\mathrm{E}_t D_{t,t+1})^{-1}]$ denotes the nominal interest rate and $g_{yt} = \log(Y_t/Y_{t-1})$ denotes the growth rate of aggregate output.[15]

To summarize the general framework, we replace the time-separable utility function (2) by the habit preferences (25) and the money-growth rule (9) by the Taylor rule (26). The rest of the model elements remain unchanged. With these modifications, we need to calibrate 4 new parameters for our quantitative experiments, including the habit-persistence parameter b and the monetary policy parameters ρ_i, ϕ_π, and ϕ_y. We set $b = 0.8$, which is in the range considered by Boldrin, et al (2001). We set $\rho_i = 0.5$, $\phi_\pi = 1.1$, and $\phi_y = 0.5$ in light of the studies by Taylor (1999b) and Clarida, et al (2000).

4.2 Quantitative Evaluations of Alternative Models

We now examine the quantitative performance of four alternative model specifications nested by our general framework, including (i) a model without nominal rigidities; (ii) a model with sticky prices and flexible nominal wages; (iii) a model with sticky nominal wages and flexible prices; and (iv) a model with sticky prices and nominal wages. In all these model specifications, we consider both the case with and without habit formation. To make our discussions precise, we measure the quantitative performance of alternative model specifications by comparing the theoretical impulse responses obtained from each model with the empirical impulse responses and the associated 95% confidence bands estimated from the SVAR.[16]

[15] We have also examined an alternative Taylor rule with the output growth rate replaced by output gap. The main difference between a rule that targets inflation and output growth (as in (26) here) and the alternative rule that targets inflation and output gap lies in the extent of policy accommodation following technology shocks. The former rule is less accommodative than the latter since a positive technology shock leads to a fall in inflation and output gap, but a rise in output growth. Under calibrated parameters, our quantitative results are not sensitive to these alternative specifications of the monetary policy rule.

[16] The stringency of this criterion in judging a model's empirical performance depends apparently on the accuracy of the VAR-based estimates (i.e., the width of the confidence bands). As reported in Section 2, we obtain more accurate estimates under the difference-specification of the SVAR than under the level-specification. Further, although the point estimates of hours response differ, the responses of wages and prices are similar across the two alternative specifications. For these reasons, we use the impulse responses estimated from the SVAR under the difference specification as a benchmark in evaluating model performance.

We first consider the quantitative performance of a model without nominal rigidities. Figure 6 compares the theoretical impulse responses of labor-market variables following a positive technology shock with the VAR-based estimates. In the absence of habit formation (dashed lines), the model predicts that hours do not respond to the technology shock (as the income effect and the substitution effect on labor supply exactly cancels out) and the real wage adjusts one-for-one with productivity. These predictions are not supported by evidence since the theoretical responses lie outside of the 95% confidence bands. Incorporating habit formation in the model (lines with stars) helps generate a short-run decline in hours, consistent with the finding in Francis and Ramey (2005) in an RBC model; and it brings the theoretical response of hours closer to the VAR-based estimates. Yet, as the model abstracts from nominal rigidities, it fails to generate the quantitative patterns in the responses of nominal wages and prices; and its predicted response of the real wage is also misaligned with our evidence.

We now evaluate a model with sticky prices and flexible nominal wages. Figure 7 compares the theoretical impulse responses from the sticky-price model with the VAR-based estimates. Without habit formation (dashed lines), the sticky-price model predicts that hours fall in the short-run, consistent with the finding by Gali (1999). This result emerges, as we have discussed in Section 3, mainly because the inertia in price adjustments translates into sluggishness in output responses for any given monetary policy accommodation. As the increase in output does not catch up with the increase in productivity, hours fall. The fall in hours leads to a lowered marginal disutility of working, which, coupled with sluggish adjustments in consumption, tends to lower the MRS between leisure and consumption, and hence the real wage. As shown in the figure, the real wage indeed falls modestly on impact. Since prices are sticky, the fall in the real wage implies an even sharper fall in the nominal wage in the impact period. These theoretical responses are at odds with evidence. In the absence of habit formation, the sticky-price model does succeed (although to a limited extent) in generating a modest short-run decline in price inflation, and the theoretical response of price inflation lies close to the 95% confidence band estimated from the SVAR.

Introducing habit formation in the sticky-price model (lines with stars) further dampens the short-run adjustments in aggregate consumption and output, and thereby generating sharper short-run declines in hours and the real wage than in the case without habit. The decline in the real wage is again accompanied by an even sharper decline in the nominal wage since prices are sticky. Moreover, with output adjustments further dampened by habit formation, firms' marginal cost declines more sharply following a productivity improvement than in the case without habit, so does price inflation. Quantitatively, as shown in Figure 7, incorporating habit formation improves the model's predictions for hours by bringing most of the hours response within the empirical confidence band (except that the initial decline seems a bit too strong); but it exacerbates the model's predictions for wages and prices.

The third model that we evaluate is a model with sticky nominal wages and flexible prices. Figure 8 plots the theoretical impulse responses and compares them with the VAR-based estimates. As price adjustments are flexible, the real wage adjusts instantaneous to its new steady-state level and price inflation declines sharply in the short-run, regardless of whether or not habit formation is incorporated. In the absence of habit formation (dashed lines), the sharp decline in the price level implies a sharp increase in aggregate output for any given money supply; with some monetary policy accommodation for the technology shock, output tends to increase further so that hours worked may actually rise in the short-run. The figure shows that hours indeed rise. Further, the model without habit predicts (incorrectly) a slight short-run increase in nominal wage inflation. Introducing habit formation in the sticky-wage model helps bring the theoretical responses of hours and nominal wage inflation more in line with the data. In particular, with habit formation (lines with stars), the sticky-wage model predicts a modest decline in hours and a slight decline in nominal wage inflation in the short run, both lie (almost entirely) within the empirical confidence bands. Incorporating habit formation helps generate a decline in hours since it dampens the response of output; it also helps generate a slight decline in nominal wage inflation (instead of a slight rise) since the fall in employment tends to generate a fall in the MRS between leisure and consumption (as adjustments in consumption is dampened by habit formation).

The final model that we discuss is our preferred model with both price and nominal wage rigidities. Figure 9 compares the theoretical impulse responses with the VAR-based estimates under the difference specification (the upper panel) and under the level specification (the lower panel). Compared to the models examined above, the model here with both price and nominal wage rigidities is better able to account for the empirical responses of wages and prices.

Even without habit formation (dashed lines), the model correctly predicts that the real wage rises modestly on impact of the shock and continues to rise until reaching a permanently higher steady state level. This pattern of real-wage adjustments arises from the interactions between nominal-wage rigidity and price rigidity. Since nominal wages are sticky, a permanent productivity improvement leads to a fall in firms' marginal cost, which is given by the wage index net of productivity. As marginal cost falls by more than does the nominal wage index, so does the price level. Thus, the real wage rises on impact. Over time, as more firms get a chance to reset prices, the price level falls further before reaching a permanently lower steady state, and the real wage rises gradually to a permanently higher steady state. The model also does well in generating the observed response of price inflation.

In the absence of habit, however, the model has some mixed success in accounting for the hours dynamics, depending on which empirical specification of the SVAR is used to evaluate the model. The hours response from the model lies outside of the confidence band estimated under the difference-specification, but it falls well within the confidence band estimated under the level-specification. The model generates an initial slight decline in hours, which subsequently rise to a level above steady state before falling back to steady state. As in the sticky-price model, there are two competing forces that drive the hours dynamics. First, the inertia in price adjustments translates into sluggishness in output adjustments for any given money supply, so that hours tend to fall following a productivity improvement. Second, under the Taylor rule, monetary policy is partially accommodative for technology shocks, and thereby raising aggregate demand and output. With nominal wage rigidity, the aggregate demand effect associated with monetary policy accommodation tends to be magnified (compared to the case with flexible wages). Thus, hours initially decline as the price-inertia effect dominates; and hours rise subsequently as the aggregate demand effect takes over. The aggregate demand effect also induces wage-setters to raise their nominal wages slightly when they have a chance to renew wage contracts, so that the model predicts incorrectly that wage inflation rises slightly on impact of the shock.

Incorporating habit formation in the model alleviates these problems and improves the model's overall quantitative fit. Habit formation essential dampens the aggregate demand effect, so that hours tend to decline by more and nominal wage inflation tends to decline (rather than rise) slightly in the impact period of the shock. Further, introducing habit formation also lowers the responses of the real wage and price inflation slightly. As shown in Figure 9, in our preferred model with sticky prices, sticky wages, and habit formation, the theoretical responses of hours, wages, and prices (lines with stars) all lie within the empirical confidence bands for most of the periods, and this is true under both specifications of the SVAR.

4.3 Quantitative Evaluations: the Volcker-Greenspan Era

Our quantitative evaluations of alternative models suggest that our preferred model with sticky prices, sticky wages, and habit formation stands out as the most promising candidate among the alternatives in accounting for the labor market dynamics following technology shocks in the postwar U.S. economy. In our earlier discussion in Section 3, we have also shown that the theoretical implications on labor market dynamics can be affected by the extent to which monetary policy accommodates technology shocks. Since many authors have argued that the Volcker-Greenspan era represents a significant shift in the conduct of monetary policy from the previous regime, it is natural to examine the extent to which such policy changes have affected the labor market responses to technology shocks, both in the data and in the model. Quantitative evaluations of the model under a monetary policy rule calibrated to the Volcker-Greenspan period provides a further test of the model's ability in generating empirically plausible labor-market dynamics.

To implement this idea, we first estimate the same SVAR models as in Section 2, but with a shorter sample period covering 1982:Q3 through 2003:Q4. We then compute the theoretical impulse responses from our preferred model, with an appropriately calibrated monetary policy to reflect changes in the conduct of monetary policy. Based on the studies by Clarida, et al (2000), we set $\phi_\pi = 2.15$ for the Volcker-Greenspan period (instead of 1.1 for the full sample) to reflect a stronger stance of U.S. monetary policy against inflation fluctuations. We keep the rest of the calibrated parameters the same.

Figure 10 plots the labor-market responses to technology shocks in the Volcker-Greenspan period, both in the data (solid lines) and in our preferred model (dashed lines). Compared to the responses estimated using the entire postwar sample reported in Figures 1 and 2, the responses of wages and prices in the Volcker-Greenspan period appear less persistent. As in the full sample, hours fall under the difference specification in the VAR and rise under the level specification, but the responses of wages and prices are not sensitive to the VAR specifications. The real wage rises modestly on impact of the shock, and continues rising (although more quickly than in the full sample) in subsequent periods to the new steady state. Unlike that in the full sample, wage inflation in the Volcker-Greenspan era *rises* in the short run, although its response remains statistically insignificant. Price inflation declines in the short-run, but to a much lesser extent than in the full sample, and the declines are statistically insignificant. This last observation is broadly consistent with the perception that monetary policy under the Volcker-Greenspan regime has put a stronger emphasis in price stability than under the previous regime (e.g., Gali, Lopez-Salido, and Valles, 2003).

Figure 10 shows that our preferred model does well in accounting for the labor-market responses to technology shocks in the post-Volcker sample period. The theoretical impulse responses of hours, wages, and prices mostly lie within the empirical confidence bands. Interestingly, under a monetary policy rule calibrated to the Volcker-Greenspan regime, our model predicts correctly that nominal wage inflation rises (rather than declines) slightly in the short-run, and the decline in price inflation is much weaker than that when the monetary policy is calibrated to the full sample. These results arise because monetary policy under the Volcker-Greenspan regime puts a greater weight in front of inflation so that price inflation declines by less. As the policy becomes more accommodative for technology shocks, aggregate demand rises by more, so that nominal wage would fall by less or even rise following a positive technology shock.

5 Conclusion

Competing business cycle theories have often been evaluated based on their implications on labor-market dynamics. Recent empirical studies find that technology improvements typically lead to a fall in employment. Yet, other studies suggest that technology improvements may also be consistent with a rise in hours worked. These findings have stimulated a lively intellectual debate, both on the empirical validity of such findings and on the theoretical implications.

The lack of a consensus about how employment responds to technology shocks presents difficulties in evaluating competing business cycle theories based solely upon their implications on employment dynamics. We have taken up this issue from a broader perspective. We have examined the effects of technology shocks on a broader set of labor market variables, including employment, wages, and prices, not just employment. We find that, although a positive technology shock can lead to a rise or a fall in employment depending on the details of empirical specifications, the shock consistently leads to a weak response of wage inflation, a modest decline in price inflation, and a modest rise in real wages on impact and a permanent rise in the long-run. These patterns of adjustments in wages and prices are remarkably consistent across our alternative empirical models. We argue on this ground that, for the purpose of evaluating competing business cycle theories, it is more informative to examine the models' predicted dynamic responses of wages and prices following technology shocks than focusing solely on employment dynamics.

Under this criterion, we have shown that a model without nominal rigidities, such as a standard RBC model (or its variants), does not pass the test. We have also shown that a pure sticky-price model does not fare better, as it predicts the wrong sign of the response of real wages and the wrong magnitude of the response of nominal wages under plausible parameters. We further propose that, an alternative model with both price and nominal wage rigidities, coupled with habit formation in preferences, has a better chance of succeeding in explaining the broader set of labor market dynamics following technology shocks.

In a broad sense, the new generation of DSGE models with micro-foundations and featuring nominal wage and price rigidities has been fairly successful in explaining the dynamic effects of monetary shocks (e.g., Huang, Liu, and Phaneuf, 2004; Christiano, Eichenbaum, and Evans, 2005). Our results suggest that this class of models, which marks a significant departure from the traditional RBC paradigm, can also be potentially useful in explaining the dynamic effects of technology shocks.

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Table 1.

Calibrated parameter values

Preferences:	$\eta = 5, \quad \beta = 0.99, \quad b \in \{0, 0.8\}$
Nominal contract duration:	
Sticky-price model:	$\alpha_p = 0.75, \quad \alpha_w = 0$
Sticky-wage model:	$\alpha_p = 0, \quad \alpha_w = 0.75$
Hybrid model:	$\alpha_p = 0.75, \quad \alpha_w = 0.75$
Elasticities of substitution:	$\epsilon_p = 10, \quad \epsilon_w = 6$
Money growth rule:	$\rho = 0.62, \quad \gamma = 0.14$
Taylor rule:	
Postwar sample:	$\rho_i = 0.5, \quad \phi_\pi = 1.1, \quad \phi_y = 0.5$
Volcker-Greenspan sample:	$\rho_i = 0.5, \quad \phi_\pi = 2.15, \quad \phi_y = 0.5$

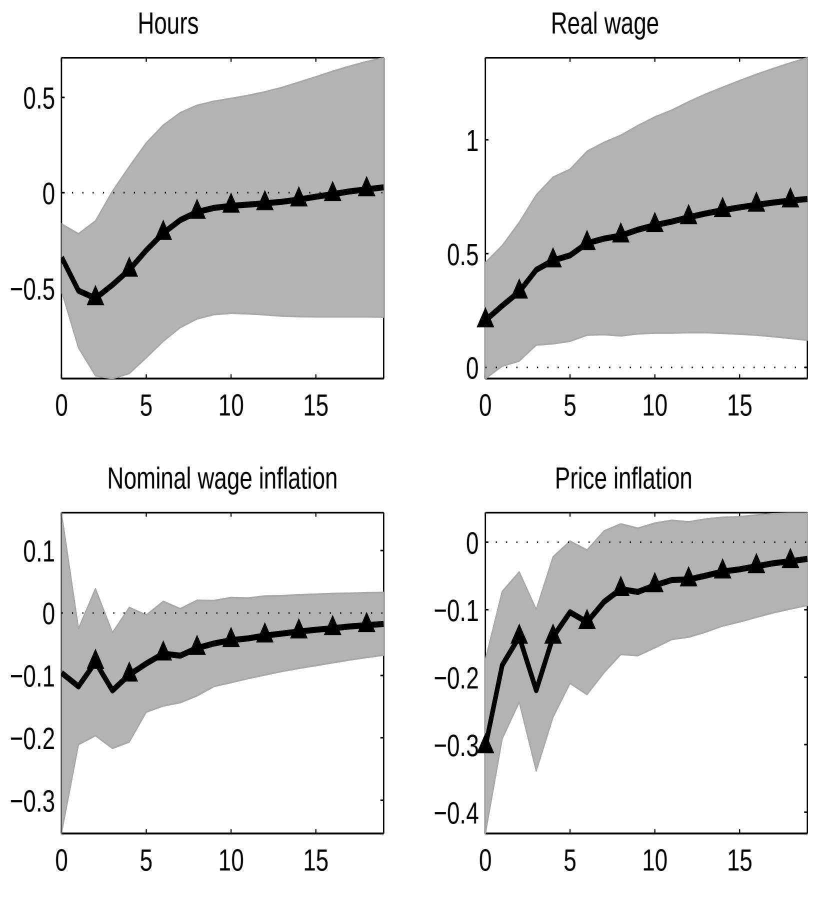


Figure 1:—Responses of hours, wages, and prices to a positive technology shock: Difference specification (sample period 1949:Q2 - 2003:Q4)

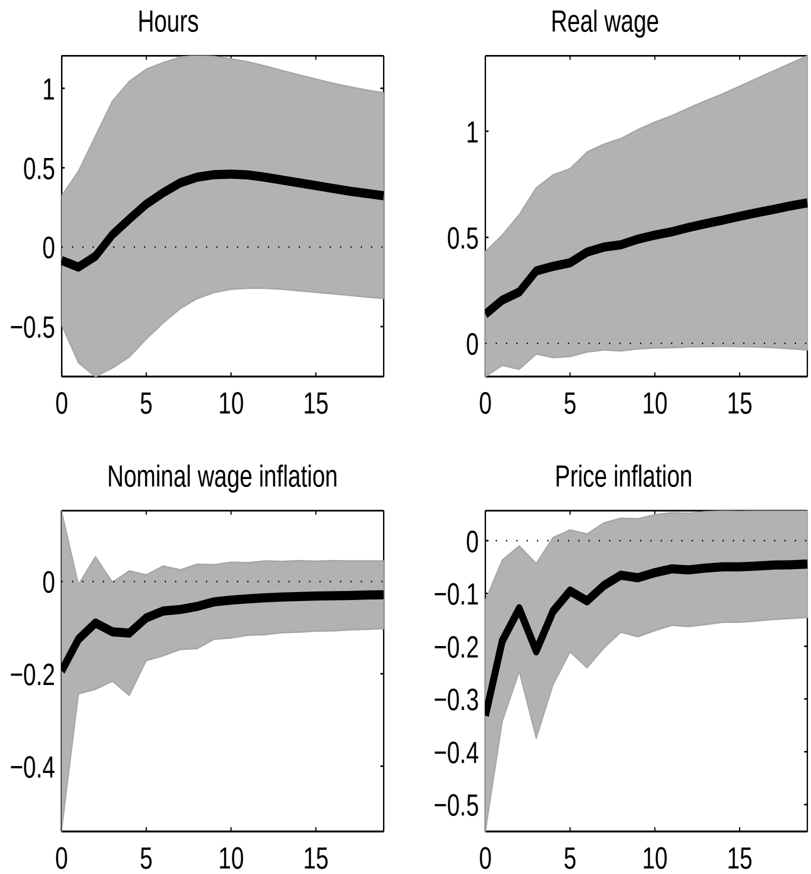
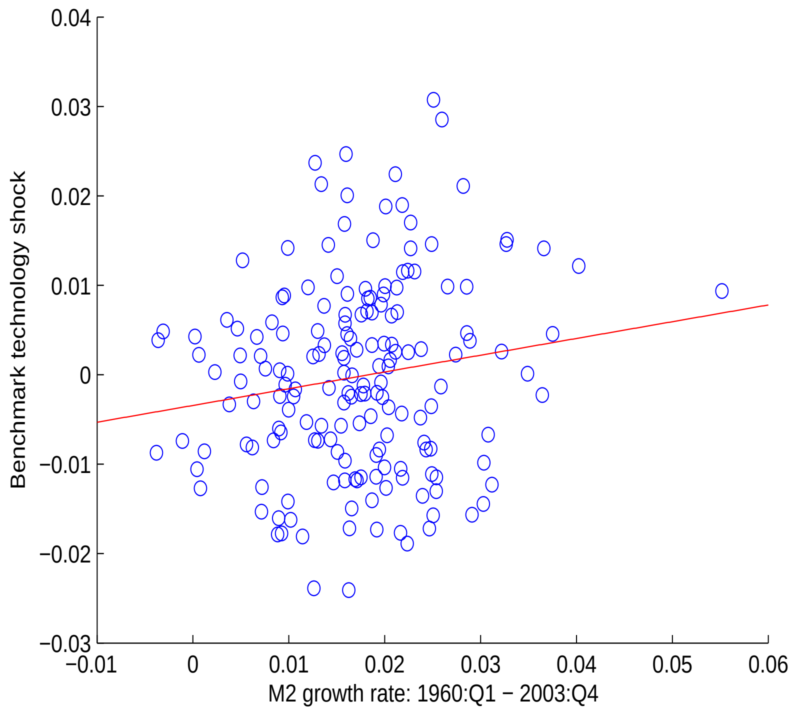


Figure 2:—Responses of hours, wages, and prices to a positive technology shock: Level specification (sample period 1949:Q2 - 2003:Q4)



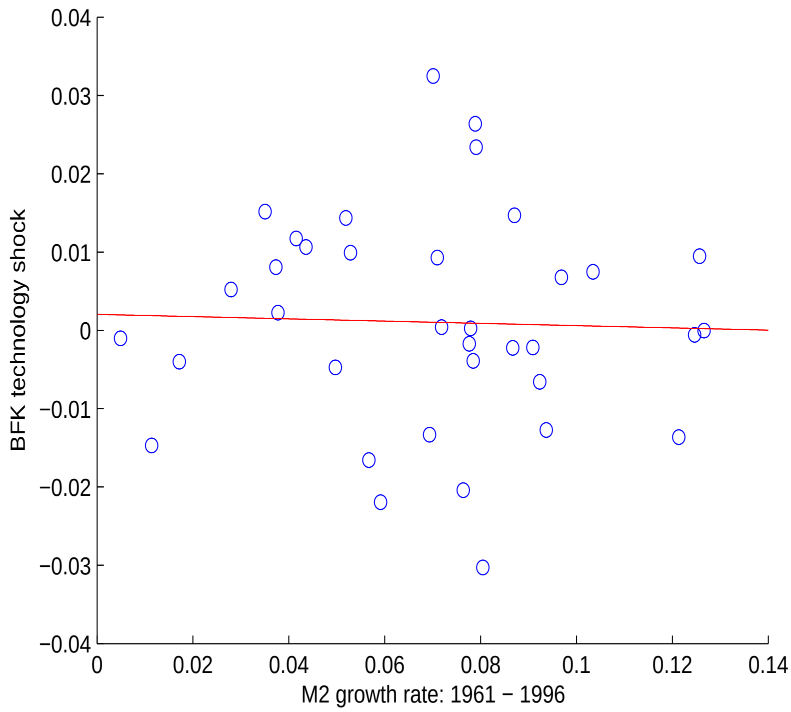


Figure 3:—Technology shocks and U.S. M2 growth rates.

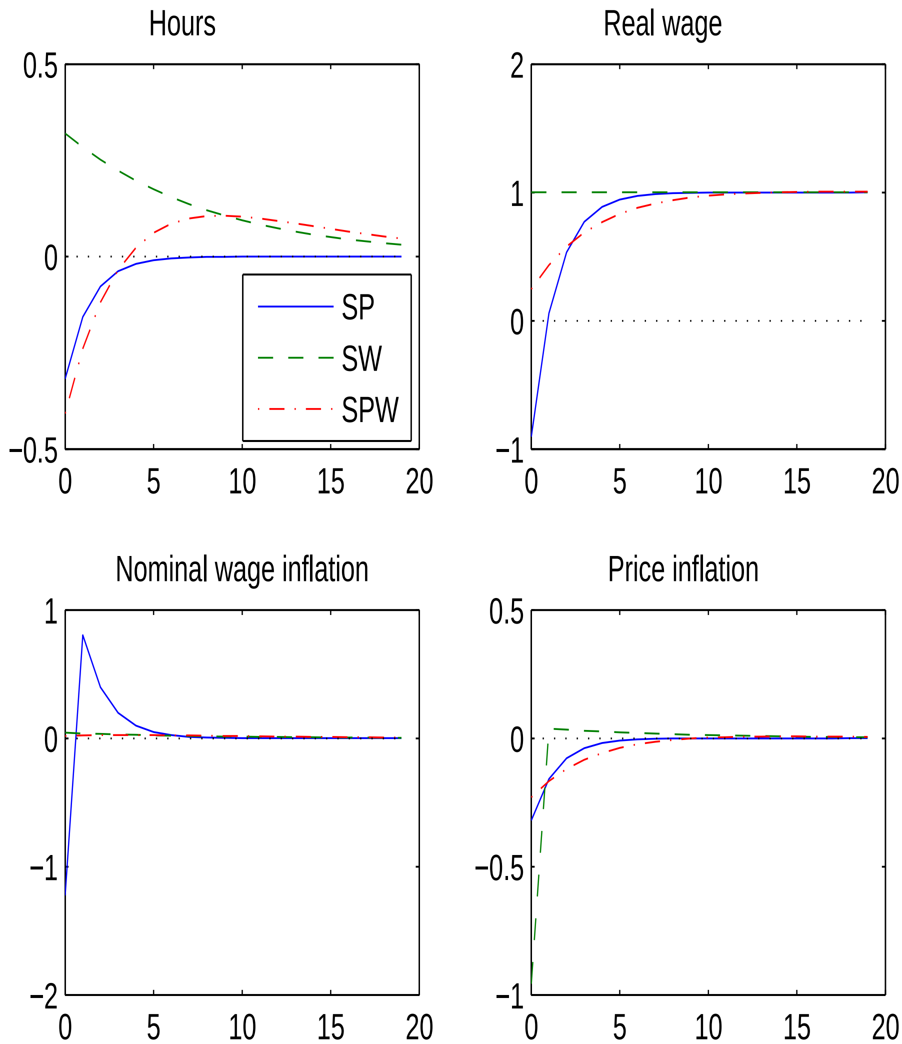


Figure 4:—Labor market responses to a positive technology shock under money growth rule

Legend: Solid line– sticky-price model (SP); Dashed line – sticky-wage model (SW); Dash-and-dotted line: model with sticky prices and wages (SPW).

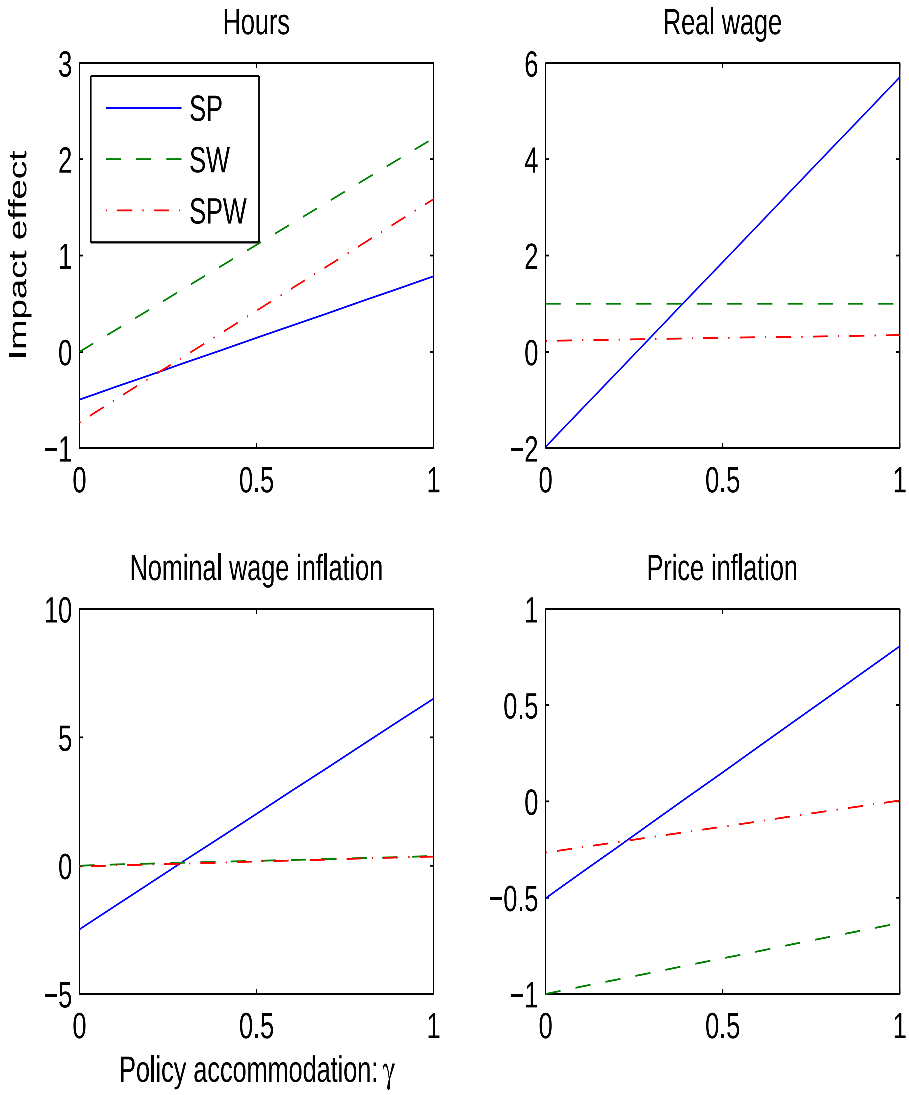


Figure 5:—Labor-market responses to a positive technology shock: Sensitivity to monetary-policy accommodation

Legend: Solid line– sticky-price model (SP); Dashed line – sticky-wage model (SW); Dash-and-dotted line: model with sticky prices and wages (SPW).

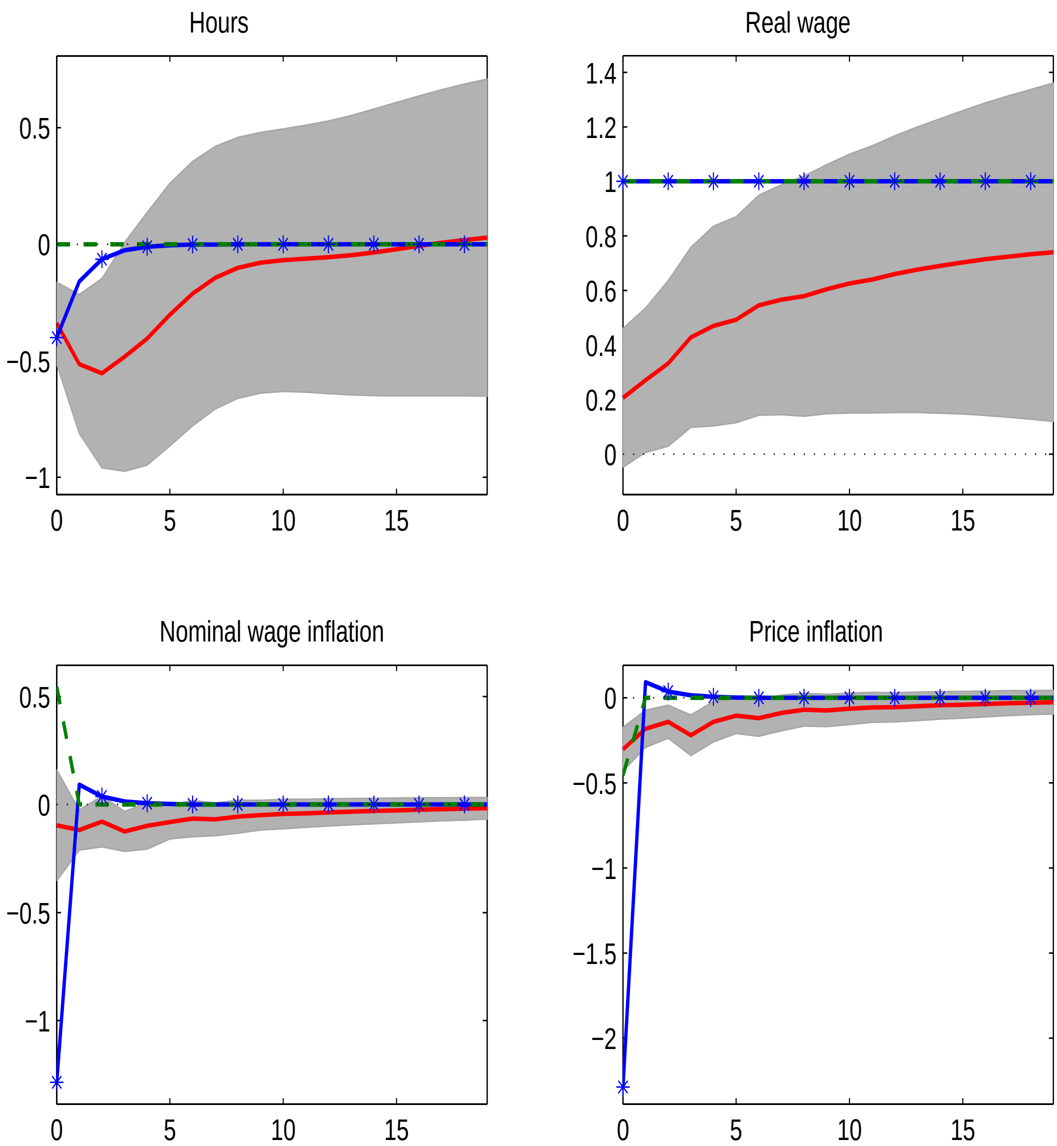


Figure 6:—Impulse responses of labor market variables: SVAR-based estimates versus theoretical impulse responses in the model without nominal rigidities

Legend: Solid line– SVAR; Line with stars– model with habit formation; Dashed line– model without habit; Gray area– 95% *confidence band for SVAR-based estimates.*

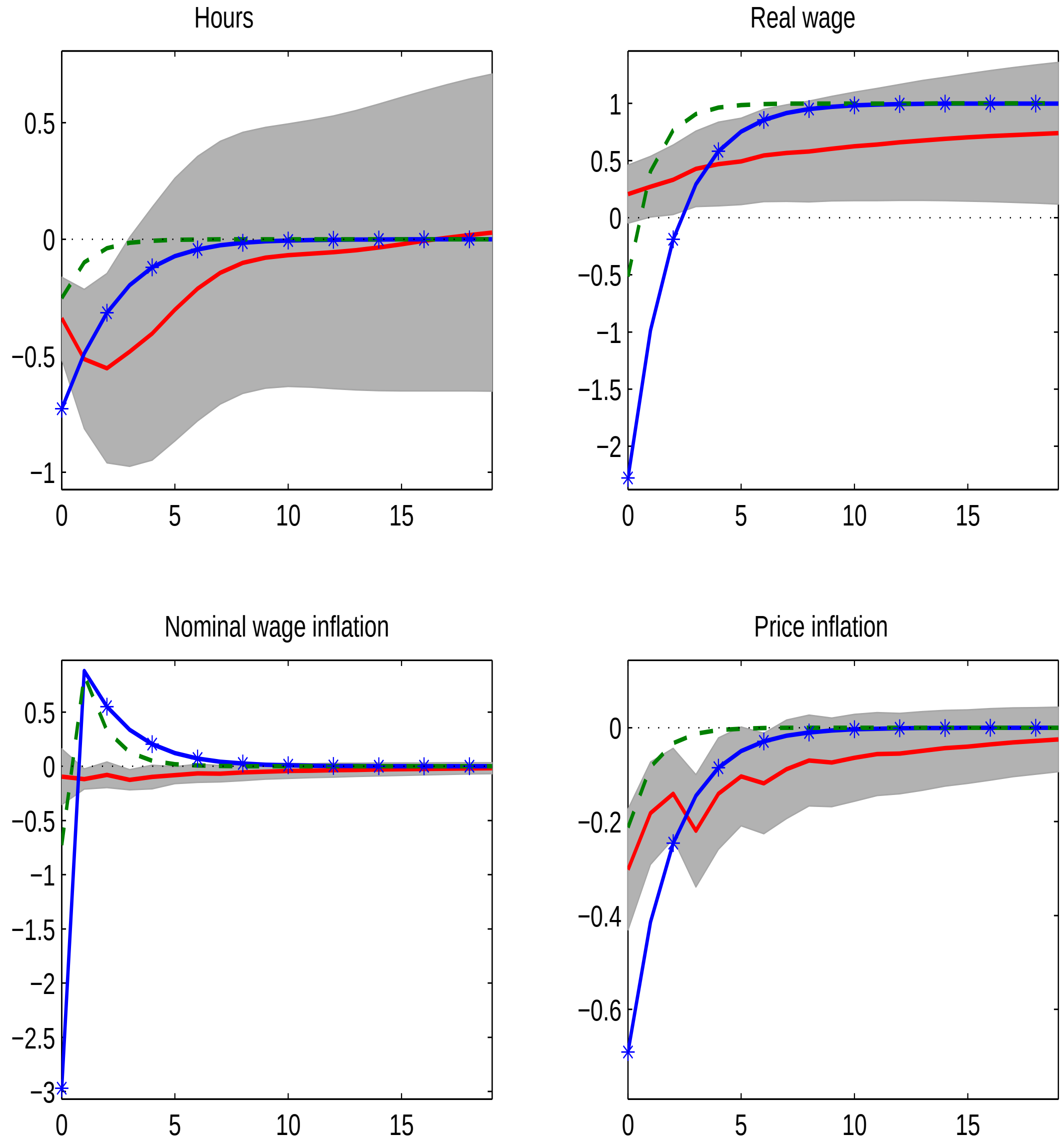


Figure 7:—Impulse responses of labor market variables: SVAR-based estimates versus theoretical impulse responses in the sticky-price model

Legend: Solid line– SVAR; Line with stars– model with habit formation; Dashed line– model without habit; Gray area– 95% *confidence band for SVAR-based estimates.*

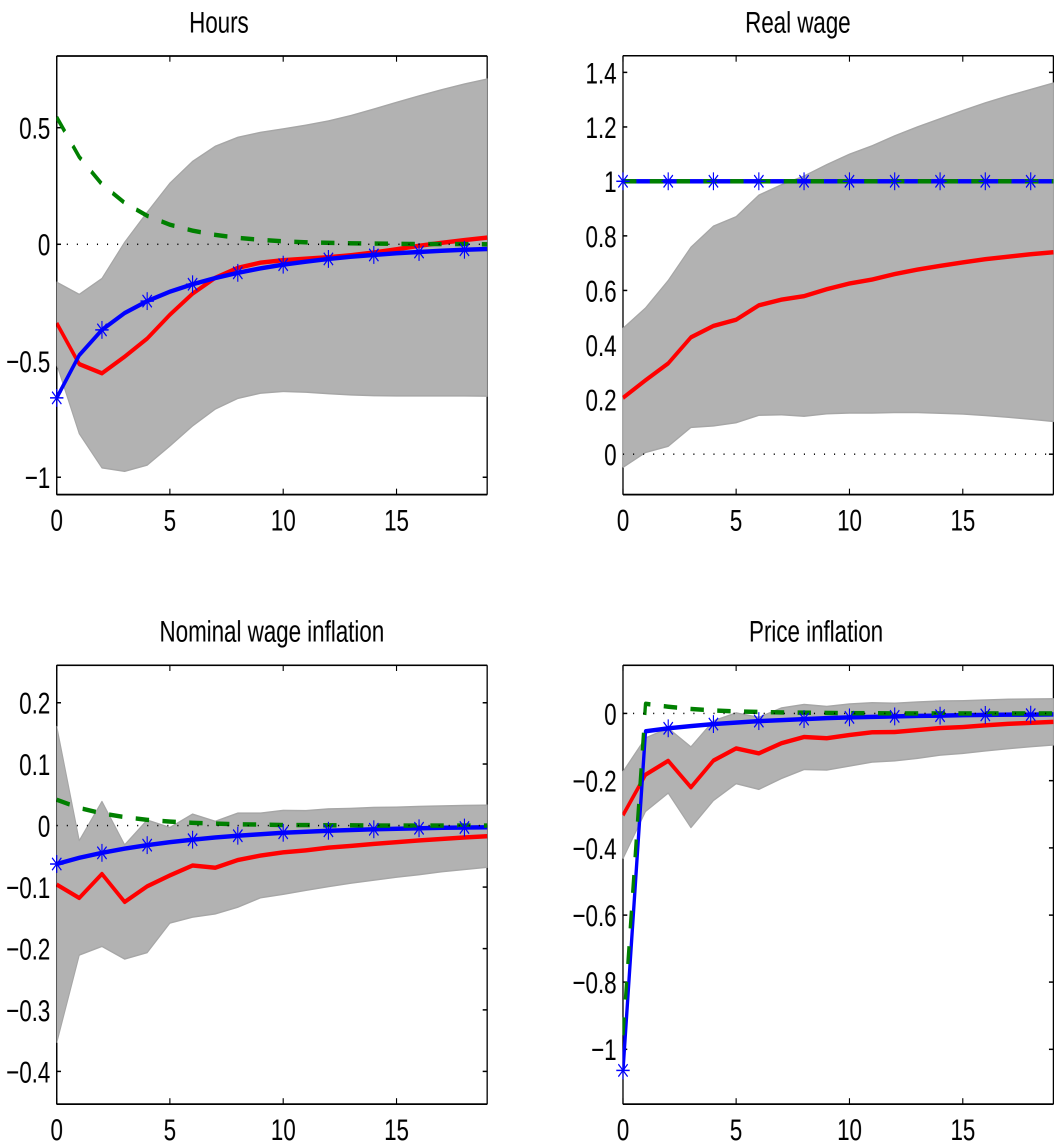


Figure 8:—Impulse responses of labor market variables: SVAR-based estimates versus theoretical impulse responses in the sticky-wage model

Legend: Solid line– SVAR; Line with stars– model with habit formation; Dashed line– model without habit; Gray area– 95% confidence band for SVAR-based estimates.

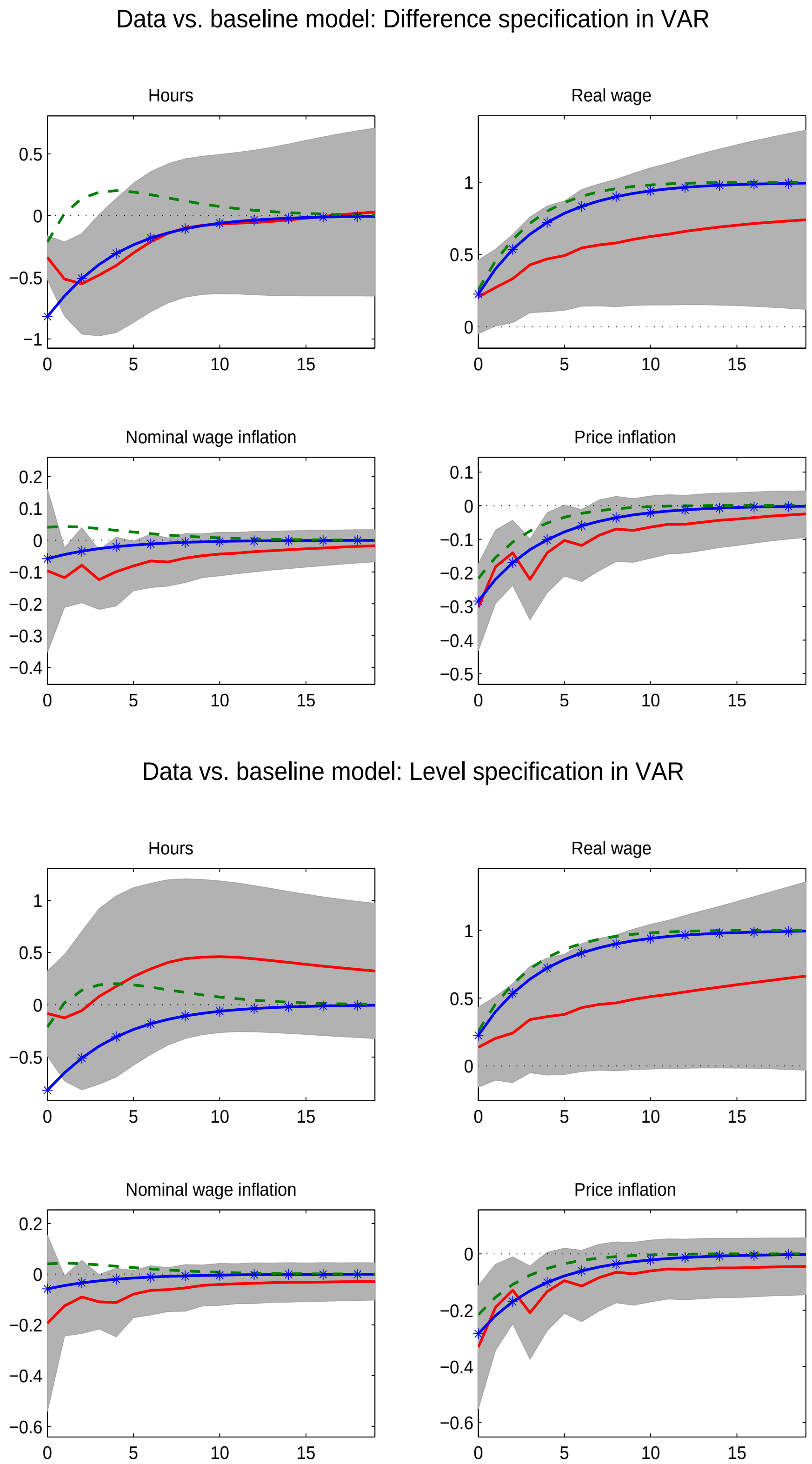


Figure 9:—Impulse responses of labor market variables: SVAR-based estimates versus theoretical impulse responses in the model with sticky prices and nominal wages

Legend: Solid line– SVAR; Line with stars– model with habit formation; Dashed line– model without habit; Gray area– 95% *confidence band for SVAR-based estimates.*

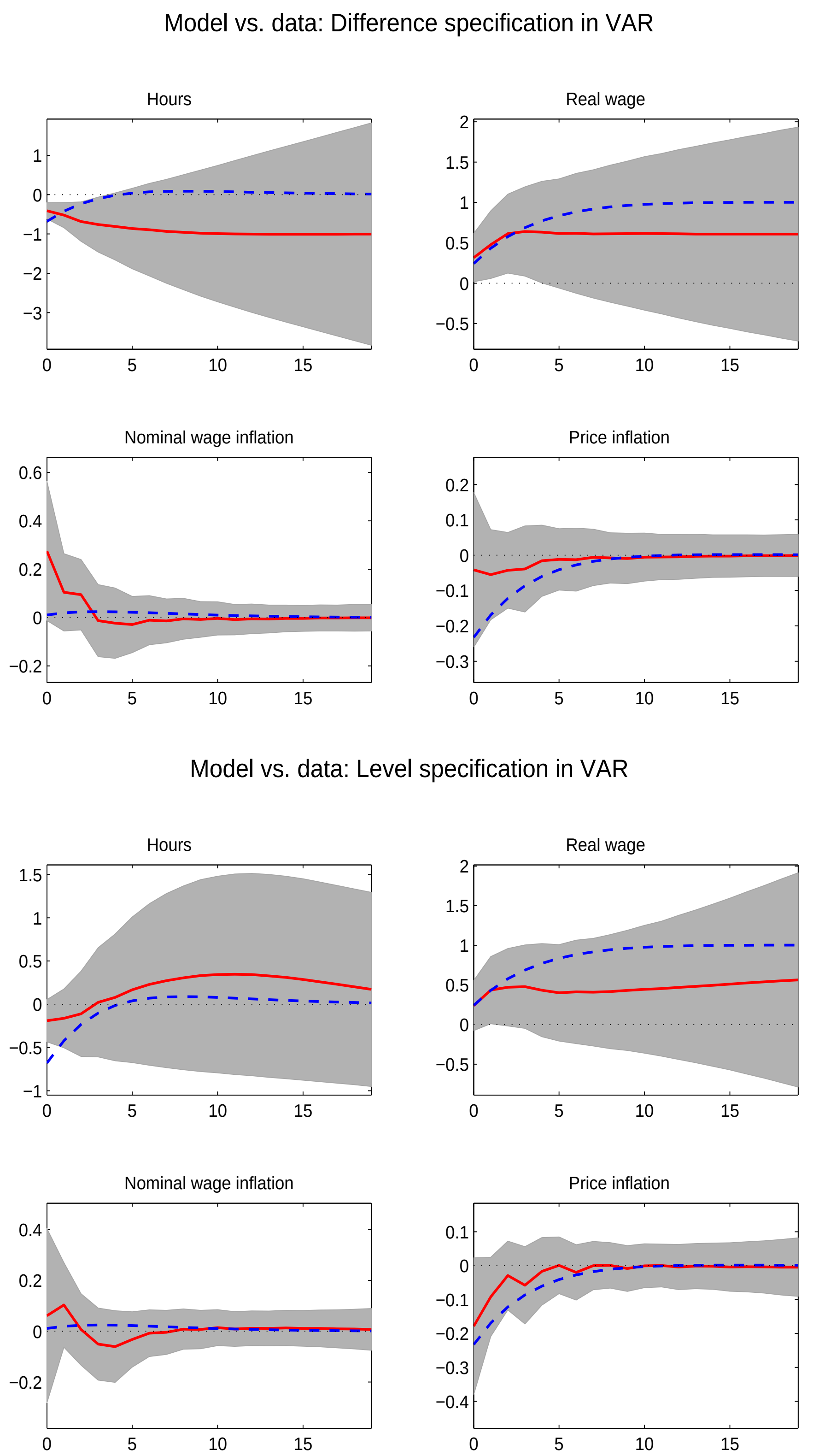


Figure 10:—Impulse responses of labor market variables in the Volcker-Greenspan period (1982:Q3 – 2003:Q4): SVAR-based estimates versus theoretical impulse responses in the baseline model with sticky prices, sticky nominal wages, and habit formation

Legend: Solid line– SVAR; Dashed line– model; Gray area– 95% confidence band for SVAR-based estimates.