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## Interest rate policy and the price puzzle in a quantitative business cycle model

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Reihe Ökonomie  
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# Interest Rate Policy and the Price Puzzle in a Quantitative Business Cycle Model

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February 2001

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Founded in 1963 by two prominent Austrians living in exile – the sociologist Paul F. Lazarsfeld and the economist Oskar Morgenstern – with the financial support from the Ford Foundation, the Austrian Federal Ministry of Education and the City of Vienna, the Institute for Advanced Studies (IHS) is the first institution for postgraduate education and research in economics and the social sciences in Austria. The **Economics Series** presents research done at the Department of Economics and Finance and aims to share “work in progress” in a timely way before formal publication. As usual, authors bear full responsibility for the content of their contributions.

Das Institut für Höhere Studien (IHS) wurde im Jahr 1963 von zwei prominenten Exilösterreichern – dem Soziologen Paul F. Lazarsfeld und dem Ökonomen Oskar Morgenstern – mit Hilfe der Ford-Stiftung, des Österreichischen Bundesministeriums für Unterricht und der Stadt Wien gegründet und ist somit die erste nachuniversitäre Lehr- und Forschungsstätte für die Sozial- und Wirtschaftswissenschaften in Österreich. Die **Reihe Ökonomie** bietet Einblick in die Forschungsarbeit der Abteilung für Ökonomie und Finanzwirtschaft und verfolgt das Ziel, abteilungsinterne Diskussionsbeiträge einer breiteren fachinternen Öffentlichkeit zugänglich zu machen. Die inhaltliche Verantwortung für die veröffentlichten Beiträge liegt bei den Autoren und Autorinnen.

## **Abstract**

In the empirical literature, monetary policy shocks are commonly measured as an innovation to a short-term nominal interest rate. In contrast, the majority of monetary business cycle models treats a broad monetary aggregate as the central bank's policy measure. We try overcome this disparity and present a business cycle model which allows to examine the effects of innovations to a non-contingent nominal interest rate rule. To obtain unique rational expectations equilibria we assume that changes in money supply are brought about open market operations. In addition to working capital, we consider staggered prices which enables real marginal costs to vary. Consistent with the empirical findings of Barth and Ramey (2000), the model predicts that real marginal cost and inflation rise in response to positive interest rate innovations. The mechanism corresponds to their 'Cost Channel of Monetary Transmission' and replicates typical monetary VAR results, including the puzzling behavior of prices.

## **Keywords**

Monetary transmission, interest rate shocks, open market operations, price puzzle

## **JEL Classifications**

E5, E3, E63

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## 1 Introduction

What happens when an unanticipated rise in the nominal interest rate, which is commonly labeled a contractionary monetary policy shock, hits the economy? On the one hand, there is a large empirical literature presenting estimated vector autoregressive (VAR) models trying to reveal monetary policy effects.<sup>1</sup> In most of these studies monetary policy shocks are identified with innovations to the federal funds rate by imposing restrictions derived from macroeconomic theory. On the other hand, in modern monetary business cycle theory researchers develop quantitative dynamic general equilibrium models in order to study the transmission mechanism of monetary policy.<sup>2</sup> The majority of the studies, which focus on the responses to monetary policy shocks, assume that the central bank controls the growth rate of a broad monetary aggregate.

The difference between these two monetary policy measures becomes apparent with the so-called liquidity puzzle and the price puzzle. Monetary policy should lead to a negative correlation between nominal interest rates and monetary aggregates, i.e., the liquidity effect. While the liquidity effect can be observed in the impulse responses to federal funds rate VAR innovations, monetary business cycle models were initially unable to replicate this negative correlation. In order to eliminate this deficiency, models with financial market trading frictions, i.e., limited participation, were developed.<sup>3</sup> In contrast, the price puzzle, which was raised by Sims (1992), is entirely an empirical phenomenon, or to be more pronounced, an empirical anomaly. What is meant by the price puzzle, is the protracted rise in the price level in response to a monetary contraction which is found in numerous VARs studies. The view that this finding should be an anomaly is supported by practically the entire monetary theory. As a solution to this puzzle, a sensitive price index is often introduced into VARs which adds to the information set of the monetary policy reaction function. By applying such an identification scheme for monetary policy shocks, Sims (1992) showed that the price anomaly can be reduced, though it can not completely be removed in VARs.<sup>4</sup> As a strategy for an appropriate selection between competing identification schemes Christiano et al. (1999) advocated to

”eliminate a policy shock measure if it implies a set of impulse response functions that is inconsistent with every element in the set of monetary models that we wish to discriminate between. This is equivalent to announcing that if none of the models that we are interested in can account for the qualitative features of a set of impulse response functions, we reject the corresponding identification assumption, not the entire set of models.” (p. 70)

The purpose of the paper is to take this approach literally. For this, we understand it as a prerequisite to consider a measure for monetary policy shocks in a business cycle model which corresponds to the shock measure in VARs, namely, innovations to a short-run nominal interest rate. This assumption is clearly not new in the monetary business

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<sup>1</sup>See Bernanke and Mihov (1998), and Christiano et al. (1999) for the presentation of VAR estimates using different approaches and for summarizing the current state of the literature.

<sup>2</sup>Examples are Yun (1996), Chari et al. (1996), Christiano et al. (1997), Bergin and Feenstra (1998), Jeanne (1998), or Huang and Liu (1999) to name but a few.

<sup>3</sup>See, e.g., Lucas (1990), Fuerst (1992), and Christiano and Eichenbaum (1992).

<sup>4</sup>Respective point estimates reveal that a small initial rise of the GDP deflator often remains even in the presence of a sensitive price index (see, e.g., Uhlig, 1999, and Christiano et al., 1996, 1999). See also Hanson’s (2000) results which cast severe doubt on this price puzzle ‘solution’.

cycle literature. Recently, several authors apply interest rate rules and in a few cases they identify monetary policy shocks with innovations to these rules.<sup>5</sup> These studies are predominantly meant to study the business cycle behavior when the central bank employs a contingent monetary policy rule, such as the Taylor-Rule.<sup>6</sup> Though, contingent interest rate rules are evidently more realistic, we apply a non-contingent interest rate rule in order to allow for an analysis of the genuine transmission mechanism of pure interest rate shocks. The questions we try to help answering could be articulated as follows: Is the price puzzle, which does not completely disappear in the impulse response functions of many VARs, really an empirical anomaly? Or, should prices actually rise when firms' optimal price setting is directly affected by rising interest rates, e.g, via interest payments on loans? To give a preview, our findings indicate that the asymmetry between the policy measure in empirical and theoretical studies is primarily responsible for puzzling results in monetary policy analysis.

The model in this paper is mainly motivated by a recent paper of Barth and Ramey (2000), titled: "The Cost Channel of Monetary Transmission". By using industrial-level data, they find that many industries exhibit rising prices in response to a rise in the nominal interest rate as the latter increases the cost of external finance. Based on their empirical findings and a partial equilibrium analysis, they presume that both a supply channel (working capital) and a demand channel (price stickiness) affect the transmission of monetary policy shocks. On the one hand, output should decline in response to a rise in the nominal interest rate due to both of these channels. On the other hand, these channels predict different reactions of real marginal costs and, hence, opposing price responses. According to the demand channel, a monetary contraction induces a decline in aggregate demand and in the price level. As an opposite impulse, the positive innovation in the nominal interest rate tends to increase the interest payments on loans which are demanded for paying the wage bill in advance, i.e., for working capital. Therefore, the inflation reaction is unclear and depends on the impact of both channels on the real marginal cost of price setting firms. Consequently, Barth and Ramey (2000) point to the still unanswered question of how monetary policy works in general equilibrium. This is where this study proceeds.

The model is fairly standard in the sense that it combines commonly used ingredients for building a monetary business cycle model.<sup>7</sup> As already noted we depart from using money growth as the exogenous policy variable and we presume that the central bank controls the nominal interest rate. We apply a non-contingent interest rate policy and identify monetary policy shocks with innovations to a pure interest rate rule. Additionally, we assume that the central bank accommodates money demand via open market operation. We adopt this assumption, as most central banks in industrialized countries conduct monetary policy in terms of directives for a short-term nominal interest rate together with accompanying open market operations. By specifying the monetary and fiscal regime in

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<sup>5</sup>Examples are Clarida, Gali, and Gertler (1997), Rotemberg and Woodford (1998), McCallum (1999), McGratten (1999), or Casares and McCallum (2000).

<sup>6</sup>In a few studies interest rate rules are considered for the analysis of agency costs effects on the monetary transmission mechanism (see Bernanke et al., 1999, and Carlstrom and Fuerst, 2000).

<sup>7</sup>It is closely related to the model in Christiano et al.'s (1997) comparative analysis of sticky price and limited participation models.



this manner we obtain unique rational expectations equilibria.<sup>8</sup> Along with Barth and Ramey (2000), we further assume that two transmission channels, i.e., price stickiness and working capital, are jointly at work. Applying Calvo's (1983) specification of price staggering, inflation evolves along with a simple forward looking 'New Keynesian Phillips Curve'.

We computed the impulse response functions of the calibrated model for different degrees of price stickiness. Here, we find that the impulse responses to a contractionary monetary policy shock are consistent with typical VAR results as, e.g., documented in Christiano et al. (1999). This includes that in our model inflation rises in response to a positive nominal interest rate innovation. In accordance with the 'Cost Channel of Monetary Transmission', it is the rise in real marginal costs induced by the increased cost of loans which causes the firms to raise their prices. However, the rise in the inflation rate should be considered in the general equilibrium framework. Coincident with a real contraction, we find that the real return on capital declines. This implies that, first, the real return on bonds must also decrease to meet the arbitrage-free condition and, second, it requires that the inflation rate rises in order to satisfy the Fisher equation. In summary, the model generally replicates empirical effects of an interest rate innovation. Particularly, the rise in the inflation rate corresponds to the 'puzzling' price response in various VAR studies. As a consequence we suggest to avoid the term 'monetary contraction' when a positive interest rate innovation is meant. Our results imply that it might be necessary to improve this widespread identification scheme for monetary policy actions in order to avoid puzzling price responses in an otherwise standard business cycle model and in empirical analyses. But this issue is clearly beyond the scope of this exercise.

In the subsequent section we describe the model and its parametrization. In section 3 we discuss the transmission mechanism and present the model's responses to an interest rate shock. Section 4 concludes.

## 2 The Model

In this section we present an economic environment based on the model in Christiano et al. (1997). Our specification mainly departs with respect to two assumptions. First, the monetary authority controls the nominal interest rate instead of the money growth rate. Second, bonds are introduced together with an explicit specification of fiscal policy. We agree to the notion of Barth and Ramey (2000) and consider that both a supply channel (working capital) and a demand channel (price stickiness) which are jointly at work.<sup>9</sup>

The economy consists of a government and numerous agents of three different types: households, firms, and intermediaries. Money demand is induced by a cash-in-advance constraint. Substantial real effects of changes in monetary variables are due to staggered prices and intraperiod loans which are necessary for production. In contrast to many recent business cycle analyses which employ a contingent policy rule, we specify monetary policy as an non-contingent nominal interest rate rule. Accordingly, monetary policy shocks

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<sup>8</sup>Woodford (1994) shows that such a combination of monetary and fiscal policy can avoid the occurrence of real indeterminacy in a cash-in-advance economy.

<sup>9</sup>Christiano et al. (1997) additionally impose that households determine the amount of deposits prior to the shock ('limited participation') to obtain a negative correlation between money growth and nominal interest rates, i.e., the liquidity effect.

are identified with innovations to an univariate nominal interest rate rule and money is endogenously supplied by the monetary authority. The government issues one-period bonds and the monetary authority accommodates money demand by an exchange of government bonds with cash in open market operations. We were guided by the findings of Woodford (1994) and adopt this kind of monetary and fiscal policy in order to avoid real indeterminacy which usually arises when an interest rate rule without any nominal anchor is applied.<sup>10</sup>

### 2.1. Households

Throughout the paper, nominal variables are denoted by upper-case letters, while real variables are denoted by lower-case letters. The typical household is infinitely lived, with preferences given by the expected value of a discounted stream of instantaneous utility  $u(\cdot)$ :

$$E_0 \left[ \sum_{t=0}^{\infty} \beta^t u(c_t, 1 - l_t) \right], \text{ with } \beta \in (0, 1), \quad (1)$$

where  $E_0$  is the expectation operator conditional on the time 0 information set and  $\beta$  is the discount factor. Throughout we assume that instantaneous utility  $u(\cdot)$  depends on a Cobb-Douglas bundle of consumption  $c$  and leisure  $1 - l$ , and is characterized by constant relative risk aversion (CRRA):

$$u(c_t, 1 - l_t) = \frac{[c_t^\gamma (1 - l_t)^{1-\gamma}]^{1-\sigma} - 1}{1 - \sigma}, \text{ with } \gamma \in (0, 1). \quad (2)$$

At the beginning of period  $t$ , the representative household owns the entire stock of money  $M_t$  in the economy. It must decide how much of this cash holdings to keep for contemporaneous consumption and investment expenditures and how much to deposit at the financial intermediary. Let  $D_t$  denote the amount of these deposits which will earn a nominal return of  $i_t$ . The rest  $M_t - D_t$  is allocated to purchases of consumption and investment goods. We assume that both goods must be completely financed with non-deposited cash as well as current labor income:

$$P_t(c_t + e_t) \leq M_t - D_t + P_t w_t l_t, \quad (3)$$

where  $P$  and  $w$  denote the aggregate price level and the real wage, respectively. The cash-in-advance constraint in (3) implies that there are no credit goods in the economy. The household receives dividends  $\frac{f}{i}$  and the rental rate  $r$  on physical capital  $k$  as additional flows from monopolistically competitive firms indexed by  $i \in (0, 1)$ . In addition they receive dividends  $\frac{b}{i}$  as well as interest payments on deposits  $i_t D_t$  from financial intermediaries. In period  $t$  the household chooses consumption  $P_t c_t$  and investment expenditures  $P_t e_t$ , nominal money holdings  $M_{t+1}$  and nominal riskless one-period pure discount bond holdings  $(1 + i_{t+1})^{-1} B_{t+1}$ .<sup>11</sup> Hence, cash and labor income left over from the goods market

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<sup>10</sup>See Kerr and King (1996) for a discussion of the conditions for real determinacy in Keynesian models with rational expectations and interest rate rules.

<sup>11</sup>Note that there is no non-negativity restriction on the level of the household's bond holdings.

are carried over into the next period for money and bond holdings:

$$\begin{aligned} & M_{t+1} + (1 + i_{t+1})^{-1} B_{t+1} \\ & = P_t r_t k_t + (1 + i_t) D_t + \bar{B}_t + (M_t - D_t - P_t(c_t + e_t - w_t l_t)) + \int_0^1 -\frac{f}{i_t} di + -\frac{b}{t}. \end{aligned} \quad (4)$$

The household maximizes (1) subject to its cash-in-advance constraint (3), its budget constraint (4), and the following condition for the accumulation of physical capital:

$$k_{t+1} = \Phi\left(\frac{e_t}{k_t}\right) k_t + (1 - \delta) k_t, \quad (5)$$

where  $\delta$  denotes the depreciation rate of capital and  $\Phi(\cdot)$  an increasing and concave adjustment cost function.<sup>12</sup> Accordingly, investment expenditures  $e$  yield a gross output of new capital goods  $\Phi(e/k)k$ . The inclusion of adjustment costs permits to analyze the cyclical behavior of the price  $q$  of physical capital.<sup>13</sup> The household's first order conditions for consumption, labor supply, deposit holdings, investment expenditures and for physical capital are given by

$$\lambda_t = \gamma \frac{[c_t^\gamma (1 - l_t)^{1-\gamma}]^{1-\sigma}}{c_t (1 + i_t)}, \quad (6)$$

$$w_t \lambda_t = (1 - \gamma) \frac{[c_t^\gamma (1 - l_t)^{1-\gamma}]^{1-\sigma}}{(1 - l_t)(1 + i_t)}, \quad (7)$$

$$\frac{\lambda_t}{\beta} = E_t \left[ \lambda_{t+1} \frac{1 + i_{t+1}}{\pi_{t+1}} \right], \quad (8)$$

$$q_t = (1 + i_t) \Phi' \left( \frac{e_t}{k_t} \right)^{-1}, \quad (9)$$

$$\frac{q_t}{\beta} = E_t \left[ \frac{\lambda_{t+1}}{\lambda_t} \left( r_{t+1} + q_{t+1} \left( \Phi \left( \frac{e_{t+1}}{k_{t+1}} \right) - \Phi' \frac{e_{t+1}}{k_{t+1}} + (1 - \delta) \right) \right) \right], \quad (10)$$

where  $\lambda$  and  $\pi$  denote the Lagrange multiplier for the budget constraint and the gross inflation rate, respectively. Furthermore, in an optimum the cash-in-advance constraint (3) holds with equality for  $i > 0$ . Regarding the household's assets, the optimal choices must also satisfy the following transversality conditions:

$$\lim_{t \rightarrow \infty} \beta^t u_{c_t} x_t = 0, \quad \text{for } x = k, m, b. \quad (11)$$

## 2.2. Production

The final good, which is consumed and invested in the stock of physical capital, is an aggregate of a continuum of differentiated goods produced by monopolistically competitive firms indexed with  $i \in (0, 1)$ . The aggregator of differentiated goods is defined as follows:

$$y_t = \left[ \int_0^1 y_{it}^{\frac{\epsilon-1}{\epsilon}} di \right]^{\frac{\epsilon}{\epsilon-1}}, \quad \text{with } \epsilon > 1, \quad (12)$$

<sup>12</sup>Casares and McCallum (2000) recommend the introduction of similar adjustment cost functions in order to generate reasonable investment responses in a sticky price model.

<sup>13</sup>The function  $\Phi$  is chosen to obtain a steady state value of the capital price  $q$  equal to one.

where  $y$  is the number of units of the final good,  $y_i$  the amount produced by firm  $i$ , and  $\epsilon$  the constant elasticity of substitution between these differentiated goods. Let  $P_i$  and  $P$  denote the price of good  $i$  set by firm  $i$  and the price index for the final good. The demand for each differentiated good is derived by minimizing the total costs of obtaining  $y$  subject to (12):

$$y_{it} = \left( \frac{P_{it}}{P_t} \right)^{-\epsilon} y_t. \quad (13)$$

Hence, the demand for good  $i$  increases with aggregate output and decreases in its relative price. Regarding the price index  $P$  of the final good, cost minimization implies:

$$P_t = \left[ \int_0^1 P_{it}^{(1-\epsilon)} di \right]^{\frac{1}{1-\epsilon}}. \quad (14)$$

A monopolistically competitive firm  $i$  produces good  $i$  using labor and physical capital according to the following technology with fixed cost of production  $\kappa$ :

$$y_{it} = \begin{cases} k_{it}^\alpha l_{it}^{1-\alpha} - \kappa, & \text{if } k_{it}^\alpha l_{it}^{1-\alpha} > \kappa \\ 0 & \text{otherwise} \end{cases} \quad \text{with } 0 < \alpha < 1, \quad (15)$$

Entry and exit into the production sector is ruled out. The firms rent labor and capital in perfectly competitive factor markets. As the first main friction generating real effects of monetary policy, we assume that wages must be paid in advance. For this, firms borrow the amount  $Z$  from financial intermediaries at the beginning of the period.

$$Z_{it} = P_t w_t l_{it}. \quad (16)$$

Repayment of loans occurs at the end of the period at the gross nominal interest rate  $(1+i)$ . Accordingly, total costs of firm  $i$  in period  $t$  consist of wages  $P_t w_t l_{it}$ , interest payments on loans  $i_t Z_{it}$  and rent on physical capital  $P_t r_t k_{it}$ . Cost minimization for given aggregate prices leads to real marginal costs which only depend on the real factor prices and the nominal interest rate  $i$  on loans:

$$mc_t(w_t, r_t, i_t) = \frac{\alpha^{-\alpha}}{(1-\alpha)^{1-\alpha}} (1+i_t)^{1-\alpha} w_t^{1-\alpha} r_t^\alpha. \quad (17)$$

As a second main friction, we introduce a nominal stickiness in form of staggered price setting as developed by Calvo (1983). Each period firms may reset their prices with the probability  $1-\phi$  independent of the time elapsed since the last price setting. The fraction  $\phi$  of firms are assumed to adjust their previous period's prices according to the following simple rule:

$$P_{it} = \bar{\pi} P_{it-1}, \quad (18)$$

where  $\bar{\pi}$  denotes the average of the inflation rate  $\pi_t = P_t/P_{t-1}$ . In each period a measure  $1-\phi$  of randomly selected firms set new prices  $\tilde{P}_{it}$  in order to maximize the value of their shares

$$\max_{\tilde{P}_{it}} E_t \left[ \sum_{s=0}^{\infty} (\beta\phi)^s \vartheta_{t,t+s} \left( \bar{\pi}^s \tilde{P}_{it} y_{it+s} - P_{t+s} mc_{t+s}(y_{it+s} + \kappa) \right) \right], \quad (19)$$

subject to  $y_{it+s} = \left(\bar{\pi}^s \tilde{P}_{it}\right)^{-\epsilon} P_{t+s}^\epsilon y_{t+s}$ .

Since the firms are owned by the households, the weights  $\vartheta_{t,t+s}$  of dividend payments consist of the marginal utilities of consumption:  $\vartheta_{t,t+s} = \frac{\lambda_{t+s}}{\lambda_t} \frac{P_t}{P_{t+s}}$ . The first order condition for the optimal price setting of flex-price producers is given by

$$\tilde{P}_{it} = \frac{\epsilon}{\epsilon - 1} \frac{\sum_{s=0}^{\infty} (\beta\phi)^s E_t \left[ \vartheta_{t,t+s} y_{t+s} P_{t+s}^{\epsilon+1} \bar{\pi}^{-\epsilon s} m c_{t+s} \right]}{\sum_{s=0}^{\infty} (\beta\phi)^s E_t \left[ \vartheta_{t,t+s} y_{t+s} P_{t+s}^\epsilon \bar{\pi}^{(1-\epsilon)s} \right]}. \quad (20)$$

Using the simple price rule for the fraction  $\phi$  of the firms (18), the price index for the final good as defined in (14) evolves recursively over time

$$P_t = \left[ \phi (\bar{\pi} P_{t-1})^{1-\epsilon} + (1-\phi) \tilde{P}_t^{1-\epsilon} \right]^{\frac{1}{1-\epsilon}}. \quad (21)$$

In the case of flexible prices ( $\phi = 0$ ) we obtain:  $P_{it} = P_t m c_t \epsilon / (\epsilon - 1)$ . Hence, in a symmetric equilibrium real marginal costs  $mc$  are constant over time when prices are flexible ( $m c_t = (\epsilon - 1)/\epsilon$ ), while they vary in the sticky price version of the model. In the latter case the inflation rate evolves according the following linear difference equation which is derived in Appendix A:  $\hat{\pi}_t = \chi \widehat{m c}_t + \beta E_t[\hat{\pi}_{t+1}]$ .<sup>14</sup> At the end of the period the nominal profits -  $\frac{f}{it}$  of firm  $i$  are distributed to the household which owns the firm.

$$-\frac{f}{it} = P_{it} y_{it} - P_t m c_t (y_{it} + \kappa). \quad (22)$$

All firms face the identical production technology and same prices for the factor inputs. In view of this symmetry the cost minimizing factor demand schedules can be written with aggregate quantities

$$w_t = m c_t \frac{(1-\alpha) k_t^\alpha l_t^{1-\alpha}}{1+i_t}, \quad (23)$$

$$r_t = m c_t \alpha k_t^{\alpha-1} l_t^{1-\alpha}. \quad (24)$$

### 2.3. Fiscal and Monetary Policy

We consider two kinds of public liabilities, i.e., monetary balances and one-period discount bonds. That is, the amount of borrowing in period  $t$  is  $E_t \left[ (1+i_{t+1})^{-1} \right] B_{t+1}$  and the amount to be repaid in period  $t+1$  is  $B_{t+1}$ . The revenues of issuing public liabilities (debt and money) net of government spending  $g$  is transferred lump-sum ( $\tau$ ) to the intermediaries.<sup>15</sup> The government's period-by-period budget constraint is given by

$$P_t \tau_t + P_t g_t + M_t + B_t = (1+i_{t+1})^{-1} B_{t+1} + M_{t+1}. \quad (25)$$

For a discussion of the government's solvency, we define the total nominal government liabilities  $W_t$  at the beginning of period  $t$ :  $W_t = M_t + B_t$ . The government's period-by-

<sup>14</sup>The term  $\chi$  denotes a positive constant and  $\hat{x}$  ( $x = \pi, mc$ ) gives the percent deviation of variable  $x$  from its steady state value  $\bar{x}$ :  $\hat{x}_t = \log(x_t/\bar{x})$ .

<sup>15</sup>The lump-sum injection of net receipts to financial intermediaries is also assumed by Carlstrom and Fuerst (1995) and is commonly applied in limited-participation models (see, e.g., Christiano et al., 1997).

period budget constraint (25) can then be rewritten as

$$W_t + P_t(\tau_t + g_t) + \frac{i_{t+1}}{1 + i_{t+1}}B_{t+1} = W_{t+1}. \quad (26)$$

We claim that the combined fiscal and monetary policy of the government must satisfy a no-Ponzi finance or solvency constraint. It states that the present value of total outstanding government liabilities converges to zero:

$$\lim_{j \rightarrow \infty} \prod_{l=1}^j \frac{1}{1 + i_{t+l}} W_{t+j} = 0. \quad (27)$$

The solvency constraint (27) implies that the present value discounted value of future receipts net of interest payments and government expenditures should allow the government to pay back its outstanding liabilities. Accordingly, the solvency constraint can also be expressed as an intertemporal budget constraint:

$$W_t = \sum_{l=0}^{\infty} \prod_{j=1}^l \frac{1}{1 + i_{t+j}} \left[ \frac{-i_{t+l+1}}{1 + i_{t+l+1}} B_{t+l+1} - p_{t+l}(\tau_t + g_t) \right]. \quad (28)$$

We assume that the monetary authority sets the short run nominal interest rate exogenously. As we focus on the monetary transmission mechanism we identify monetary policy shocks with innovations to a pure or 'open-loop' nominal interest rate rule.<sup>16</sup> This non-contingent policy specification differs from interest rate rules entailing endogenous variables like the inflation rate or output (such as the prominent Taylor-rule):

$$\log i_t = \rho_i \log i_{t-1} + (1 - \rho_i) \log \bar{i} + \varepsilon_{it}, \quad (29)$$

where  $\bar{i}$  denotes the stationary value of the nominal interest rate. The autoregressive parameter  $\rho_i$  is smaller than one and the innovations  $\varepsilon_i$  are i.i.d., with  $\varepsilon_i \sim N(0, \sigma_i^2)$ . The monetary authority accommodates changes in money demand through open market operations. Here, money balances are traded in exchange for riskless debt instruments, namely, one-period government bonds:

$$M_{t+1} - M_t = -(B_{t+1} - B_t). \quad (30)$$

Hence, the amount of beginning-of-period total nominal government liabilities  $W$  is constant over time. This specification of public liabilities might also be interpreted as a balanced-budget condition, where the primary surplus equals the interest payments on outstanding bonds.<sup>17</sup> Regarding the government expenditures, we assume that the government sets the path for its spendings  $\{g_t\}_{t=0}^{\infty}$  exogenously. Since this paper is not concerned with the analysis of fiscal shocks, we assume that the government expenditures  $\bar{g}$  are fixed and amount a constant fraction of the steady state value of GDP. The government budget

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<sup>16</sup>The pure interest rate rule is also recently applied in Carlstrom and Fuerst (2000).

<sup>17</sup>An analysis of the price level determination with a similar budget rule and different monetary policy regimes is presented by Schmith-Grohe and Uribe (2000).

constraint (25) can then be rewritten as:

$$-i_{t+1}B_{t+1} = (1 + i_{t+1})P_t(\tau_t + \bar{g}). \quad (31)$$

By inspecting the intertemporal government budget constraint (28), it can be immediately seen that given our specification of fiscal and monetary policy the government's solvency constraint (27) is fulfilled in every period.<sup>18</sup>

#### 2.4. Financial Intermediation

The financial intermediaries are perfectly competitive. In each period  $t$ , they receive deposits  $D_t$  from households and lump-sum injections  $P_t\tau_t$  from the monetary authority. These funds are supplied as loans  $Z_t$  to the firms at the gross nominal interest rate  $(1 + i_t)$ . At the end of the period, the deposits  $D_t$  together with the interest  $i_tD_t$  are repaid and the intermediary profits  $- \frac{b}{t}$  are distributed to the owners, i.e., the households:<sup>19</sup>

$$- \frac{b}{t} = (1 - i_t)D_t - (1 - i_t)Z_t + P_t\tau_t. \quad (32)$$

#### 2.5. Rational Expectation Equilibrium

In order to induce stationarity, the model is expressed in real terms:  $d_t = D_t/P_t$ ,  $z_t = Z_t/P_t$ ,  $m_t = M_t/P_{t-1}$ ,  $b_t = B_t/P_{t-1}$ . The endogenous state of the economy is represented by values taken by  $s = (k, m, b)$ . Though we introduced a stochastic process for the nominal interest rate, we restrict our attention to equilibria with positive values of the nominal interest rate so that the household's cash-in-advance (3) constraint always binds. A rational expectation equilibrium, then, consists of an allocation  $\{c_t, e_t, l_t, d_t, k_{t+1}, m_{t+1}, b_{t+1}, \tau_t, g_t\}_{t=0}^{\infty}$ , a sequence of prices and costates  $\{\pi_t, w_t, r_t, mc_t, q_t, \lambda_t, i_t\}_{t=0}^{\infty}$  such that

(i) The household's first order conditions (6)-(10) together with the cash-in-advance constraint (3), the capital accumulation equation (5) and the transversality conditions are satisfied. (ii) The factor demand conditions (23) and (24) as well as the pricing equations (20) and (21) are fulfilled. (iii) The government budget constraint (25) is satisfied, while the nominal interest rate is given by the autoregressive process (29) and government liabilities evolve according to (30). (v) The markets for intermediated funds and final output clear, i.e., the following conditions hold:

$$y_t = c_t + e_t + g_t, \quad (33)$$

$$w_t l_t = d_t + \tau_t. \quad (34)$$

#### 2.6. Model Parametrization

The model is calibrated at the non-stochastic balanced growth path by matching the model's parameter values with their empirical counterparts. The values for the preference and technology parameters are fairly standard in the business cycle literature.<sup>20</sup> The discount factor of households  $\beta$  is set equal to  $1.03^{-0.25}$ . The production elasticity of

<sup>18</sup>As noted by Benhabib et al. (1999), such a monetary-fiscal regime is a 'Ricardian' policy following the definition of Benhabib et al. (1998).

<sup>19</sup>In equilibrium profits  $- \frac{b}{t}$  equal  $P_t\tau_t i_t$ .

<sup>20</sup>See, e.g., Christiano and Eichenbaum (1992).

capital  $\alpha$  is set equal to 0.36. Quarterly depreciation of physical capital  $\delta$  is assigned a value of 0.0212. Steady state labor input is equal to 0.33 implying a value of 0.25 for the consumption expenditure share in the utility function  $\gamma$ .<sup>21</sup> The parameter  $\sigma$  which governs the risk aversion of the household is set to 2.

The elasticity of the price of capital with respect to the investment ratio,  $\Phi'' \cdot (\frac{e}{k}) / \Phi'$ , is set to -0.25. This value is taken from Bernanke et al. (1998) where monetary policy shocks are also identified with innovations to the nominal interest rate. Following Christiano et al. (1997), the price elasticity of demand  $\epsilon$  is assigned a value of 6, implying a mark-up equal to 1.2.<sup>22</sup> The value for the share of government expenditures  $g/y = 21\%$  is taken from Edelberg et al. (1998). The parameter of the AR1 process for the federal funds rate ( $\rho_i = 0.934$ ) and the steady state inflation rate ( $\bar{\pi} = 1.0189$ ) are estimated with time series from 1984-1998. We choose this period to ensure a stable monetary policy regime.

In the business cycle literature, the probability for a retailer to receive a price signal  $1 - \phi$  is often assigned a value of 0.25.<sup>23</sup> This value accords to the estimates of Galí and Gertler (1999) and is consistent with an average period of one year between two price adjustments. As the inflation's response to a monetary policy shock is of central interest in this paper, we apply three different values (0.25, 0.5, 0.75) for the fraction  $1 - \phi$  of the price adjusting firms.<sup>24</sup>

Table 1: Values of Preference and Technological Parameters

Parameter	Descriptions	Value
$\alpha$	Production Elasticity of Capital	0.36
$\sigma$	Relative Risk Aversion	2
$\epsilon$	Substitution Elasticity of Retail Goods	6
$\beta$	Discount Rate	0.9926
$\delta$	Depreciation Rate of Physical Capital	0.0212
$\Phi'' \frac{e}{k} / \Phi'$	Elasticity of Capital Adjustment Cost	-0.25
$g/y$	Government Expenditure Share	0.21
$\bar{l}$	Steady State Labor Supply	0.33
$\rho_i$	Autoregressive Parameter	0.934
$\bar{\pi}$	Steady State Inflation	1.0189
$1 - \phi$	Probability of Price Adjustment	0.25, 0.5, 0.75

### 3 Quantitative Properties

The equilibrium conditions are transformed in stationary variables and are log-linearized at the steady state.<sup>25</sup> After calibrating the model, we solved it recursively applying the method of King et al. (1987). Regarding the dynamic properties of the model, we find that the rational expectations equilibrium of the linear model is unique. Real determinacy is

<sup>21</sup>The value 0.25 for  $\gamma$  is also chosen by Cooley and Nam (1998) for their nominal business cycle model.

<sup>22</sup>Given the value of the elasticity  $\epsilon$ , the fix costs of production can be calculated with:  $\kappa = (\epsilon - 1)^{-1} y$ .

<sup>23</sup>See, e.g., Jeanne (1998), and Galí and Monacelli (2000).

<sup>24</sup>These values for the fraction  $1 - \phi$  are also applied in Yun (1996).

<sup>25</sup>The log-linear model is presented in Appendix B.



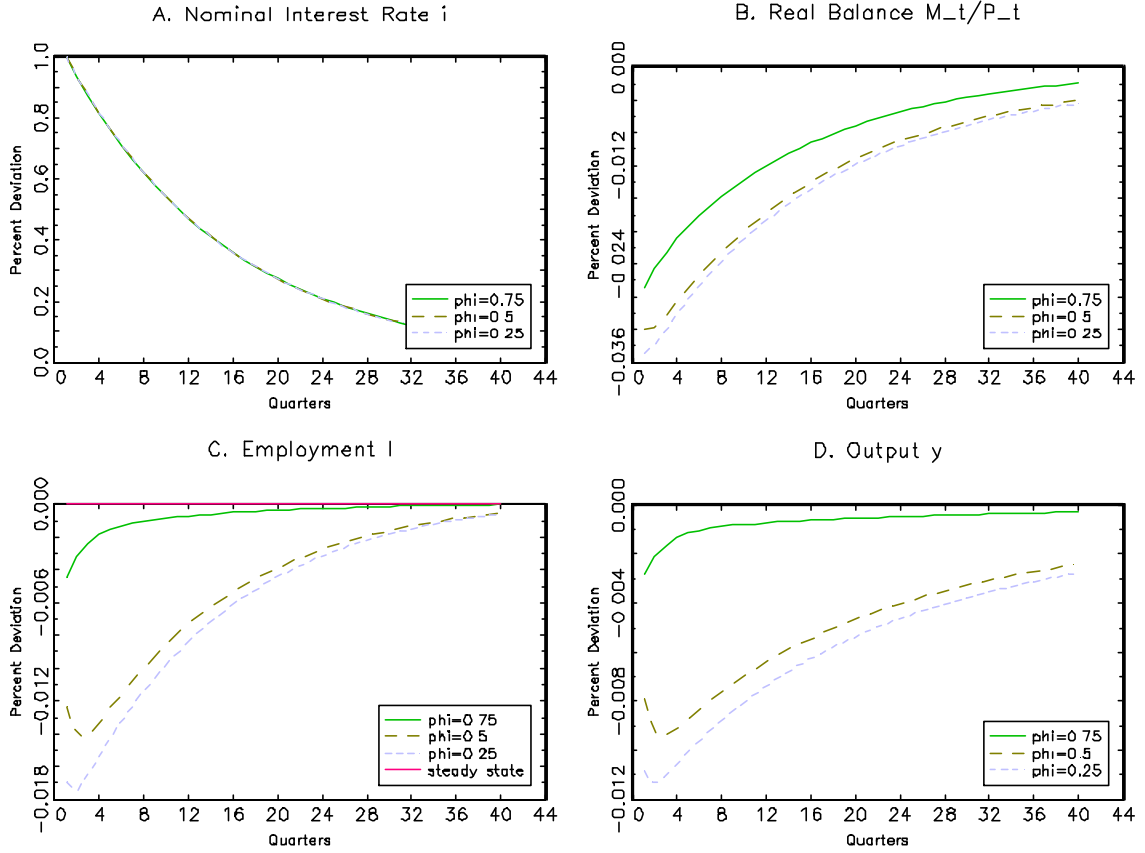


Figure 1: Impulse Responses to a Positive Interest Rate Innovation ( $i, M/P, l, y$ )

a robust feature of our model for several parameters variations over a range of reasonable values. This property is consistent with the results of Woodford (1994). He shows in a cash-in-advance economy that a combination of an interest rate peg and open market operations, which is comparable to our specification of monetary and fiscal policy, leads to unique rational expectations equilibria. It should be noted that this kind of monetary and fiscal policy is not proposed in order to avoid nominal indeterminacy, in the sense of Patinkin (1949) or Sargent and Wallace (1975), which commonly arises when the nominal interest rate is pegged.

### 3.1. Aggregate Effects of Interest Rate Shocks

For an investigation of the particular transmission mechanism of the calibrated model, we computed the impulse responses of the model to policy shocks, i.e., innovations to the nominal interest rate rule (29). The impulse responses presented in this paper refer to percent deviations of the variables from their steady state values. The Figures 1-3 present impulse responses of the model for three different degrees of price stickiness. Particularly, we vary the value of the probability  $\phi$  for the firms of not receiving a price signal ( $\phi = 0.25, 0.5, 0.75$ ), where a larger value of  $\phi$  indicates a higher degree of price stickiness.

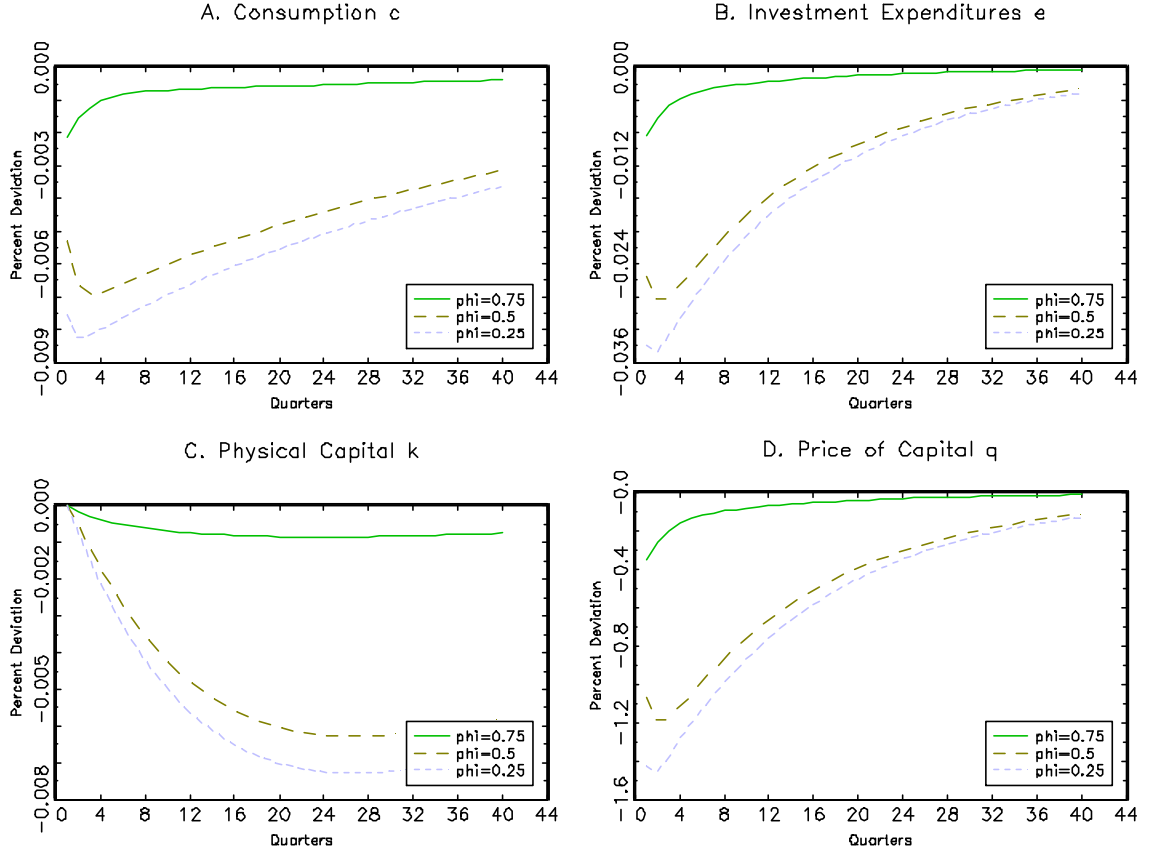


Figure 2: Impulse Responses to a Positive Interest Rate Innovation ( $c, e, k, q$ )

Figure 1 and 2 present macroeconomic reactions to a nominal interest rate shock which are consistent with conventional expectations about monetary policy effects. Figure 1B displays that the monetary policy shock leads to a decline in liquidity, as the persistent rise in the nominal interest rate is associated with reduced holdings of real balances. Induced by the increased cost of loans, the firms' loan demand falls and employment declines (Figure 1C). Consequently, output falls immediately as can be seen from Figure 1D. Surprisingly, the decline in output is even stronger when prices are less sticky. This counterintuitive result is a direct consequence of the two main sources of non-neutrality which are jointly at work in this model. Lump-sum transfers, which are determined by the government budget constraint (31), rise as the negative amount of bonds is reduced while the nominal interest rate increases.<sup>26</sup> This expansionary impact is enhanced by higher degrees of price stickiness and leads to a smaller contraction in output which is caused by the working capital channel.

In equilibrium, the real contraction is accompanied by a reduced aggregate demand of the households. According to their cash constraint (3), the demand for both types of goods,

<sup>26</sup>The respective impulse response functions are presented in Appendix C.

i.e., the consumption and investment expenditures, fall symmetrically in response to the monetary contraction (Figure 2A and B). As a direct consequence of reduced investment expenditures, the price as well as the stock of physical capital decreases as shown in Figure 2C and D. Concerning the assets of the households, the portfolio adjustments can immediately be deduced from the aforementioned responses.<sup>27</sup> Consistent with the reduced real balance holdings and the associated open market exchanges, real bond holdings rise in response to the interest rate shock. At the same time the amount of deposits, which earn the same interest as bonds, is lowered as employment and wages fall in equilibrium as can be seen from the market clearing condition for intermediated funds (34).

Up to this point, it can be summarized that our model's responses to interest rate shocks are consistent with conventional wisdom and with VAR evidence. Regarding the aggregate production, the model predicts that output responds persistently and even in a hump-shaped manner in the case of moderate price stickiness. This pattern as well as the magnitude of the output response functions are comparable to the impulse response functions of typical VAR estimates.<sup>28</sup>

### 3.2. Real Marginal Cost and Inflation

In the following subsection, we take a closer look at the responses of factor prices, real marginal cost and the inflation rate to an interest rate shock. This strategy follows Barth and Ramey (2000) who study the impact of monetary policy shocks on firms' optimal price setting in a partial equilibrium model. Their first order condition for the price setters corresponds to the forward looking pricing equation in our model which is derived from the conditions (20) and (21). This so-called 'New Keynesian Phillips Curve' states that the current inflation depends on current real marginal cost and expected future inflation:<sup>29</sup>

$$\hat{\pi}_t = \chi \widehat{mc}_t + \beta E_t [\hat{\pi}_{t+1}], \text{ with } \chi > 0, \quad (35)$$

where  $\hat{x}$  ( $x = \pi, mc$ ) denotes the percent deviations from steady state value  $\bar{x}$ . For a given value of expected future inflation, equation (35) predicts that inflation should fall when real marginal cost decreases. According to the firm's cost minimizing condition (17), real marginal cost depends positively on real factor prices and the nominal interest rate. The linearly transformed version of this condition is given by:

$$\widehat{mc}_t = (1 - \alpha) \frac{\bar{i}}{1 + \bar{i}} \hat{i}_t + (1 - \alpha) \hat{w}_t + \alpha \hat{r}_t, \text{ with } 0 < \alpha < 1. \quad (36)$$

Obviously, the behavior of inflation depends on cost components ( $i, w, r$ ) which may reveal different responses after a monetary contraction. Given our monetary policy specification, a monetary tightening always tends to raise real marginal costs due to the rise in the nominal interest rate. Thus, for real marginal cost and, therefore, for the inflation rate response it is decisive whether the factor prices, i.e., real wages  $w$  and the rental rate on capital  $r$ , decline in response to a monetary contraction and to what extent.

<sup>27</sup>They are also displayed in Appendix C.

<sup>28</sup>See Bernanke and Mihov (1998), and Christiano et al. (1996, 1999).

<sup>29</sup>The parameter  $\chi$  depends on the probability  $\phi$  of receiving a price signal and the discount factor  $\beta$ :  $\chi = (1 - \phi) (1 - \beta\phi) \phi^{-1}$  (see Appendix A).

Given the standard properties of the production function (15), the decreased stock of physical capital tends to raise the rental rate on capital, while the latter is lowered by the decline in employment. Figure 3A reveals that these opposing effects result in a rising rental rate in the case of higher price stickiness ( $\phi = 0.75$ ), whereas the rental rate initially falls when prices are more flexible.<sup>30</sup> No matter which degree of price stickiness prevails, real wages always decline in response to a monetary contraction (Figure 3B). When prices are not too sticky ( $\phi < 0.75$ ), both factor price reactions would predict a decrease of real marginal cost in the absence of interest payments on loans. In our model, the nominal interest rate does affect real marginal cost according to (36) and, as displayed in Figure 3C, causes a rise of the real marginal cost for all three degrees of price stickiness. The increase in real marginal cost leads to declining real profits, as can be seen from the impulse response function of the firms' profits in Appendix C. This feature of our model is consistent with empirical findings, which can not be replicated by a standard sticky price model with money growth shocks.<sup>31</sup>

The most remarkable property of the model's transmission mechanism is presented in Figure 3D. Here, it can be observed that the inflation rate rises in response to a positive innovation to the nominal interest rate. It turns out that this behavior is persistent and robust. Moreover, after one year the responses of the inflation rate are almost identical for all three degrees of price stickiness. Only in the first periods we find differences in the inflation reactions which are small and opposed to the differences in the real marginal cost responses (Figure 3C). However, the response of inflation in our model is consistent with the persistent rise in the price level commonly found in VARs when a sensitive price index is omitted.<sup>32</sup>

So far, it can be proposed that it is the rise in the nominal interest rate as a cost component which is responsible for the unusual response of the inflation rate to a monetary contraction. Barth and Ramey (2000) call this effect of monetary policy on the inflation rate the 'Cost Channel of Monetary Transmission'. In general equilibrium, the rise in the inflation rate is consistent with the household's arbitrage-free condition (10) which can be interpreted as a Fisher equation containing the variable price  $q$  of physical capital. This first order condition for the household's asset holdings can be rewritten as:

$$E_t \left[ \frac{1 + i_{t+1}}{\pi_{t+1}} \right] = E_t \left[ \frac{(r_{t+1} + q_{t+1} \zeta_{t+1})}{q_t} \right], \quad (37)$$

$$\text{with } \zeta_t = \Phi \left( \frac{e_t}{k_t} \right) - \Phi' \frac{e_t}{k_t} + (1 - \delta),$$

where  $\zeta$  is positive and weighs the price of capital depending on the elasticity of the adjustment cost function  $\Phi$ .<sup>33</sup> The condition (37) claims that the expected value of the total real return on capital equals the expected real interest rate on bonds. Thus, when the total real return on capital is expected to fall in response to an increase in the nominal

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<sup>30</sup>The divergence in the responses of the rental rate are due to the different weights of the expansionary effect of rising lump-sum transfers. Since investments are assumed to be cash-goods, lump-sum transfers directly affect the price of capital as well as the rental rate on capital.

<sup>31</sup>See Christiano et al. (1997) for a critical discussion of sticky price models.

<sup>32</sup>See, e.g., Christiano et al. (1996).

<sup>33</sup>Obviously,  $\zeta$  is equal to  $1 - \delta$  in the steady state.

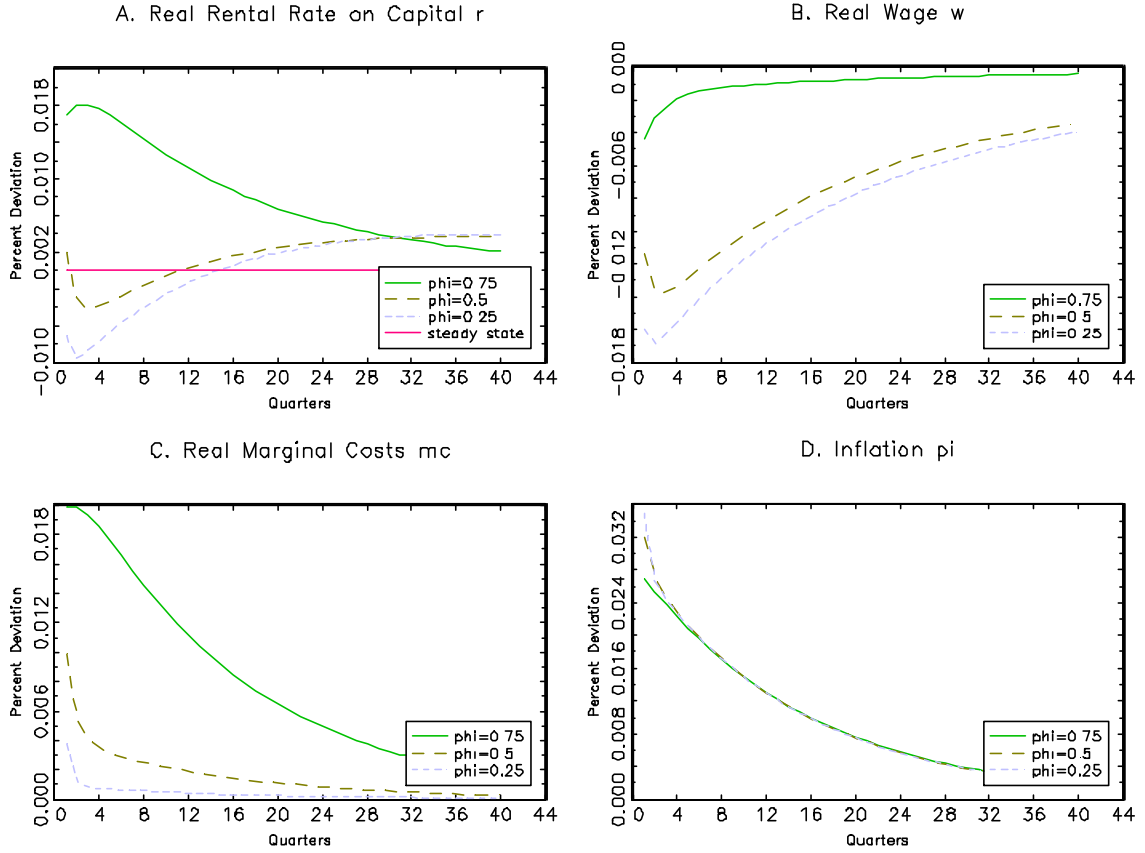


Figure 3: Impulse Responses to a Positive Interest Rate Innovation ( $r, w, mc, \pi$ )

interest rate, the expected value of the inflation rate must rise in order to ensure the equality.<sup>34</sup> This implies that, holding the other variables constant, higher expected values of the rental rate  $r$  should be accompanied by lower expected values of inflation. This pattern can be observed in Figure 3A and D.

## 4 Conclusion

The majority of monetary business cycle models treats a broad monetary aggregate as an exogenous policy measure of the central bank, whereas in the empirical literature the federal funds rate is mostly applied as the policy measure. This paper tries to overcome this disparity and presents a monetary business cycle model which allows to examine the effects of innovations to a non-contingent nominal interest rate rule while ensuring real determinacy. In addition to a working capital assumption we consider staggered price setting which enables real marginal costs to vary. It is shown that the model is able to replicate typical responses to interest rate shocks of monetary VARs. Consistent with Barth and Ramey's (2000) 'Costs Channel of Monetary Transmission', we particularly find

<sup>34</sup>This argument is confirmed by the impulse response of the real return on bonds given in Appendix C.

that real marginal costs and inflation rise in response to positive interest rate innovation. As the model's transmission mechanism provides a rationale for the so-called price puzzle in monetary VARs, we suggest that the latter should not be treated as an empirical anomaly. Obviously, this result is incompatible with conventional monetary theory and should not be taken as an advice to rethink monetary theory. Though, it casts doubt on the appropriateness of the measures for an unanticipated change in monetary policy, which are applied in this model and in many VARs.

## Appendix

### Appendix A: Derivation of the New Keynesian Phillips Curve

We start by linearizing equation (21), which determines the evolution of the price index  $P$ . For this, it is transformed in stationary variables:

$$1 = \left[ \phi \left( \bar{\pi} \pi_t^{-1} \right)^{1-\epsilon} + (1-\phi) \tilde{P}_{qt}^{1-\epsilon} \right]^{\frac{1}{1-\epsilon}}, \text{ with } \tilde{P}_{qt} = \frac{\tilde{P}_{it}}{P_t} \text{ and } \pi_t = \frac{P_t}{P_{t-1}}, \quad (\text{A1})$$

where  $\hat{x}$  denotes the percent deviation of  $x$  from its steady state value  $\bar{x}$ . Linearization of (A1) at the steady state leads to:

$$\frac{\phi}{1-\phi} \hat{\pi}_t = \hat{\tilde{P}}_{qt}. \quad (\text{A2})$$

Further, we need the first order condition for the firm's optimal price  $\tilde{P}_{it}$  (20). For the linearization at the steady state, it is also transformed in stationary variables:

$$\tilde{P}_{qt} \frac{\epsilon-1}{\epsilon} \sum_{s=0}^{\infty} (\beta\phi)^s E_t \left[ \vartheta_{t,t+s} y_{t+s} \pi_{t,t+s}^\epsilon \bar{\pi}^{(1-\epsilon)s} \right] = \sum_{s=0}^{\infty} (\beta\phi)^s E_t \left[ \vartheta_{t,t+s} y_{t+s} \pi_{t,t+s}^{\epsilon+1} m c_{t+s} \bar{\pi}^{-\epsilon s} \right], \quad (\text{A3})$$

where  $\pi_{t,t+s}$  denotes a cumulative inflation rate:  $\pi_{t,t+s} = \frac{P_{t+s}}{P_t} = \prod_{k=1}^s \pi_{t+k}$ . Linearizing equation (A3) at the perfect foresight steady state we obtain:

$$\begin{aligned} & \sum_{s=0}^{\infty} (\beta\phi)^s \bar{P}_q \frac{\epsilon-1}{\epsilon} y \bar{\pi}^{(1-\epsilon)s} \bar{\pi}^{s(\epsilon-1)} E_t \left[ \hat{\vartheta}_{t,t+s} + \hat{y}_{t+s} + \epsilon \hat{\pi}_{t,t+s} + \hat{\tilde{P}}_{qt} \right] \\ & = \sum_{s=0}^{\infty} (\beta\phi)^s \overline{m c y \pi}^{-\epsilon s} \bar{\pi}^{s\epsilon} E_t \left[ \hat{\vartheta}_{t,t+s} + \hat{y}_{t+s} + (\epsilon+1) \hat{\pi}_{t,t+s} + \hat{m c}_{t+s} \right]. \end{aligned} \quad (\text{A4})$$

Using that  $\bar{P}_q \frac{\epsilon-1}{\epsilon} = \overline{m c}$  holds in the steady state and substituting  $\bar{P}_q$  out with (A2), equation (A4) can be simplified to:

$$\frac{\phi}{(1-\phi)} \hat{\pi}_t = (1-\beta\phi) \sum_{s=0}^{\infty} (\beta\phi)^s E_t [\hat{\pi}_{t,t+s} + \hat{m c}_{t+s}]. \quad (\text{A5})$$

Taking the period  $t+1$  expression for equation (A5) times  $\beta\phi$  and subtracting it from (A5), gives:

$$\frac{\phi}{(1-\phi)} (\hat{\pi}_t - \beta\phi E_t [\hat{\pi}_{t+1}]) = (1-\beta\phi) \left( \hat{m c}_t - \beta\phi \sum_{s=0}^{\infty} (\beta\phi)^s E_t [-\hat{\pi}_{t+1}] \right). \quad (\text{A6})$$

Equation (A6) can then be rewritten, leading to the 'New Keynesian Phillips Curve' in (35):

$$\hat{\pi}_t = \chi \hat{m c}_t + \beta E_t [\hat{\pi}_{t+1}], \text{ with } \chi = (1-\phi)(1-\beta\phi)\phi^{-1}. \quad (\text{A7})$$

*Appendix B: The Log-linear Model*

State variables:  $k_t, m_t \equiv \frac{M_t}{P_{t-1}}, b_t = \frac{B_t}{p_{t-1}}$

Costates:  $\lambda_t, q_t, p_i$

Control variables:  $c, l, e, w, r, z, \tau, mc$

Exogenous states:  $i$

Dynamic Equations:

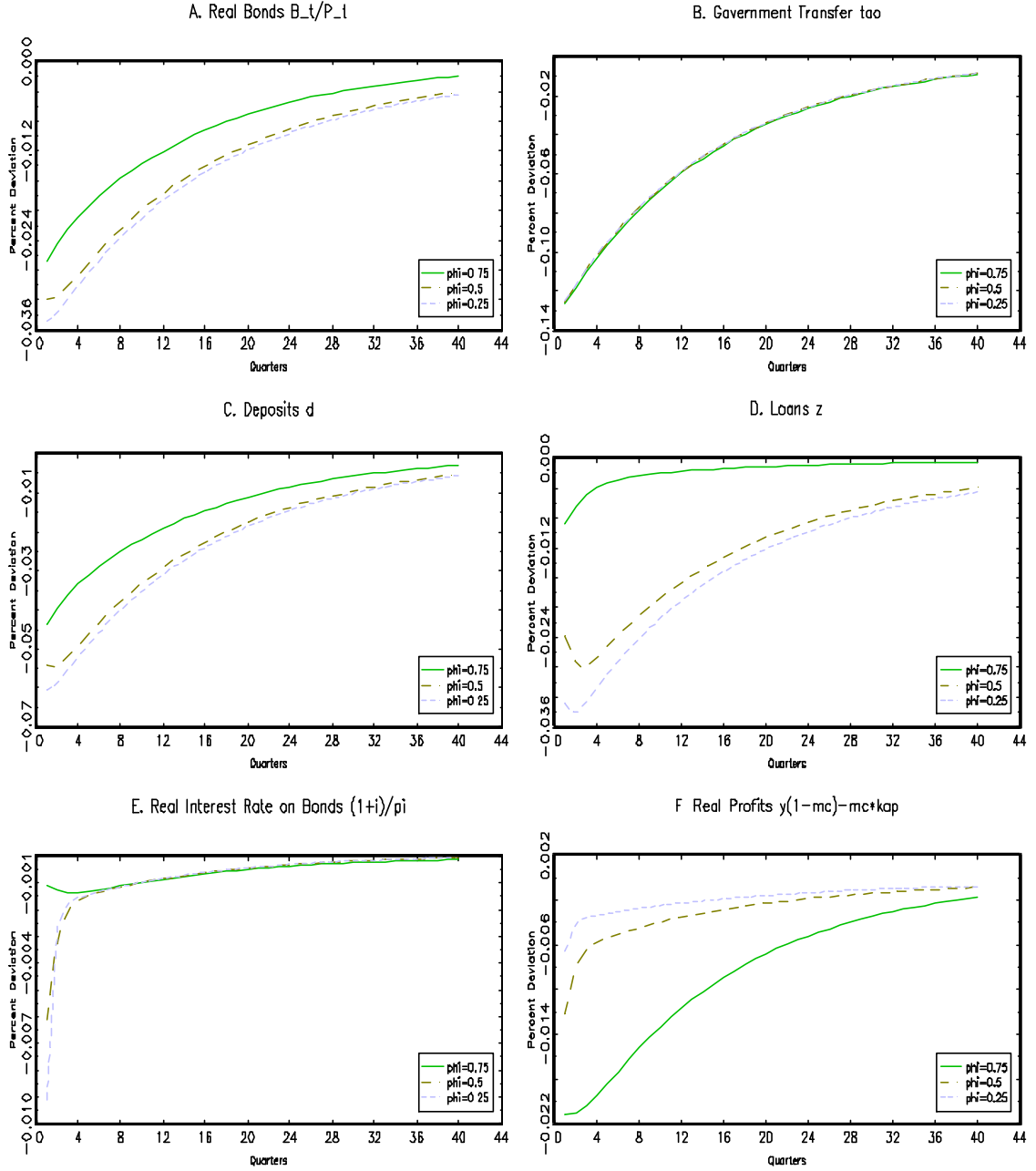
$$\begin{aligned}
 \hat{k}_{t+1} - (1 - \phi' \frac{e}{k}) \hat{k}_t &= \phi'(\cdot) \frac{e}{k} \hat{e}_t & (A8) \\
 \beta \phi'' \left( \frac{e}{k} \right)^2 \hat{k}_{t+1} + \hat{\lambda}_{t+1} + \beta \left( 1 - \phi' \frac{e}{k} \right) \hat{q}_{t+1} - \hat{\lambda}_t - \hat{q}_t &= \beta \phi'' \left( \frac{e}{k} \right)^2 \hat{e}_{t+1} - \frac{\beta}{q} r \hat{r}_{t+1} \\
 -\hat{\lambda}_{t+1} + \hat{\lambda}_t + \hat{\pi}_{t+1} &= \frac{i}{1+i} \hat{i}_{t+1} \\
 \hat{b}_{t+1} &= \frac{\tau}{\tau+g} \hat{\tau}_t - \frac{1}{1+i} \hat{i}_{t+1} \\
 -\frac{\phi}{(1-\phi)(1-\beta\phi)} \beta \hat{\pi}_{t+1} + \frac{\phi}{(1-\phi)(1-\beta\phi)} \hat{\pi}_t &= \hat{m} c_t \\
 m \hat{m}_{t+1} + b \hat{b}_{t+1} - \frac{m}{\pi} \hat{m}_t - \frac{b}{\pi} \hat{b}_t + \left( \frac{m+b}{\pi} \right) \hat{\pi}_t &= 0
 \end{aligned}$$

Contemporaneous Equations:

$$\begin{aligned}
 [(1-\sigma)\gamma - 1] \hat{c}_t - (1-\sigma)(1-\gamma) \frac{l}{1-l} \hat{l}_t &= \hat{\lambda}_t + \frac{i}{1+i} \hat{i}_t & (A9) \\
 (1-\sigma)\gamma \hat{c}_t - [(1-\sigma)(1-\gamma) - 1] \frac{l}{1-l} \hat{l}_t - \hat{w}_t &= \hat{\lambda}_t + \frac{i}{1+i} \hat{i}_t \\
 e \hat{e}_t + c \hat{c}_t - w \hat{l}_t - w \hat{w}_t + z \hat{z}_t &= \frac{m}{\pi} \hat{m}_t - \frac{m}{\pi} \hat{\pi}_t \\
 \alpha \hat{l}_t + \hat{w}_t - \hat{m} c_t &= \alpha \hat{k}_t - \frac{i}{1+i} \hat{i}_t \\
 -(1-\alpha) \hat{l}_t + \hat{r}_t - \hat{m} c_t &= -(1-\alpha) \hat{k}_t \\
 \frac{\phi''}{\phi'} \frac{e}{k} \hat{e}_t &= \frac{\phi''}{\phi'} \frac{e}{k} \hat{k}_t - \hat{q}_t + \frac{i}{1+i} \hat{i}_t \\
 \frac{c}{y} \hat{c}_t - (1-\alpha) \hat{l}_t + \frac{e}{y} \hat{e}_t &= \alpha \hat{k}_t \\
 w \hat{l}_t + w \hat{w}_t - z \hat{z}_t + \tau \hat{\tau}_t &= 0
 \end{aligned}$$



Appendix C: Additional Impulse Response Functions



Impulse Responses to a Positive Interest Rate Innovation ( $B/P, \tau, d, z, (1+i)\pi^{-1}, -f/P$ ). Note that, the impulse responses of government transfers and real bonds indicate increases as the steady state values are negative. The responses of the profits are given in absolute values.

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