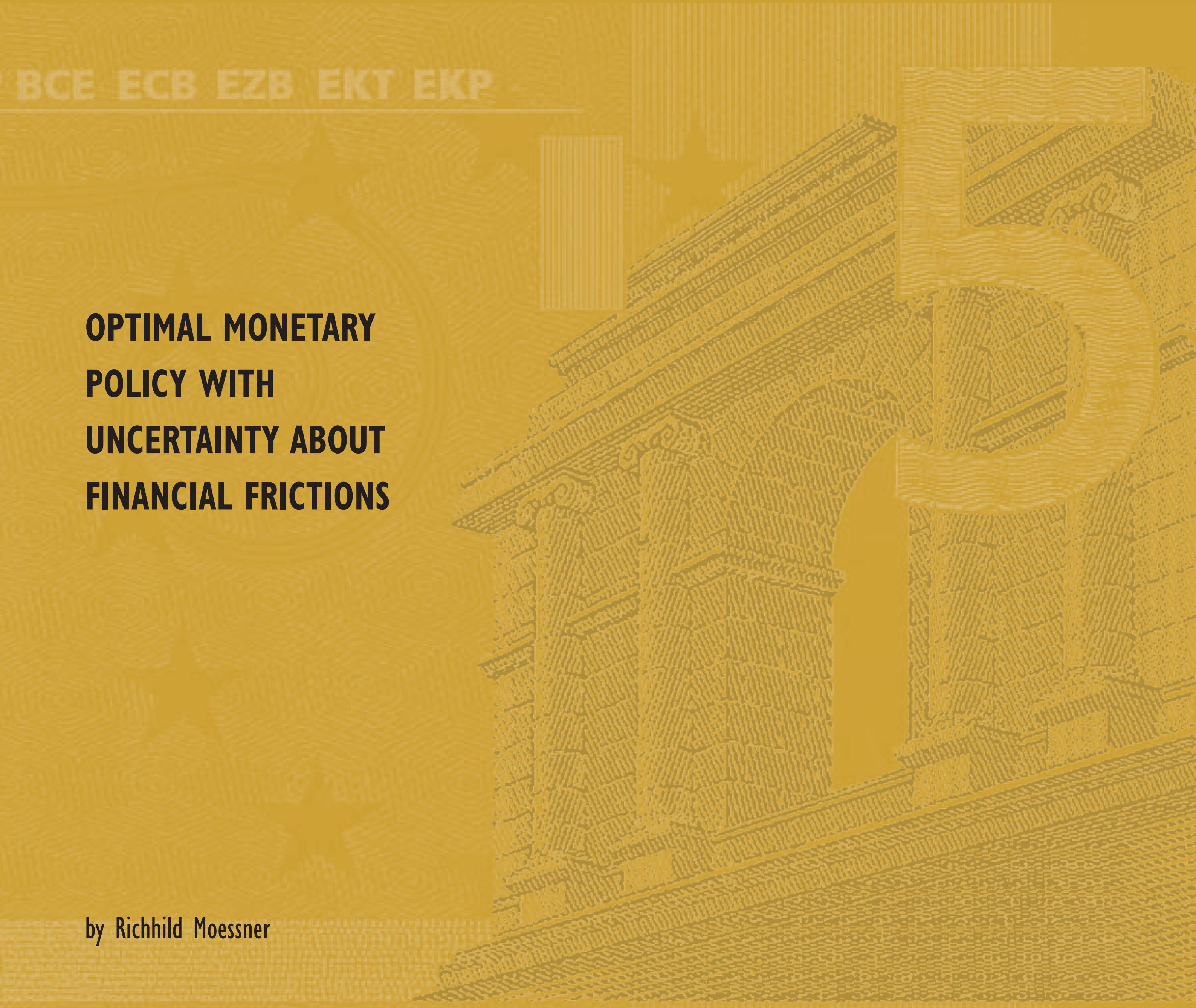
EUROPEAN CENTRAL BANK

WORKING PAPER SERIES
NO 639 / JUNE 2006



OPTIMAL MONETARY POLICY WITH UNCERTAINTY ABOUT FINANCIAL FRICTIONS

by Richhild Moessner

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In 2006 all ECB publications will feature a motif taken from the €5 banknote.

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[1] I would like to thank Klaus Adam, Bill Allen, Charlie Bean, Thomazs Chmielewski, Gunter Coenen, Fiorella De Fiore, Kalin Nikolov, Frank Smets, David Vestin, and seminar participants at the European Central Bank and at the annual meeting of the Verein für Socialpolitik for helpful comments and discussions. This paper represents the views and analysis of the author and should not be thought to represent those of the Bank of England or the European Central Bank.

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ISSN 1561-0810 (print)
ISSN 1725-2806 (online)

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Abstract

This paper studies optimal discretionary monetary policy in the presence of uncertainty about the degree of financial frictions. Changes in the degree of financial frictions are modelled as changes in parameters of a hybrid New-Keynesian model calibrated for the UK, following Bean, Larsen and Nikolov (2002). Uncertainty about the degree of financial frictions is modelled as Markov switching between regimes without and with strong financial frictions. Optimal monetary policy is determined for different scenarios of permanent and temporary regime shifts in financial frictions, as well as for variations in financial frictions over the business cycle. Optimal monetary policy is found to be state-dependent. In each state, optimal monetary policy depends on the transition probabilities between the different regimes.

JEL classification: E52, E58, E61, E44
Key words: monetary policy; uncertainty; financial frictions.

Summary

This paper studies optimal discretionary monetary policy in the presence of uncertainty about the degree of financial frictions, following the approach of Bean, Larsen and Nikolov (2002) of modelling changes in the degree of financial frictions within a hybrid New-Keynesian model calibrated for the UK. Optimal monetary policy is considered within different scenarios of temporary and permanent regime changes. Such scenario analysis may help to inform policy, based on judgements about likely developments in the degree of financial frictions. We also investigate optimal monetary policy in the presence of variations in financial frictions over the business cycles, since credit constraints are more likely to be binding in times of an economic downturn.

Uncertainty about the degree of financial frictions is assumed to be governed by a Markov process in two model parameters characterising the degree of financial frictions, the interest sensitivity of demand and the degree of endogenous output persistence. Optimal monetary policy is found to be state-dependent; in each state, optimal policy depends on the transition probabilities between states with different degrees of financial frictions. Associated impulse responses to cost-push shocks and demand shocks are also presented.

For the calibration of the model and of the regimes without and and with strong financial frictions for the UK considered here, optimal policy is found to react more aggressively to the lagged output gap when transitions to the state with strong financial frictions are more likely. The dependence of the coefficients of the optimal policy feedback rule on the transition probabilities between the states without and with strong financial frictions is found to be nonlinear.

1 Introduction

This paper studies optimal discretionary monetary policy in the presence of uncertainty about the degree of financial frictions. Changes in the degree of financial frictions are modelled as changes in parameters of a hybrid New-Keynesian model calibrated for the UK, following Bean, Larsen and Nikolov (2002). Uncertainty about the degree of financial frictions is modelled as Markov switching between regimes of no and strong financial frictions. Optimal monetary policy is determined for different scenarios of permanent and temporary regime shifts in financial frictions, as well as for variations in financial frictions over the business cycle.

The role of financial frictions in closed economies has been studied in structural models for example in Bernanke, Gertler and Gilchrist (1999), Carlstrom and Fuerst (1995), Kiyotaki and Moore (1997) and Cooley and Quadrini (1999). The question of how monetary policy should be conducted optimally in the presence of uncertainty about financial frictions has been considered more recently for example in Bean, Larsen and Nikolov (2002) and Bean (2003). Bean, Larsen and Nikolov (2002) study optimal policy under commitment within a hybrid New-Keynesian model with different degrees of financial frictions. They also consider robust optimal policy when there is uncertainty about the model parameters governing the degree of financial frictions.

The modelling of the degree of financial frictions in this paper follows Bean, Larsen and Nikolov (2002), who model changes in the degree of financial frictions as changes in the values of the interest sensitivity of demand and the degree of endogenous output persistence in the IS curve, within a hybrid New-Keynesian model calibrated for the UK. A higher interest sensitivity of demand in a regime with strong financial frictions may be motivated by higher debt levels of households, making households more exposed to increases in interest rates, and consequently amplifying the response of demand to changes in interest rates. Higher endogenous output persistence in the state of strong financial frictions may be motivated by the presence of credit-constrained firms, whose investment decisions will partly depend on past profits and cash flow. This is a simple approach which does not model financial frictions structurally, but captures two key features that tend to be generated by financial frictions, namely more persistent demand and output movements, and an amplified response of demand to changes in interest rates. Note, however, that these two parameters may also change for reasons other than changes in financial frictions, such as changes in investment adjustment costs or in habit persistence of consumption.

Endogenous credit constraints are one mechanism which may generate both intrinsic output persistence and amplification (see Kocherlakota (2000)). Due to incomplete enforceability of contracts between borrowers and lenders, and a moral hazard problem in debt markets, credit limits may depend on the value of assets used as collateral, such as land and housing. As asset prices fall in an economic downturn, borrowing limits become binding for more firms and households. Consequently, fewer firms can borrow against their expected future profits, and fewer households can borrow against their expected future income. Therefore, investment decisions depend to a greater extent on past profits and cash flow, leading to greater persistence, and consumption decisions depend to a greater extent on current income. The reduction in debt capacity is likely to lead to a decrease in investment and consumption, exacerbating the economic downturn, thereby providing an amplification mechanism.

We extend the modelling approach of Bean, Larsen and Nikolov (2002) by allowing for temporary changes in the degree of financial frictions in the economy over time between regimes without and with strong financial frictions, and for variations over the business cycle. The motivation for studying optimal monetary policy within different scenarios of temporary and permanent regime changes is to inform policy, based on judgements about likely developments in the degree of financial frictions. For example, policy makers might be interested to determine how interest rates should be set optimally given the possibility of a large fall in house prices, and an associated increase in financial frictions, as a function of the likelihood assigned to such an event. It is also of interest to study optimal monetary policy in the presence of variations in financial frictions over the business cycles, since credit constraints are likely to be more binding in times of recession, and less binding in an economic boom.

The degree of financial frictions is assumed to be governed by a Markov process in the two parameters of the model characterizing the degree of financial frictions.[1] The motivation for this approach is to be able to capture the likely episodic and asymmetric nature of changes in the degree of financial frictions. Modelling the changes between regimes without and with strong

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[1] The Markov process governing the uncertainty about the degree of financial frictions is assumed to be known to all agents in the economy.

financial frictions as a Markov process allows to study optimal monetary policy with low as well as high transition probabilities between regimes, and for asymmetric as well as symmetric regime shifts. Optimal policy is determined as a function of the transition probabilities of the Markov process governing the uncertainty about the degree of financial frictions, using a method for solving for optimal discretionary policy in rational expectations models with regime switching (see Moessner (2006)), which is described in the appendix. An alternative algorithm for time-consistent optimal policy with Markov switching based on a semi-structural model representation is presented in Blake and Zampolli (2006), for backward-looking models in Zampolli (2006), and other algorithms for optimal monetary policy with Markov regime switching, under both commitment and discretion, are presented in Svensson and Williams (2005) .

This paper considers optimal monetary policy in the presence of regime switching in the degree of financial frictions, modelled as Markov processes in two parameters, the degree of endogenous output persistence and the interest elasticity of demand, as a function of the transition probabilities of the Markov process. Earlier papers have studied optimal policy when one or both of these parameters are uncertain, assuming a symmetric prior probability distribution on the part of the central bank, and focussing on the question of whether policy is certainty-equivalent or not. In particular, Brainard (1967) found within a static model that policy should be more cautious when the policy multiplier is uncertain. Soederstroem (2002) found within a dynamic backward-looking model that policy is more cautious when the interest elasticity of demand is uncertain, but that policy may respond more aggressively to shocks when endogenous persistence is uncertain. This paper focusses on determining optimal monetary policy in each of two possible states characterizing the degree of financial frictions, with possible shifts between the two, as a function of the transition probabilities between the two states, within a rational expectations model.

While optimal policy under commitment is desirable from a normative viewpoint (see Woodford (1999)), from a positive viewpoint, central banks generally do not have a commitment technology available, and central bank behaviour is best described as discretionary (see Issing et al. (2001)). This paper therefore considers optimal discretionary monetary policy with uncertainty about financial frictions. Optimal monetary policy is found to be state-dependent. In each state, optimal monetary policy depends on the transition probabilities between the two regimes. We consider low as well as high transition probabilities, and asymmetric as well as symmetric regime changes. Associated impulse responses to cost-push shocks and demand shocks are also presented.

The outline of the paper is as follows. Section 2 describes the New-Keynesian model and the regimes without and with strong financial frictions. Section 3 introduces uncertainty about the degree of financial frictions, solves for optimal discretionary policy in the face of uncertainty about the degree of financial frictions, and presents associated impulse responses. Finally, Section 4 concludes.

2 Baseline model

We study optimal policy within a hybrid New-Keynesian model (see Clarida, Gali and Gertler (1999)) used in Bean, Larsen and Nikolov (2002), calibrated for the UK,

$$\begin{aligned} y_t &= \alpha E_t y_{t+1} + (1-\alpha) y_{t-1} - \sigma(i_t - E_t \pi_{t+1}) + e_{gt} && (1) \\ \pi_t &= \beta \omega E_t \pi_{t+1} + \beta(1-\omega)\pi_{t-1} + \mu y_t + e_{ut} && (2) \\ e_{gt+1} &= \rho_g e_{gt} + \eta_{gt+1} && (3) \\ e_{ut+1} &= \rho_u e_{ut} + \eta_{ut+1} && (4) \end{aligned}$$

We use the calibration of this model for the UK of Bean, Larsen and Nikolov (2002) (see Table A), who consider iid shocks. We therefore set the autocorrelations of the shocks to very small values ($\rho_g = \rho_u = 10^{-11}$).

The calibration of the regimes without and with strong financial frictions is also taken from Bean, Larsen and Nikolov (2002). The state with strong financial frictions is modelled as having a higher interest sensitivity of demand, σ, and a higher degree of endogenous output persistence in the IS-curve, $(1-\alpha)$ (see Table B).

Table A: Calibration of benchmark model parameters (see Bean, Larsen and Nikolov (2002)).

β	0.99
α	0.5
σ	0.6
μ	0.1
ω	0.2

Table B: Calibration of the scenarios for the degree of financial frictions (see Bean, Larsen and Nikolov (2002)).

	No financial frictions	Strong financial frictions
α	0.9	0.1
σ	0.4	0.8

The higher interest sensitivity of demand could arise for example from higher debt levels of households, making households more exposed to increases in interest rates, and consequently amplifying the response of demand to changes in interest rates. Higher endogenous output persistence in the state of strong financial frictions could arise from the presence of credit-constrained firms, whose investment decisions will partly depend on past profits and cash flow. This introduces additional persistence (see Bean, Larsen and Nikolov (2002) for a more detailed discussion). This approach does not explicitly model financial frictions, but captures two key features of financial frictions, namely that financial frictions tend to generate greater persistence in demand and output movements, and that they tend to amplify responses of demand to changes in interest rates.

The central bank is assumed to conduct optimal monetary policy under discretion, minimizing the loss function

$$L = E_0 \sum_{t=0}^{\infty} \beta^t \left[\pi_t^2 + \lambda_y y_t^2 + \lambda_i (i_t - i_{t-1})^2 \right]. \tag{5}$$

Here, π_t, y_t and i_t denote log-deviations of inflation, the output gap and the gross nominal interest rate from their steady-state values. The parameters of the central bank's loss function are chosen as follows, $\lambda_y = 1$ to reflect a concern of the monetary authority for output stabilisation, and $\lambda_i = 0.25$ to reflect a concern for smoothing short-term nominal interest rates. As shown in Woodford (1999), a concern for interest rate smoothing on the part of the central bank is desirable when conducting optimal discretionary policy.

The policy maker's control variable is the nominal interest rate i_t. Predetermined state variables are lagged output and inflation, y_{t-1} and π_{t-1}, and the two shocks e_{gt} and e_{ut}; jump variables are output and inflation, y_t and π_t.

3 Optimal policy with uncertainty about the degree of financial frictions

We consider optimal discretionary policy in the model of Bean, Larsen and Nikolov (2002), extending it to allow for temporary changes in the degree of financial frictions over time. We model the changes in the economy's degree of financial frictions as a Markov-switching process in the parameters characterizing the degree of financial frictions, namely the interest sensitivity of demand, and the degree of endogenous output persistence in the IS curve. The first state without financial frictions is modelled as having a lower interest sensitivity of demand ($\sigma^1 = 0.4$) and a lower degree of endogenous output persistence ($1-\alpha^1 = 0.1$) than the second state with strong financial frictions, where $\sigma^2 = 0.8$ and $1 - \alpha^2 = 0.9$ (see Table B). The transition of the economy between these two states is assumed to be governed by a Markov process with transition probability matrix P=(p_{ij}), where p$_{ij}$ is the probability of moving from state i to state j,

$$P = \begin{bmatrix} 1-p & p \\ q & 1-q \end{bmatrix}.$$

We assume that the states and the transition probabilities of the Markov process are known to all agents in the economy. But while current realisations of the Markov states are assumed to be observable, future realisations of the Markov states are assumed to be unobservable. Under optimal discretionary policy in the presence of regime switching, the interest rate is set by the policy authority as a function of the predetermined variables of the model. Moreover, the optimal interest rate feedback rule is state-dependent, with different coefficients in each of the two states $(i = 1, 2)$,

$$i_t = f_y^i y_{t-1} + f_\pi^i \pi_{t-1} + f_g^i e_{gt} + f_u^i e_{ut} + f_R^i i_{t-1} \ , \quad i = 1, 2. \tag{6}$$

The optimal monetary policy rule in each state depends on the transition probabilities between the regimes. It is determined below using the algorithm described in the appendix.

As a benchmark, the coefficients of the optimal policy rule in each state, assuming that no transitions between the two states are possible, are given in Table C. In the state with strong financial frictions, it is optimal for interest rates to respond more strongly to the lagged output gap and deviations of inflation from steady-state. With higher endogenous output persistence in the IS-curve, it is optimal for policy to respond more aggressively to lagged output deviations, since otherwise these deviations would persist for longer, causing larger deviations in future periods. This effect dominates the impact of the higher interest sensitivity of demand. If only the interest sensitivity of demand increased, but endogenous output persistence remained unchanged, then it would be optimal for policy to respond less to the lagged output gap in the state of strong financial frictions.

Table C: Coefficients of optimal policy rule in each state, assuming no transitions between the states without and with strong financial frictions are possible $(p = q = 0)$.

	f_y^i	f_π^i	f_g^i	f_u^i	f_R^i
No financial frictions	0.08	0.69	0.84	0.88	0.29
Strong financial frictions	0.77	1.19	0.86	1.51	0.11

3.1 Scenario analysis for permanent and temporary regime changes

In this section we study optimal policy within different scenarios of temporary and permanent regime changes in the degree of financial frictions. The motivation for studying optimal monetary policy within different scenarios of temporary and permanent regime changes is to perform scenario analysis of how interest rates should be set optimally, for example based on policy makers' judgement of likely developments in the degree of financial frictions. Policy makers might for example be interested in the possible effect on the optimal interest rate feedback rule of a large fall in house prices, and an associated increase in financial frictions, depending on the likelihood assigned to such a fall.

The case of a permanent regime change is considered first. The coefficients of the optimal policy rule in each state are shown in Figure 1, for the case where there is a non-zero probability, p, of a permanent change from the state without financial frictions to the state with strong financial frictions. For one value of $p = 0.1$, the corresponding results for the coefficients of the optimal interest rate feedback rule in each state are presented in Table D.

Table D: Coefficients of optimal policy rule in each state, allowing for a permanent shift from the regime without to the regime with strong financial frictions $(p = 0.1, q = 0)$.

	f_y^i	f_π^i	f_g^i	f_u^i	f_R^i
No financial frictions	0.47	0.99	0.94	1.25	0.16
Strong financial frictions	0.77	1.19	0.86	1.51	0.11

We can see from Table D and Figure 1 that in the presence of regime switching, the optimal interest rate feedback rule is state-dependent, with different coefficients in each state. We can also see that when there is a non-zero probability of moving away from the original state, the magnitude of the coefficients in the optimal policy rule depends on the transition probability to the other state. Due to the existence of lags in the transmission mechanism of monetary policy, and due to the forward-looking nature of policy setting and private agents' expectations, it becomes optimal for the central bank to take the uncertainty about the degree of financial frictions into account when setting interest rates. The magnitudes of the coefficients of the optimal policy rule depend nonlinearly on the transition probabilities.[2] We can see from Figure 1 that as p increases, it becomes optimal to respond more aggressively to the lagged output gap and inflation, as well as to the cost-push

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[2] If interest rate volatility, i_t^2, rather than $(i_t - i_{t-1})^2$, enters the central bank's loss function, the pattern for the dependence of the feedback coefficients of the optimal policy rule on the transition probability, p, is similar to that shown in Figure 1, but there is no feedback on lagged interest rates.

shock. This happens since it becomes more likely to move to the state with strong financial frictions, where output deviations persist for longer, potentially requiring greater output contractions in future. It is therefore optimal for policy to prevent large deviations initially by reacting more aggressively to shocks. By contrast, the optimal policy response to demand shocks as a function of p shows no clear pattern. This may happen since there are two competing effects. While greater endogenous output persistence on its own would require a stronger initial reaction to the demand shock, to prevent large shocks from entering the system during a possible regime of strong financial frictions, the possibility of a greater interest elasticity of demand has an opposing effect. If only the interest elasticity of demand increased in the regime with strong financial frictions, then it would be optimal for policy to respond less aggressively to demand shocks, since a given change in interest rates is able to offset the shock to a greater extent when demand is more sensitive to interest rates.

Similarly, Figure 2 shows the coefficients of the optimal policy rule in each state when there is a non-zero probability, q, of a permanent change from the state with strong financial frictions to the state without financial frictions. We can see that as the probability of moving to a regime without financial frictions increases, it becomes optimal for policy to respond less aggressively to deviations in the output gap and inflation and to cost-push shocks. As it becomes more likely to move to a regime without financial frictions, where output deviations are less persistent, policy does not need to react as aggressively, since less persistent deviations potentially require less output contraction in future, and are therefore less costly. In analogy to the case of a regime shift in the opposite direction shown in Figure 1, the pattern for the response to demand shocks as a function of the transition probability is less clear, due to the two opposing effects of a change in endogenous output persistence and in the interest elasticity of demand.

We can see from Figures 1 and 2 that there is an asymmetry between the two states in the dependence of the coefficients of the optimal interest rate rule on the transition probability from the original to the other state. For a small transition probability, assuming a permanent change, the coefficients change by more when there is a chance of moving from the state without financial frictions to the state with strong financial frictions (see Figure 1), than when there is a chance of moving from the state with strong financial frictions to the state without financial frictions (see Figure 2). For a transition probability of 0.5 from the original state to the other state, assuming a permanent change, the value of the coefficients are closer to the values in the state with strong financial frictions, than to those in the state without financial frictions in the absence of regime switching.

Results for optimal policy with temporary regime changes are presented in Figure 3. Figure 3 shows the coefficients of the optimal monetary policy rule when temporary regime changes between the states with and without financial frictions are possible, as a function of the transition probability, p, from state 1 to state 2, for a given transition probability in the opposite direction of $q = 0.5$. Now the coefficients in both states depend on the transition probability p, and it is optimal for policy to respond more aggressively to lagged output deviations as the transition probability to the state with strong financial frictions increases. For one value of $p = 0.1$, the corresponding values for the coefficients of the optimal interest rate feedback rule are presented in Table E.

Table E: Coefficients of optimal policy rule in each state, allowing for temporary shifts between the regimes without and with strong financial frictions $(p = 0.1, q = 0.5)$.

	f_y^i	f_π^i	f_g^i	f_u^i	f_R^i
No financial frictions	0.47	0.99	0.93	1.25	0.16
Strong financial frictions	0.71	1.15	0.86	1.45	0.12

The dependence of the coefficients of the optimal policy rule on the transition probabilities governing the uncertainty about the degree of financial frictions is also reflected in the impulse responses of output and inflation to demand and cost-push shocks, which are considered next. Figure 4 shows impulse responses to a cost-push shock, on average over 1000 different realizations of the Markov process, for transition probabilities of 0.1 between the states with and without financial frictions in both directions. Figure 5 shows the corresponding impulse responses to a demand shock. We can see that the asymmetry of the dependence of the coefficients of the optimal policy rule on the transition probabilities between the two states is reflected in the impulse responses. For the symmetric transition probabilities considered here, the impulse responses tend to lie closer to those in the state with strong financial frictions in the absence of regime switching. This is in agreement with the results for the coefficients of the optimal policy rule presented in Figures 1 and 2.

3.2 Business cycle variations in financial frictions

It is also interesting to study optimal monetary policy in the presence of variations in financial frictions over the business cycles, since credit constraints are likely to be more binding in times of recession, and less binding in an economic boom. Business cycle fluctuations are typically associated with fluctuations over 6 to 32 quarters, based on the definition of Burns and Mitchell (1946), as used more recently for example in Baxter and King (1999). Here, we choose a value of 20 quarters for the duration of a business cycle, lying in the middle of that range.

Business cycle fluctuations are modelled by allowing the demand shock in equation 1, e_{gt}, to follow a Markov process, reflecting variations in the natural real interest rate over the business cycle, rather than representing an iid shock as assumed above. The Markov states are chosen as a state with a positive value for the business cycle indicator e_{gt} of $+0.5$ (state 1), and a state with a negative value of -0.5 (state 2), with a probability of remaining in each state on average for 10 quarters, which implies a transition probability of $p = q = 0.1$ between the two states. Business cycle variations in the degree of financial frictions are then modelled by assuming that the changes between the regimes without and with strong financial frictions follow the same Markov process as that governing the changes in the business cycle indicator. The optimal interest rate feedback rule in the two states is now given by

$$i_t = f_y^i y_{t-1} + f_\pi^i \pi_{t-1} + f_c^i + f_u^i e_{ut} + f_R^i i_{t-1} \quad , \qquad i = 1, 2 \tag{7}$$

with a state-dependent intercept f_c^i.

If the degree of financial frictions does not change over the business cycle, with model parameters taking their benchmark values of Table A, then the intercepts f_c^i have the same magnitude and opposite signs in the two states $(i = 1, 2)$.

Table F: Coefficients of optimal policy rule in each state, with business cycle fluctuations in financial frictions ($p = q = 0.1$).

	f_y^i	f_π^i	f_c^i	f_u^i	f_R^i
Positive demand shock	0.47	0.99	-0.01	1.25	0.16
Negative demand shock	0.76	1.19	-0.54	1.50	0.11

However, if the degree of financial frictions varies over the business cycle, this is no longer the case. Instead, the intercept in state 1 may even become slightly negative, given the possibility of moving to a state with a negative demand shock in the presence of strong financial frictions (see Table F). This may happen since there is a possibility that the demand shock has a negative realization in the regime where output fluctuations are more persistent, which would be relatively costly. The gain from offsetting some of the potentially contractionary demand shock, should the economy move to a regime with strong financial frictions, outweighs the loss from not offsetting a positive demand shock in the less persistent regime without financial frictions, should no regime shift occur, since less persistent shocks are less costly. The results of the previous section for the behaviour of the other coefficients of the optimal policy rule in the states with different degrees of financial frictions carry over to the case of business cycle fluctuations considered here.

4 Conclusions

This paper studied optimal discretionary monetary policy in the presence of uncertainty about the degree of financial frictions, following the approach of Bean, Larsen and Nikolov (2002) of modelling changes in the degree of financial frictions within a hybrid New-Keynesian model calibrated for the UK. Optimal monetary policy within different scenarios of temporary and permanent regime changes was considered. Such scenario analysis may help to inform policy, based on judgements about likely developments in the degree of financial frictions. We also studied optimal monetary policy in the presence of variations in financial frictions over the business cycles, since credit constraints are likely to be more binding in times of an economic downturn.

Uncertainty about the degree of financial frictions was assumed to be governed by a Markov process in two model parameters characterising the degree of financial frictions, the interest sensitivity of demand and the degree of endogenous output persistence in the IS curve. Optimal monetary policy was found to be state-dependent. In each state, optimal policy was found to depend on the transition probabilities between states with different degrees of financial frictions. Associated impulse responses were also presented.

For the calibration of the model and of the regimes with high and low degrees of financial frictions for the UK considered here, optimal policy was found to react more aggressively to the lagged output gap when transitions to the state with strong financial frictions are more likely. The nonlinear dependence of the coefficients of the optimal policy feedback rule on the transition probabilities between the states with high and low degrees of financial frictions was also illustrated.

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A Algorithm for optimal discretionary policy with regime switching

This appendix describes an algorithm for solving for optimal discretionary policy in rational expectations models with regime switching (see Moessner (2005) for more details). This algorithm is based on the state-space representation of the rational expectations model, and extends the solution method of Backus and Driffill (1986) (see also Soederlind 1999) to the case with regime switching.[3] The algorithm is used in the main part of the paper to solve for optimal discretionary policy with regime switching in the degree of financial frictions. The central bank is assumed to minimise the loss function

$$L = E_0 \sum_{t=0}^{\infty} \beta^t r(x_t, u_t), \tag{8}$$

where x_t is the vector of state variables, consisting of the predetermined variables x_{1t} and the jump variables x_{2t}, and u_t is the vector of control variables. The function $r(x_t, u_t)$ is assumed to be quadratic, and may be written as

$$r(x_t, u_t) = x_t' Q x_t + x_t' U u_t + u_t' U' x_t + u_t' R u_t \tag{9}$$

Under discretion, the central bank reoptimises every period, taking x_{1t} and the private agents' expectations as given. Without regime-switching, the optimisation is subject to linear transition equations for x_t describing the evolution of the economy,

$$\begin{bmatrix} x_{1t+1} \\ E[x_{2t+1} \mid I_t] \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} x_{1t} \\ x_{2t} \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} u_t + \begin{bmatrix} \varepsilon_{t+1} \\ 0_{n_2 x 1} \end{bmatrix}, \tag{10}$$

where the vector $x_t = \binom{x_{1t}}{x_{2t}}$ of state variables has been partitioned into n_1 predetermined state variables x_{1t}, and n_2 jump variables x_{2t}, and I_t is the information set at time t of all agents in the economy. The errors ε_{t+1}

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[3] An alternative algorithm for time-consistent optimal policy with Markov switching based on a semi-structural model representation is presented in Blake and Zampolli (2006), for backward-looking models in Zampolli (2006), and other algorithms for optimal policy with Markov regime switching under both commitment and discretion are presented in Svensson and Williams (2005).

are assumed to be i.i.d. shocks with zero mean, whose covariance matrix $\Sigma = E_t^{\varepsilon}\left[\varepsilon_{t+1}'\varepsilon_{t+1}\right]$ is time-invariant, and which are uncorrelated with the predetermined variables x_{1t}. $0_{n_2x1}$is a zero matrix of size n_2x1.

Regime switching is assumed to follow a Markov process. The probability of moving from one state s^t at time t to another state s^{t+1} at time $t+1$ is modelled as a Markov chain with transition probabilities $p(s^{t+1}|s^t)$, with s^t and s^{t+1} lying in the set S of possible states of the economy. The transition probabilities are summarized in the transition matrix

$$P = (p_{ij}), \quad i, j = 1, ..., N, \tag{11}$$

where $p_{ij} \equiv p(s^{t+1} = j|s^t = i)$, and the set of possible states, S, is assumed to contain N different states. At time t, the current state, s^t, is assumed to be observed by all agents in the economy, while the state in the next period, s^{t+1}, is not yet observed. Private agents' expectations include expectations over the unknown states $s^{t+1} \in S$ in the next period,

$$E[x_{2t+1} \mid I_t] = \sum_{s^{t+1} \in S} p(s^{t+1}|s^t)E_t^{\varepsilon}x_{2t+1} \,. \tag{12}$$

The matrices A and B governing the evolution of the economy from time t to $t+1$ are allowed to be state-dependent, depending on the state in the next period, s^{t+1}, which is not observable at time t. Taking expectations for the private sector in equation 10 over the Markov states gives

$$\begin{bmatrix} x_{1t+1} \\ E[x_{2t+1} \mid I_t] \end{bmatrix} = \begin{bmatrix} A_{11}\left(s^{t+1}\right) & A_{12}\left(s^{t+1}\right) \\ \bar{A}_{21}\left(s^t\right) & \bar{A}_{22}\left(s^t\right) \end{bmatrix} \begin{bmatrix} x_{1t} \\ x_{2t} \end{bmatrix} + \begin{bmatrix} B_1\left(s^{t+1}\right) \\ \bar{B}_2\left(s^t\right) \end{bmatrix} u_t + \begin{bmatrix} \varepsilon_{t+1} \\ 0_{n_2x1} \end{bmatrix}, \tag{13}$$

where

$$\bar{A}_{21}\left(s^t\right) \equiv \sum_{s^{t+1} \in S} p(s^{t+1}|s^t)A_{21}\left(s^{t+1}\right), \quad \bar{A}_{22}\left(s^t\right) \equiv \sum_{s^{t+1} \in S} p(s^{t+1}|s^t)A_{22}\left(s^{t+1}\right),$$

$$\bar{B}_2\left(s^t\right) \equiv \sum_{s^{t+1} \in S} p(s^{t+1}|s^t)B_2\left(s^{t+1}\right).$$

Since at time t the policy authority does not know the Markov states in the next period, s^{t+1}, the Bellman equation under partial information with regime switching is given by (following Pearlman (1992))

$$v(x_t, s^t) = \min_{u_t}\left\{ r(x_t, u_t) + \beta \sum_{s^{t+1} \in S} p(s^{t+1}|s^t)E_t^{\varepsilon}\left[v(x_{t+1}, s^{t+1})\right] \right\}, \; s^t \in S \tag{14}$$

subject to the transition equations 13, with private sector expectations $E[x_{2t+1} \mid I_t]$ and x_{1t} taken as given in the optimisation, and with a state-dependent value function. Indexing the current state, s^t, by i, and the state in the next period, s^{t+1}, by j, and denoting the state-dependence of matrices by superscripts i, the optimisation problem can be solved by assuming the following functional forms,

$$v(x_t, i) = x'_{1t} V_t^i x_{1t} + v_t^i, \tag{15}$$

$$u_t = -F_{1t}^i x_{1t}, \tag{16}$$

$$x_{2t} = C_t^i x_{1t}. \tag{17}$$

The optimal policy rule is assumed to depend linearly on predetermined variables in each state, as is appropriate for linear quadratic problems. But the coefficients of the optimal policy rule switch between the values in the different states, which makes optimal policy nonlinear over time, as the parameter values switch between the different possible regimes.[4] This assumption follows Zampolli (2005) for backward-looking models. Private agents form expectations about x_{2t+1} according to equation 17, based on their limited information set, I_t. The matrices C_t^i and V_t^i are assumed not to depend on the additive shocks.

The optimisation problem can be transformed further to

$$x'_{1t} V_t^i x_{1t} + v_t^i = \min_{u_t} \left\{ \begin{array}{c} x'_{1t} Q_t^{i*} x_{1t} + x'_{1t} U_t^{i*} u_t + u'_t U_t^{i*\prime} x_{1t} + u'_t R_t^{i*} u_t + \\ \beta \sum_{j=1}^{N} p_{ij} E_t^{\varepsilon} \left[\begin{array}{c} (A_t^{ij*} x_{1t} + B_t^{ij*} u_t + \varepsilon_{t+1})' V_{t+1}^j \\ (A_t^{ij*} x_{1t} + B_t^{ij*} u_t + \varepsilon_{t+1}) + v_{t+1}^j \end{array} \right] \end{array} \right\}$$

$$i = 1, ..., N \ , \tag{18}$$

where

$$A_t^{ij*} \equiv A_{11}^j + A_{12}^j D_t^i,$$

$$B_t^{ij*} \equiv B_1^j + A_{12}^j G_t^i,$$

$$D_t^i = \left[\sum_{j=1}^{N} p_{ij} (A_{22}^j - C_{t+1}^j A_{12}^j) \right]^{-1} \left[\sum_{j=1}^{N} p_{ij} (C_{t+1}^j A_{11}^j - A_{21}^j) \right],$$

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[4] While this assumption yields an algorithm converging to a solution, it is not self-evident that this solution is unique. Other assumptions about the form of the optimal policy rule, such as a nonlinear dependence on predetermined variables in each state, may also yield a solution, but choosing a particular form for such a nonliear dependence in each state seems somewhat arbitrary.

$$G_t^i = \left[\sum_{j=1}^{N} p_{ij}(A_{22}^j - C_{t+1}^j A_{12}^j)\right]^{-1} \left[\sum_{j=1}^{N} p_{ij}(C_{t+1}^j B_1^j - B_2^j)\right],$$

and $x_{2t} = D_t^i x_{1t} + G_t^i u_t = C_t^i x_{1t}$,with

$$C_t^i = D_t^i - G_t^i F_{1t}^i, \tag{19}$$

and

$$\begin{aligned} Q_t^{i*} &= Q_{11} + Q_{12} D_t^i + D_t^{i\prime} Q_{21} + D_t^{i\prime} Q_{22} D_t^i, \\ U_t^{i*} &= Q_{12} G_t^i + D_t^{i\prime} Q_{22} G_t^i + U_1 + D_t^{i\prime} U_2, \\ R_t^{i*} &= R + G_t^{i\prime} Q_{22} G_t^i + G_t^{i\prime} U_2 + U_2' G_t^i, \\ i &= 1, ..., N, \end{aligned}$$

where the matrices Q and U have been partitioned conformably with x_{1t} and x_{2t}.

Equations for the matrices in the optimal feedback rule and the value function can then be derived as

$$F_{1t}^i = \left[R_t^{i*} + \beta \sum_{j=1}^{N} p_{ij}(B_t^{ij*\prime} V_{t+1}^j B_t^{ij*})\right]^{-1} \left[U_t^{i*\prime} + \beta \sum_{j=1}^{N} p_{ij}(B_t^{ij*\prime} V_{t+1}^j A_t^{ij*})\right], \tag{20}$$

$$V_t^i = Q_t^{i*} - U_t^{i*} F_{1t}^i - F_{1t}^{i\prime} U_t^{i*\prime} + F_{1t}^{i\prime} R_t^{i*} F_{1t}^i + \beta \sum_{j=1}^{N} p_{ij}(A_t^{ij*} - B_t^{ij*} F_{1t}^i)' V_{t+1}^j (A_t^{ij*} - B_t^{ij*} F_{1t}^i),$$

$$i = 1, ..., N. \tag{21}$$

A stationary solution may be found by iterating backwards in time until convergence on equations 19, 20 and 21, and this is done to solve for optimal policy in the main part of the paper.

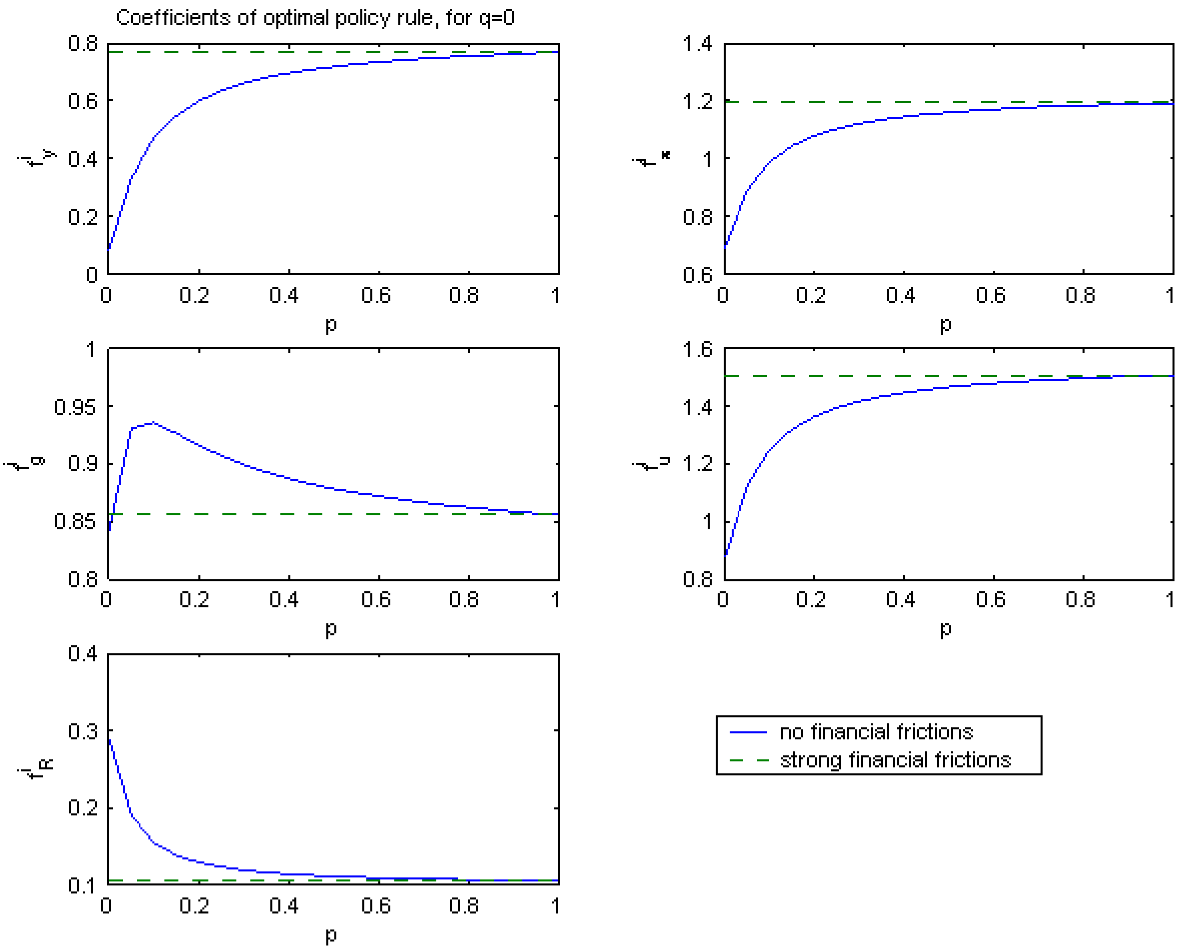

Figure 1: State-dependent coefficients of the optimal policy feedback rule in the regimes without and with strong financial frictions, as a function of the transition probability p from the state without financial frictions to the state with strong financial frictions; assuming a zero probability, q, of moving in the opposite direction from the state with strong financial frictions to the state without financial frictions.

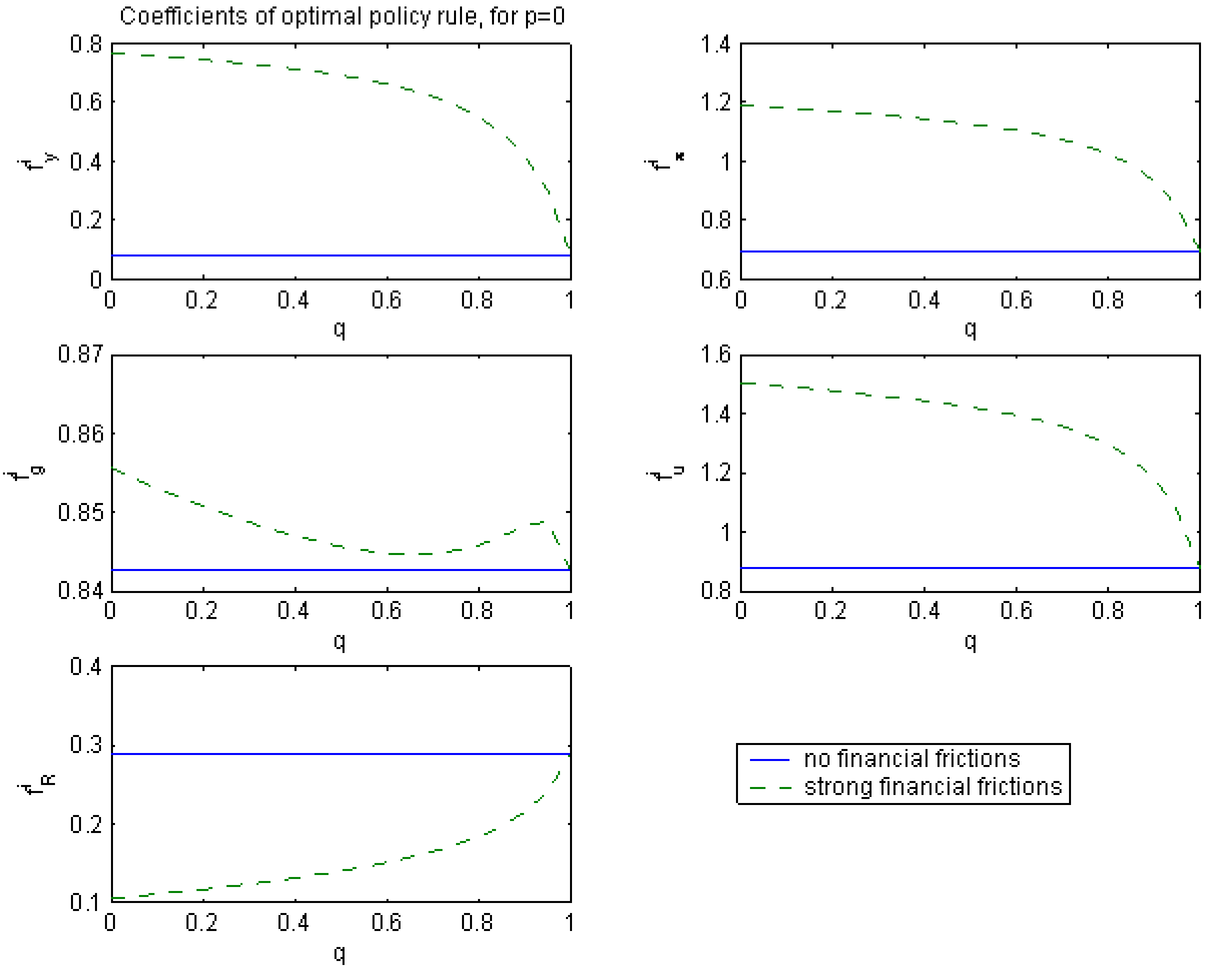

Figure 2: State-dependent coefficients of the optimal policy feedback rule in the regimes without and with strong financial frictions, as a function of the transition probability q from the state with strong financial frictions to the state without financial frictions; assuming a zero probability, p, of moving in the opposite direction from the state without financial frictions to the state with strong financial frictions.

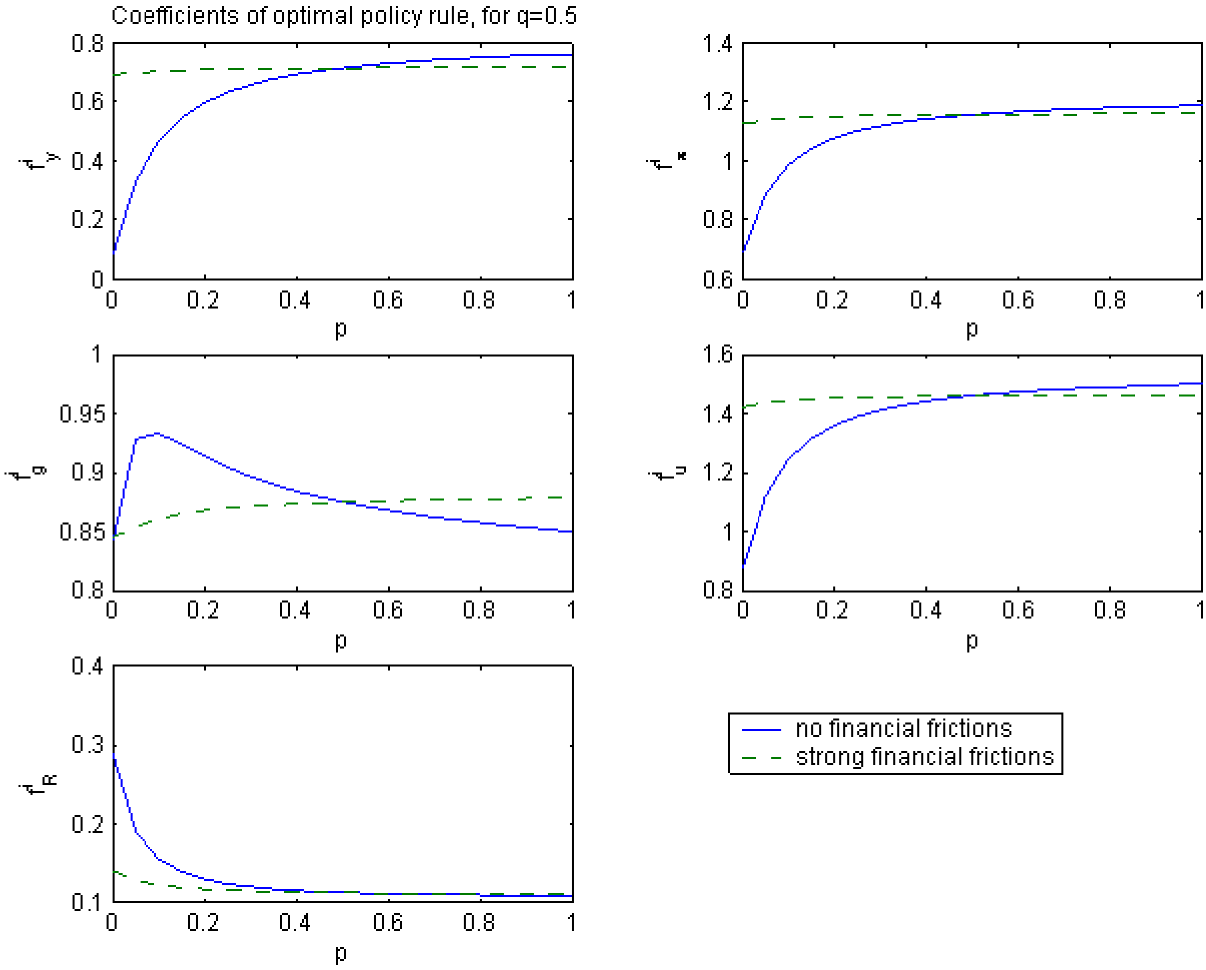

Figure 3: State-dependent coefficients of the optimal policy feedback rule in the regimes without and with strong financial frictions, as a function of the transition probability p from the state without financial frictions to the state with strong financial frictions; assuming a nonzero probability, $q = 0.5$, of moving in the opposite direction from the state with strong financial frictions to the state without financial frictions.

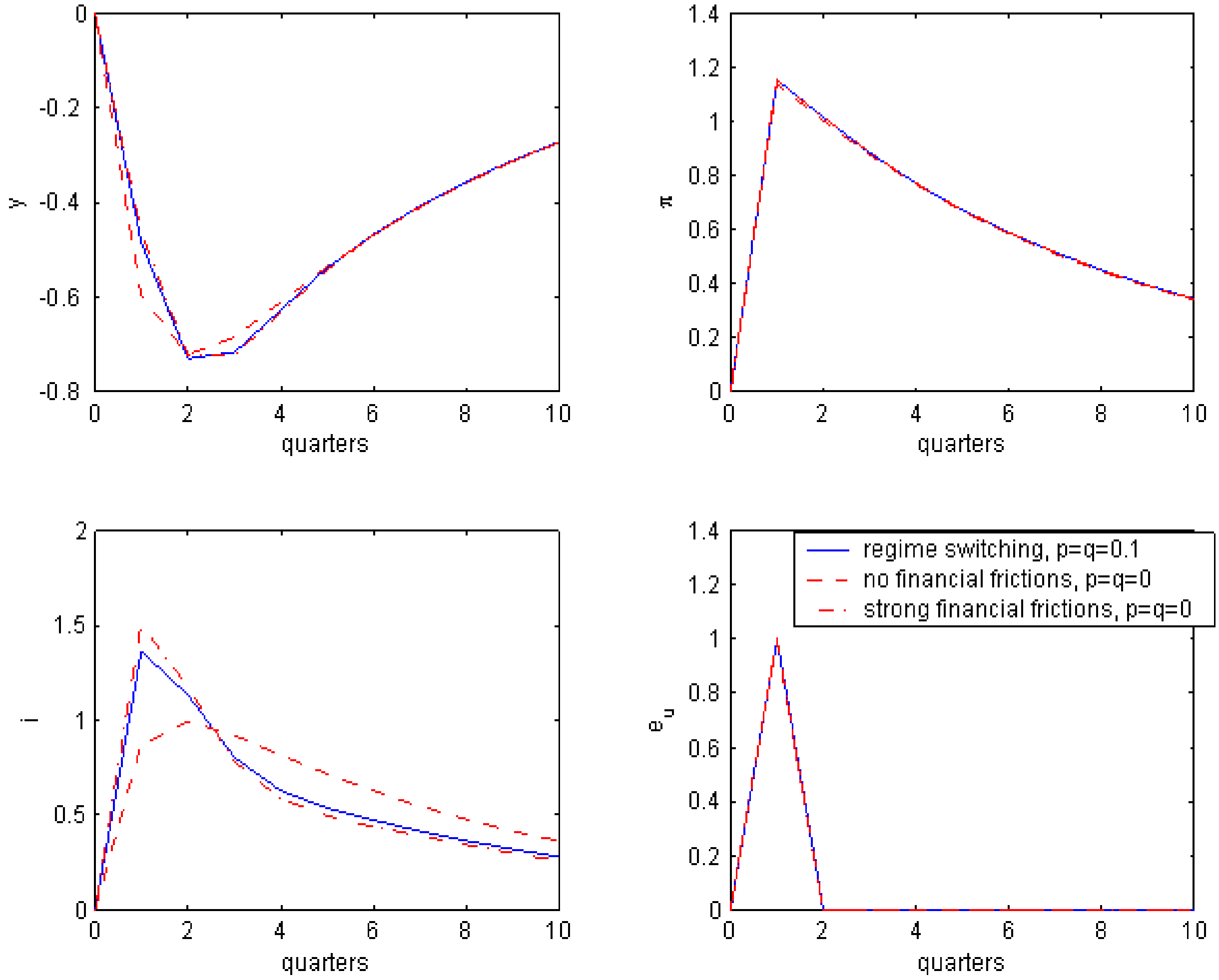

Figure 4: Impulse responses to a cost-push shock, allowing for transitions between the two states without and with strong financial frictions ($p = q = 0.1$), on average over Markov processes (solid line). The case with zero transition probabilities is shown for comparison, in the state without financial frictions (dashed line), and in the state with strong financial frictions (dash-dotted line).

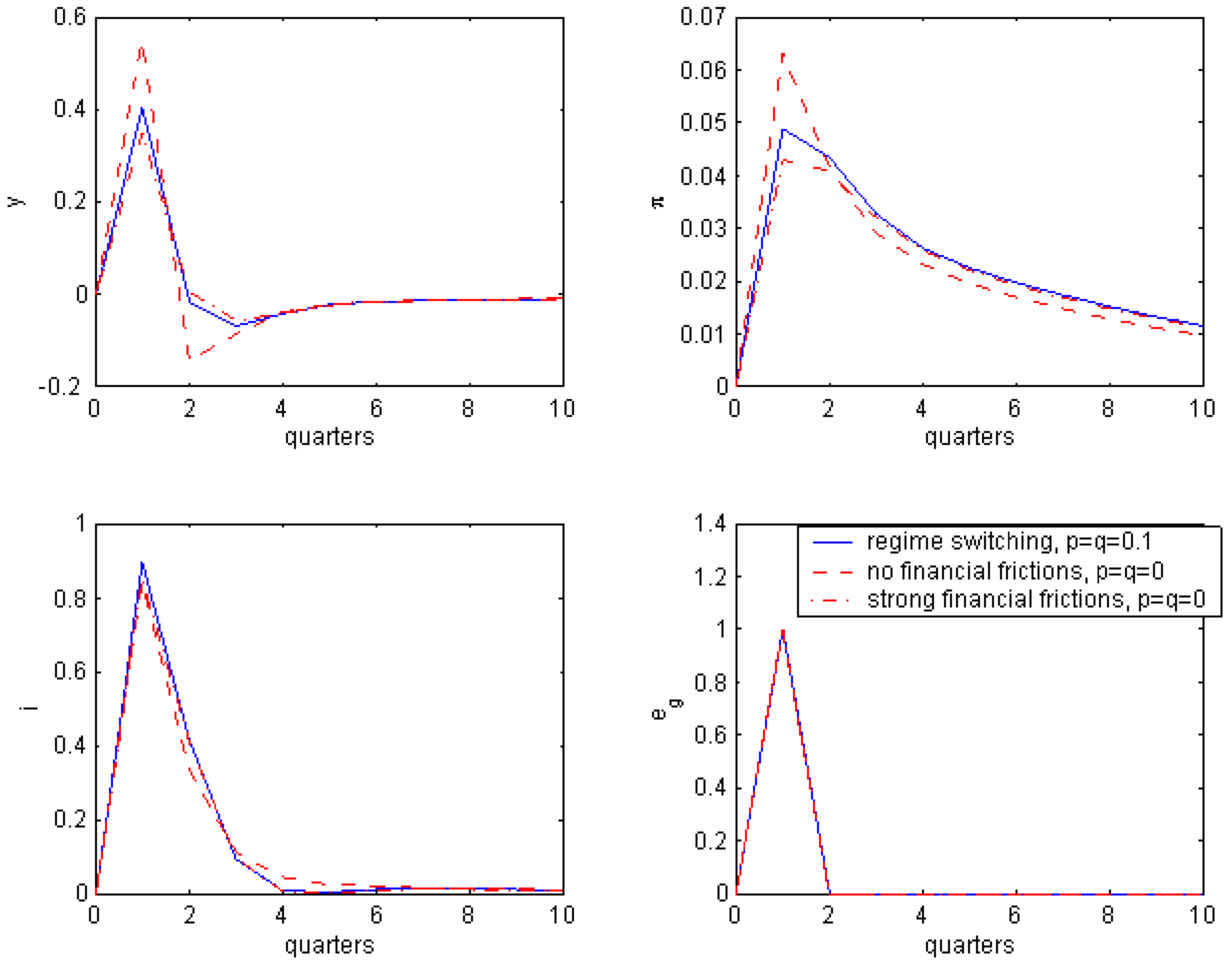

Figure 5: Impulse responses to a demand shock, allowing for transitions between the two states without and with strong financial frictions ($p = q = 0.1$), on average over Markov processes (solid line). The case with zero transition probabilities is shown for comparison, in the state without financial frictions (dashed line), and in the state with strong financial frictions (dash-dotted line).

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