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Cross-Checking Optimal Monetary Policy with Information from the Taylor Rule

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Abstract: This paper shows that monetary policy should be delegated to a central bank that cross-checks optimal policy with information from the Taylor rule. Attaching some weight to deviations of the interest rate from the interest rate prescribed by the Taylor rule is beneficial if the central bank aims at optimally stabilizing inflation and output gap variability under discretion. Placing a weight on deviations from a simple Taylor rule increases the overall relative weight of inflation volatility in the effective loss function, which reduces the stabilization bias of discretionary monetary policy. The welfare-enhancing role of this modified loss function depends on the size of the stabilization bias, i.e. on the degree of persistence in the cost-push shock process, and the relevance of demand shocks. These results can be interpreted in terms of the optimal composition of monetary policy committees.

Keywords: optimal monetary policy, stabilization bias, monetary policy delegation, robustness, Taylor rule, monetary policy committee

JEL classification: E43, E52

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1 Introduction

When setting interest rates, central banks often strive for a balance between the optimality of their policy on the one hand and the robustness on the other. Based on a particular model of the economy and a well-defined objective function, monetary policy wants to implement the optimal policy path. At the same time, however, the model that describes the economy is typically not known with certainty. As a consequence, central bankers and their staff refer to rules that are known to be relatively robust with respect to deviations of the model from the benchmark specification. One such rule is the Taylor (1993) rule that prescribes a simple relationship between the policy instrument and both inflation and output.

Recently, Røisland and Sveen (2010) study these two motives. They specify a central bank's loss function that is a weighted average between a standard part that increases in inflation and output variances and a non-standard part that penalizes squared deviations of the interest rate from its level prescribed by the Taylor rule. They simulate a series of economic models under this particular loss function under the assumption that monetary policy is able to commit to the optimal policy path. Their results show a clear trade-off between robustness and optimality. Putting some weight on deviations from the robust rule leads to a welfare loss but avoids high losses if an alternative model is the true description of the economy.

In this paper we show that if the central bank cannot commit to the first-best policy and instead formulates policy under discretion, the trade-off can break down. Delegating monetary policy to a central bank that attaches some weight on deviations from the Taylor rule can actually improve welfare in terms of inflation and output volatility. Put differently, policy should be delegated to a central banker that cross-checks optimal interest rate setting with information from a simple Taylor rule.

The reason for this finding is that placing a weight on deviations from a Taylor rule increases the effective weight of inflation volatility in the loss function, which reduces the stabilization bias of discretionary monetary policy.[2] Since the public knows that inflation will respond less to a cost-push shock, expected future inflation is subdued.

[2]See Clarida, Galí, and Gertler (1999) and Walsh (2010) for a detailed derivation and characterization of this inefficiency under discretionary monetary policy.

Stabilizing inflation becomes less costly in terms of future output contraction. The welfare-enhancing role of this modified loss function crucially depends on the size of the stabilization bias, i.e. on the degree of persistence in the cost-push shock process, and the role of demand shocks. A higher persistence eventually translates into higher volatility and aggravates the stabilization bias.[3]

The paper's main rationale draws on the seminal approach of Rogoff (1985), who pioneered the idea of modifying the central bank's loss function in order to address the suboptimal outcome under discretion. Alternative approaches to solve the stabilization bias through the delegation of a non-standard loss-function are presented in Walsh (1995) and Walsh (2003). This paper shows that instead of appointing a conservative central banker as in Rogoff (1985), i.e. a central banker who attaches a larger weight on inflation stabilisation than the social planner, delegating monetary policy to a central banker who puts some weight on a Taylor rule mitigates the bias of discretionary policy. Alternatively, the paper's main idea can be interpreted in terms of the composition of a monetary policy committee that takes consensus decisions about interest rate setting. Under these conditions, appointing some committee members that follow a Taylor rule is beneficial. Delegating policy to a central bank that cross-checks interest rate decisions with the prescription of an instrument rule is an alternative way to enhance the welfare performance of discretionary monetary policy. It is probably easier to implement than appointing a Rogoff-type conservative central banker.[4]

Central banks routinely use the result from a Taylor rule as an input to their policy deliberation. For example, Taylor (2005) argues that "central bank staffs sometimes review recommendations of policy rules with the monetary policy committee along with simulations of interest rate paths implied by the rules in future periods. This would serve as a 'cross-check' ... ." Likewise, Qvigstad (2005), the deputy governor of the Norwegian central bank, argues that "it is ... necessary to cross-check our interest

[3] Svensson (1997) coins the term "stabilization bias". Dennis and Söderström (2006) provide a detailed quantitative analysis of the size of the stabilization bias and the gains from commitment, respectively.

[4] The delegation of monetary policy in this paper is similar to recent work by Kilponen and Leitemo (2008). These authors show that under model uncertainty policy should be delegated to a policymaker that follows a Friedman-type money growth rule.

rate setting by assessing the policy in light of simple rules which are less dependent on a specific analytical framework".[5] Asso et al (2010) study the transcripts of meeting of the Federal Reserve's Federal Open Market Committee and document frequent references to the Taylor rule in policy deliberations.

We discuss monetary policy under discretion. In this context, Woodford (2001) points out that the original Taylor rule, when used as an instrument rule for monetary policy, lacks any kind of history-dependence, which is a decisive characteristic of monetary policy under the first-best commitment solution. Our results shows that cross-checking interest rate decisions with information from a Taylor rule nevertheless improves upon the outcome under pure discretion.

This paper is organized as follows. Section two introduces the economic model and, in particular, the central bank's loss function from which optimal monetary policy is derived. Section three discusses the welfare implications of alternative relative weights in the loss function, both analytically and based on a simulations. Section four extends the model to allow for a working capital channel and section five interprets the findings in terms of the composition of a monetary policy committee. Section six draws some tentative conclusions.

2 The model

2.1 The economic structure

Consider the simplest version of a New-Keynesian model, which represents a set of log-linearized equilibrium conditions derived from a standard sticky-price general equilibrium model. Inflation is described by a forward-looking Phillips curve (1). Here π_t is the inflation rate, x_t the output gap, and $\mathbb{E}_t$ is the expectations operator. The discount factor is denoted by $\beta < 1$ and κ, the slope coefficient of the Phillips curve, is inversely related to the degree of nominal rigidities

$$\pi_t = \beta \mathbb{E}_t \pi_{t+1} + \kappa x_t + e_t. \tag{1}$$

[5] See Alstadheim et al. (2010) for a survey of monetary policy analysis at Norges Bank. Since optimal policy is vulnerable to model uncertainty, monetary policy analysis places some weight on simple interest rate rules.

The IS curve (2) describes the demand side of the economy

$$x_t = \mathbb{E}_t x_{t+1} - \sigma^{-1} \left(R_t - \mathbb{E}_t \pi_{t+1} \right), \tag{2}$$

where R_t is the risk-free interest rate controlled by the central bank and the coefficient σ is the inverse of the intertemporal elasticity of substitution. The cost-push shock e_t introduces a stabilization motive for monetary policy and exhibits some degree of persistence described by the AR(1) coefficient $0 \leq \rho < 1$

$$e_t = \rho e_{t-1} + \varepsilon_t \quad \text{with } \varepsilon_t \sim \mathcal{N}(0,1). \tag{3}$$

We first sketch the basic mechanism in the absence of demand shocks. To complete the model, however, a demand shock is introduced below. The next section completes the model with a description of monetary policy.

2.2 The central bank's loss function

The social planner and the central bank share a standard loss function L_t^{stab} that is quadratic in inflation and output gap deviations from their respective target values, which are set to zero. This amounts to

$$L_t^{stab} = \pi_t^2 + \lambda x_t^2, \tag{4}$$

where output enters with a relative weight $\lambda > 0$.

The crucial assumption in this paper is that monetary policy is delegated to a central bank that is also concerned about the robustness of its interest rate policy. The central bank cross-checks optimal monetary policy with information from a simple Taylor (1993) rule. In particular, the central bank wants to minimize squared deviations of the policy instrument R_t from the path described by the Taylor rule. This motive is captured by the loss function L_t^{rob}

$$L_t^{rob} = \left(R_t - R_t^{rule} \right)^2, \tag{5}$$

where

$$R_t^{rule} = \phi_\pi \pi_t + \phi_x x_t \tag{6}$$

gives the interest rate prescribed by the Taylor rule. The rule specifies the interest rate as a function of inflation and output gap deviations, respectively, which are weighted by $\phi_\pi > 1$ and $\phi_x > 0$. As mentioned in the introduction, the Taylor rule is used at many central banks as a cross-check for interest rate decisions. It is known to perform reasonably well even if the underlying economic model turns out to be different from the one considered by the central bank when formulating optimal policy. As Taylor and Williams (2010, p. 29) argue, simple policy rules are "not fine-tuned to specific assumptions" and "are more robust to mistaken assumptions". Put differently, minimizing deviations from a Taylor rule can be interpreted as robustifying monetary policy. The overall aim of monetary policy remains the minimization of L_t^{stab}. Minimizing L_t^{rob} is not an aim per se. In the remainder we will show that putting some weight on L_t^{rob} actually helps to minimize L_t^{stab}.

The central bank uses an effective loss function which is a convex combination between L_t^{stab} and L_t^{rob} weighted by a parameter $0 \leq \gamma < 1$

$$\mathbb{E}_t \frac{1}{2} \sum_{i=0}^{\infty} \beta^i \left\{ (1-\gamma) L_{t+i}^{stab} + \gamma L_{t+i}^{rob} \right\}.$$

The loss function collapses to the standard case for $\gamma = 0$. As mentioned in the introduction, we can also understand γ as measuring the share of members of the monetary policy committee following a Taylor rule. In the remaining sections, we will evaluate the effect of γ on welfare.

2.3 Optimal monetary policy

The Lagrangian considered by the optimizing central bank is

$$\begin{aligned} \mathcal{L} \;=\; & \frac{1}{2}(1-\gamma)\left(\pi_t^2 + \lambda x_t^2\right) + \frac{1}{2}\gamma\left(R_t - \phi_\pi \pi_t - \phi_x x_t\right)^2 \\ & - \mu_t^\pi \left(\pi_t - \beta \mathbb{E}_t \pi_{t+1} - \kappa x_t - e_t\right) \\ & - \mu_t^x \left(x_t - \mathbb{E}_t x_{t+1} + \sigma^{-1}\left(R_t - \mathbb{E}_t \pi_{t+1}\right)\right), \end{aligned} \tag{7}$$

where μ_t^π and μ_t^x are the Lagrange multipliers associated with the Phillips curve and the consumption Euler equation, respectively.

We assume that a commitment technology is unavailable. Hence, the central bank formulates optimal monetary policy under discretion taking expectations as given.

The first-order conditions are

$$
\begin{aligned}
(1-\gamma)\lambda x_t - \gamma\phi_x (R_t - \phi_\pi \pi_t - \phi_x x_t) + \kappa\mu^\pi - \mu_t^x &= 0 \qquad (8)\\
\mu_t^\pi - (1-\gamma)\pi_t + \gamma\phi_\pi (R_t - \phi_\pi \pi_t - \phi_x x_t) &= 0 \qquad (9)\\
\mu_t^x - \sigma\gamma (R_t - \phi_\pi \pi_t - \phi_x x_t) &= 0, \qquad (10)
\end{aligned}
$$

which can be rearranged to

$$
x_t = -\frac{\kappa}{\lambda}\pi_t + \frac{\gamma}{1-\gamma}\frac{A}{\lambda}(R_t - \phi_\pi \pi_t - \phi_x x_t) \qquad (11)
$$

with $A \equiv \sigma + \kappa\phi_\pi + \phi_x$. Interestingly, to the extent that $\gamma > 0$, the central bank's concern about deviations from the Taylor rule drives a wedge into the optimality condition known from standard models. The wedge is larger, the smaller λ, i.e. the larger the relative weight of inflation stabilization. A given inflation rate is addressed by a more vigorous output contraction if $\gamma > 0$.

Alternatively, for $\gamma > 0$ the first-order conditions can be rearranged to

$$
R_t = \left(\phi_\pi + \frac{1-\gamma}{\gamma}\frac{\kappa}{A}\right)\pi_t + \left(\phi_x + \frac{\lambda}{A}\frac{1-\gamma}{\gamma}\right)x_t.
$$

For $\gamma = 1$, the benchmark Taylor rule obtains.

The solution will consist of inflation and output being a linear function of the model's only exogenous state variable, i.e. the cost-push shock. Guessing a solution of the form

$$
\begin{aligned}
\pi_t &= \psi_\pi e_t\\
x_t &= \psi_x e_t
\end{aligned}
$$

implies that $\mathbb{E}_t\pi_{t+1} = \psi_\pi \rho e_t$ and $\mathbb{E}_t x_{t+1} = \psi_x \rho e_t$. We use the method of undetermined coefficients to obtain the solutions for the coefficients ψ_π and ψ_x as

$$
\begin{aligned}
\psi_\pi &= \Omega^{-1}\{\lambda(1-\gamma) + \gamma\sigma(1-\rho)A + \gamma\phi_x A\} \qquad (12)\\
\psi_x &= \Omega^{-1}\{\gamma A(\rho - \phi_\pi) - \kappa(1-\gamma)\} \qquad (13)
\end{aligned}
$$

with

$$
\begin{aligned}
\Omega = {} & \lambda(1-\gamma)(1-\beta\rho) + \gamma\sigma A(1-\rho)(1-\beta\rho) \qquad (14)\\
& +\gamma\phi_x A(1-\beta\rho) + \kappa^2(1-\gamma) - \kappa\gamma A(\rho - \phi_\pi).
\end{aligned}
$$

This solution is derived in the appendix. Note that under the assumptions made before, i.e. $\rho < 1$, $0 \leq \gamma < 1$, and $\phi_\pi > 1$, the denominator Ω is strictly positive.
For $\gamma = 0$ the solution collapses to the standard result for inflation and output under discretionary monetary policy, i.e.

$$\begin{aligned} \psi_\pi &= \frac{\lambda}{\lambda(1-\beta\rho)+\kappa^2} \\ \psi_x &= \frac{-\kappa}{\lambda(1-\beta\rho)+\kappa^2}. \end{aligned} \tag{15}$$

3 The welfare effects of delegation

3.1 Analytical results

For the ease of exposition, let us assume that $\gamma = 0$. One way to overcome the stabilization bias in this case is to delegate policy to a central bank that differs from the social planner with respect to the weight attached to conflicting policy objectives. The social planner weights fluctuations in the output gap with a weight λ^P, which is not restricted to coincide with the weight of the central bank. The social planner then chooses λ in order to minimize the welfare loss resulting from the equilibrium outcome given in (15) for a given λ

$$\min_\lambda \left\{ \left[\frac{\lambda}{\lambda(1-\beta\rho)+\kappa^2}\right]^2 + \lambda^P \left[\frac{-\kappa}{\lambda(1-\beta\rho)+\kappa^2}\right]^2 \right\}.$$

The minimization problem results in the following optimality condition

$$\lambda = \lambda^P (1-\beta\rho).$$

Since $\beta\rho < 1$, the optimal output weight of the central bank lies below the weight the social planner attaches to output gap fluctuations. Hence, the social planner chooses a central banker who puts more weight on inflation stabilization than the social planner. The central bank is conservative in the sense of Rogoff (1985).
Rather than delegating policy to conservative central banker, this paper offers an alternative delegation scheme. Let us go back to the assumption that $\lambda = \lambda^P$. Instead, we show that delegating policy to a central bank with $\gamma > 0$ also improves the discretionary solution. In contrast to the Rogoff-type solution, however, we cannot

easily derive an optimal value of γ, which forces us to calibrate the model. To compute the variances of inflation and output as well as the resulting welfare metric, we use standard parameter values taken from the literature. In particular, we set $\lambda = 0.25$, $\kappa = 0.1$, $\phi_x = 0.3$ and $\beta = 0.99$. The inverse of the real interest rate elasticity of aggregate demand is set to $\sigma = 1.8$. The persistence of the shock process is calibrated to $\rho = 0.75$.

Figure (1) plots the welfare loss, i.e. the value of L_t^{stab}, as a function of γ and ϕ_π. For a vigorous interest rate response to inflation, i.e. ϕ_π is large, attaching a small weight of about $\gamma = 0.15$ to deviations of the interest rate from the Taylor rule minimizes the welfare loss. Put differently, a welfare gain can be realized if the central bank cross-checks with the Taylor rule. The reason for this result is straightforward. Discretionary monetary policy suffers from a stabilisation bias, i.e. inflation volatility is suboptimally high. This bias can be mitigated if policy is delegated to a central bank that attaches some weight on a rule with a strong response to inflation. With this additional constraint, the relative weight of inflation in the effective loss function increases, thus leading to a reduction in inflation volatility.[6]

In figure (2) we plot the resulting welfare loss if the central banker responds only to inflation, i.e. for $\phi_x = 0$. In this case the welfare-improving effect of attaching a small weight to the Taylor rule is clearly visible for large values of ϕ_π.

For a much smaller degree of persistence, i.e. for $\rho = 0.50$, a welfare gain can be realized once we accept a somewhat higher real interest rate elasticity of aggregate demand, e.g. $\sigma = 1$. Again, see figure (3), there is an optimal value of γ around 0.15 for which the welfare loss is lowest. For larger values of γ, however, welfare sharply deteriorates. The welfare-enhancing effect prevails even for a relatively small stabilization bias. Attaching too much weight on deviations from the Taylor rule, however, sharply increases the welfare loss in this case. Since the Taylor rule requires a strong interest rate response to inflation, a high interest rate elasticity of output translates this interest rate response into a suboptimally large adjustment of output. As a bottom line, it appears that, for a wide range of parameters, attaching a small

[6] Recently, Dennis (2010) also finds that robustness can lower the cost of discretion. In contrast to his work, however, this paper presents a straightforward way to address the stabilisation bias which is easy to communicate.

weight to deviations of the interest rate from the level suggested by the Taylor rule is indeed beneficial. For our baseline scenario with a persistence of $\rho = 0.75$ and a moderate inflation response in the Taylor rule, however, the welfare loss falls monotonically in γ. The reason is that the simple model lacks a demand shock. In the absence of a Taylor rule restriction for optimal policy, i.e. for $\gamma = 0$, demand shocks can be fully stabilized. With a positive weight on a Taylor rule, however, demand shocks lead to fluctuations in inflation and output and, as a consequence, to a welfare loss. Therefore, allowing for demand shocks gives rise to a detrimental effect on welfare if the central bank uses information from the Taylor rule. It follows that the optimal γ trades-off this welfare loss against the gain from mitigating the stabilization bias. We address this issue in the following subsection.

3.2 Results from a simulated model

To address the role of demand shocks, this subsection presents a simulated model and derives both welfare and impulse responses. We add a demand shock u_t to the IS curve

$$x_t = \mathbb{E}_t x_{t+1} - \sigma^{-1} \left(R_t - \mathbb{E}_t \pi_{t+1} \right) + u_t \tag{16}$$

with

$$u_t = \varphi u_{t-1} + \nu_t \quad \text{with } \nu_t \sim \mathcal{N}(0,1) \tag{17}$$

and $0 \leq \varphi < 1$. All other parts of the model remain unchanged. We set $\rho = \varphi = 0.75$, $\phi_\pi = 1.8$ and $\phi_x = 0.3$ and use standard algorithms to solve the model. Figure (4) plots the resulting welfare loss L_t^{stab} as a function of γ (see the blue line). In contrast to the supply shocks-only model in figure (1), the full model gives rise to minimum welfare loss at $\gamma = 0.25$ even for $\phi_\pi = 1.8$.

Figures (5) and (6) depict the responses of output, inflation and the nominal interest rate to a supply and demand shock, respectively. Following a supply shock, the central bank raises the interest rate more strongly for $\gamma = 0.25$ than for $\gamma = 0$. As a result, the inflation response is depressed while the output response is amplified. After a demand shock, in contrast, the interest rate is raised less vigorously if the central bank avoids deviations from the Taylor rule, which prevents output and inflation from being fully stabilized.

These results strengthen those from the previous subsection. Delegating monetary policy to a monetary policy committee that puts some weight on deviations from the Taylor rule results in a welfare gain.

4 A simple extension: the role of a working capital constraint

In this section we evaluate how the existence of a credit market alters the basic finding. A particularly simple way to include a credit market is to allow for firms holding working capital in oder to finance the wage bill. Firms pay wages at the beginning of the period and receive the proceeds from selling their products at the end of the period. To bridge this gap, firms hold working capital borrowed at the nominal interest rate R_t. Such a cost channel is introduced into the New Keynesian model by Ravenna and Walsh (2006). They show that the aggregate supply schedule becomes

$$\pi_t = \beta E_t \pi_{t+1} + \kappa \left\{ x_t + \frac{\phi}{\sigma + \eta} R_t \right\} + e_t \tag{18}$$

where η is the elasticity of labor supply, and ϕ, describes the size of the cost capital channel. Under this cash-in-advance constraint for firms, the nominal interest rate enters the Phillips curve as a higher interest rate increases the costs of holding working capital and, thus, firms marginal costs.

The remaining parts of the model remains unchanged. As shown by Ravenna and Walsh (2006), the existence of a cost channel of monetary transmission does not affect the central bank's welfare function. To simulate the model, we set $\eta = 1$. The size of the cost channel is set to $\phi = 0.8$, which roughly corresponds to the mean of the available empirical estimates. While Ravenna and Walsh (2006) estimate a cost channel coefficient of about unity for the U.S. economy, Chowdhury, Hoffmann, and Schabert (2006) find $\phi = 1.3$ for both the UK and the U.S., but only 0.2 for France and an insignificant estimate for Germany.

Figure (4) reports the resulting welfare loss as a function of γ (see the green line). The welfare-minimizing γ is even larger than in the absence of a cost channel of monetary transmission. Since the presence of a cost channel makes interest rate adjustments costly for the monetary authority due to their supply-side impact on inflation, the use of the interest rate as a stabilization tool is suppressed. This aggravates the stabilization bias under discretion. A larger weight on inflation is needed in order to minimize the welfare loss. This additional weight on inflation stabilization is obtained by attaching more weight to information from the Taylor rule.

5 Implications for the composition of monetary policy committees

The previous subsections showed that a weight of $\gamma = 0.25$ on deviations from a simple instrument rule minimizes the welfare loss under discretionary monetary policy. Since at almost all central banks monetary policy decisions are taken by monetary policy committees (MPC), these findings can be interpreted in terms of the optimal composition of these committees.

Assume an MPC that decides by consensus. If the committee does not take majority decisions, the median-voter theorem does not apply and interest rate recisions reflect the heterogeneity of preferences in the committee. The results imply that about one quarter of the seats in an MPC should be filled with firm believers in simple policy rules. The remaining three quarters of committee members should set optimal monetary policy based on the standard trade-off under discretion. Delegating policy to an MPC designed like this would lead to a more active interest rate setting and, as a consequence, a better stabilization outcome.

Riboni and Ruge-Murcia (2010) recently study the empirical implications of monetary policy making by committee under four different voting protocols. For the Bank of Canada, the Bank of England, the European Central Bank, the Swedish Riksbank, and the Federal Reserve they indeed find that the consensus model fits actual policy decisions better than alternative models such as an agenda-setting model or model with simple majority voting. Put differently, delegating policy to a committee in which a fraction of members follow the Taylor rule would have the consequences outlined above.

6 Conclusions

Discretionary monetary policy suffers from an inefficiency. Since policy cannot commit to stabilize future inflation, inflation will be too volatile relative to the commitment outcome. This paper showed that the stabilisation bias can be mitigated if the central bank, besides stabilizing inflation and output gap variability per se, also aims at minimizing deviations of the policy instrument from the interest rate level prescribed by a Taylor rule. Monetary policy should be delegated to a central banker or a monetary policy committee, respectively, that puts a small weight on the Taylor rule. If roughly one quarter of committee members set interest rates according to a Taylor rule and the remaining three quarters set policy optimally based on standard principles, the welfare loss is minimized.

This proposal follows the same logic as the seminal approach of Rogoff (1985). If commitment is not feasible, delegating a non-standard loss-function to the central bank is beneficial. In contrast to Rogoff (1985), however, this paper's proposition is easy to implement since the Taylor rule is widely used as a benchmark, e.g. at the Norges Bank, against which interest rate decisions are evaluated.[7]

In the wake of the recent financial crisis, critiques of the Fed argue that around 2004-2006 monetary policy deviated from the policy rule that describes interest rate setting over the previous decade. Overly expansionary policy, the argument goes, laid the ground for the build-up of property price bubbles. The debate about this "Great Deviation" (Taylor 2010) suggests that the benefits from cross-checking optimal policy with a Taylor rule might go beyond the stabilization policy addressed in this paper.

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7 Appendix

This appendix presents the solution for inflation and output. The first-order conditions can be reformulated to

$$x_t = -\frac{\kappa}{\lambda}\pi_t + \frac{\gamma}{1-\gamma}\frac{A}{\lambda}\left(R_t - \phi_\pi \pi_t - \phi_x x_t\right). \tag{19}$$

Replacing R_t by the IS curve and using our conjectured solutions with $\mathbb{E}_t \pi_{t+1} = \rho \pi_t$ and $\mathbb{E}_t x_{t+1} = \rho x_t$ gives

$$x_t = -\frac{\kappa}{\lambda}\pi_t + \frac{\gamma}{1-\gamma}\frac{A}{\lambda}\left(\left(-\sigma\left(1-\rho\right)x_t + \rho\pi_t\right) - \phi_\pi \pi_t - \phi_x x_t\right) \tag{20}$$

or

$$x_t = \frac{-\kappa\left(1-\gamma\right) + \gamma A\left(\rho - \phi_\pi\right)}{\lambda\left(1-\gamma\right) + \gamma\sigma\left(1-\rho\right)A + \gamma\phi_x A}\pi_t. \tag{21}$$

For $\gamma = 0$ we get the standard trade-off that is well-known from e.g. the work of Clarida, Galí, and Gertler (1999)

$$x_t = -\frac{\kappa}{\lambda}\pi_t.$$

Inserting (21) as well as the conjectured solution into the Phillips curve gives

$$\pi_t = \frac{\lambda\left(1-\gamma\right) + \gamma\sigma\left(1-\rho\right)A + \gamma\phi_x A}{\lambda\left(1-\gamma\right) + \gamma\sigma\left(1-\rho\right)A + \gamma\phi_x A + \kappa^2\left(1-\gamma\right) - \kappa\gamma A\left(\rho - \phi_\pi\right)}\left[\beta\rho\psi_\pi + 1\right]e_t.$$

We can collect terms to obtain the solution coefficient for inflation

$$\psi_\pi = \Omega^{-1}\left\{\lambda\left(1-\gamma\right) + \gamma\sigma\left(1-\rho\right)A + \gamma\phi_x A\right\} \tag{22}$$

with

$$\begin{aligned}\Omega &= \lambda\left(1-\gamma\right)\left(1-\beta\rho\right) + \gamma\sigma A\left(1-\rho\right)\left(1-\beta\rho\right) \\ &\quad + \gamma\phi_x A\left(1-\beta\rho\right) + \kappa^2\left(1-\gamma\right) - \kappa\gamma A\left(\rho - \phi_\pi\right).\end{aligned} \tag{23}$$

From (21) and (22) the solution coefficient for output is obtained

$$\psi_x = \Omega^{-1}\left\{\gamma A\left(\rho - \phi_\pi\right) - \kappa\left(1-\gamma\right)\right\}. \tag{24}$$

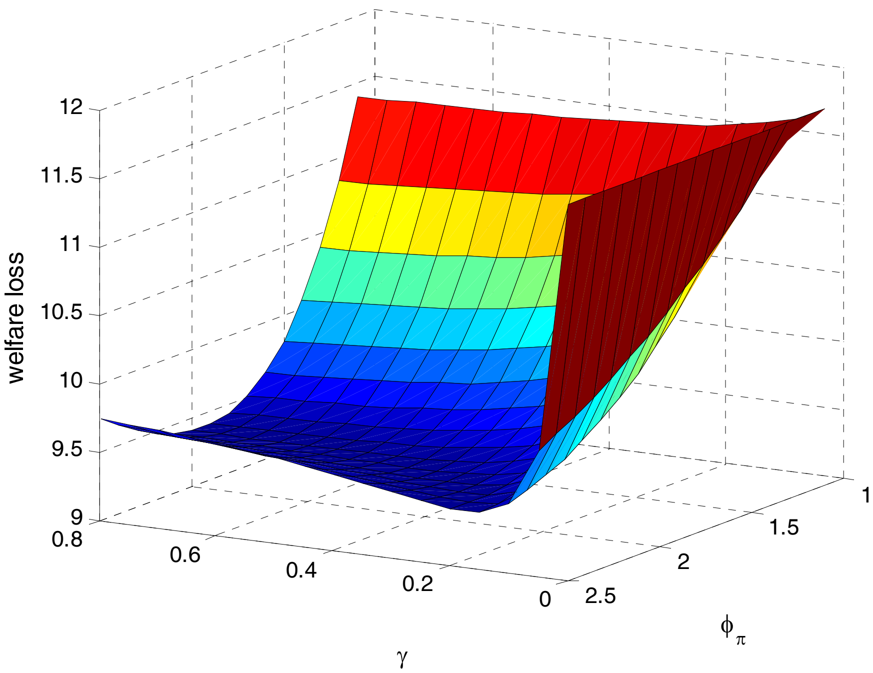

Figure 1: The welfare loss as a function of γ and ϕ_π for $\rho = 0.75$ and $\sigma = 1.8$

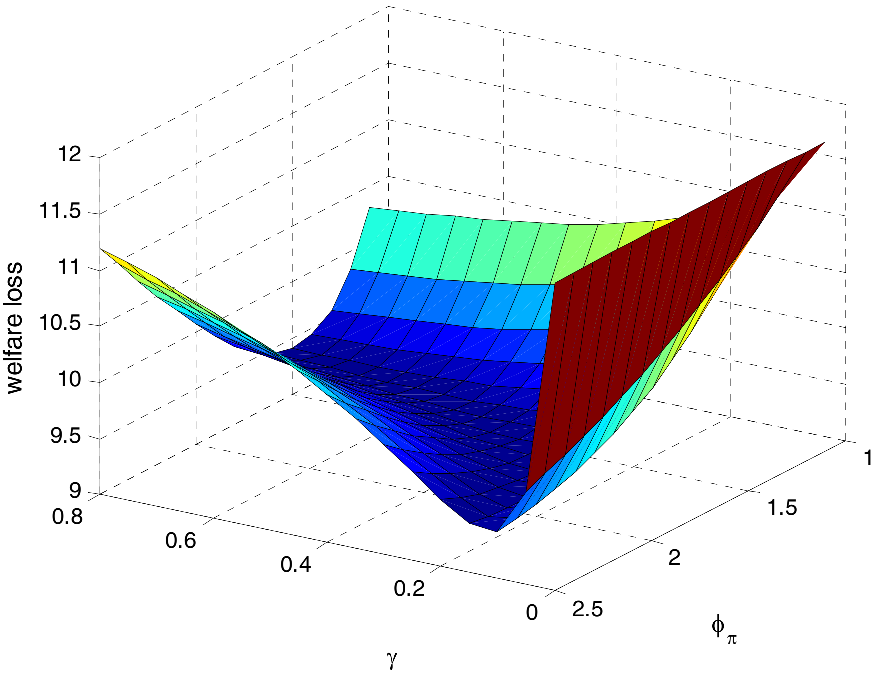

Figure 2: The welfare loss as a function of γ and ϕ_π for $\phi_x = 0$, $\rho = 0.75$, and $\sigma = 1.8$

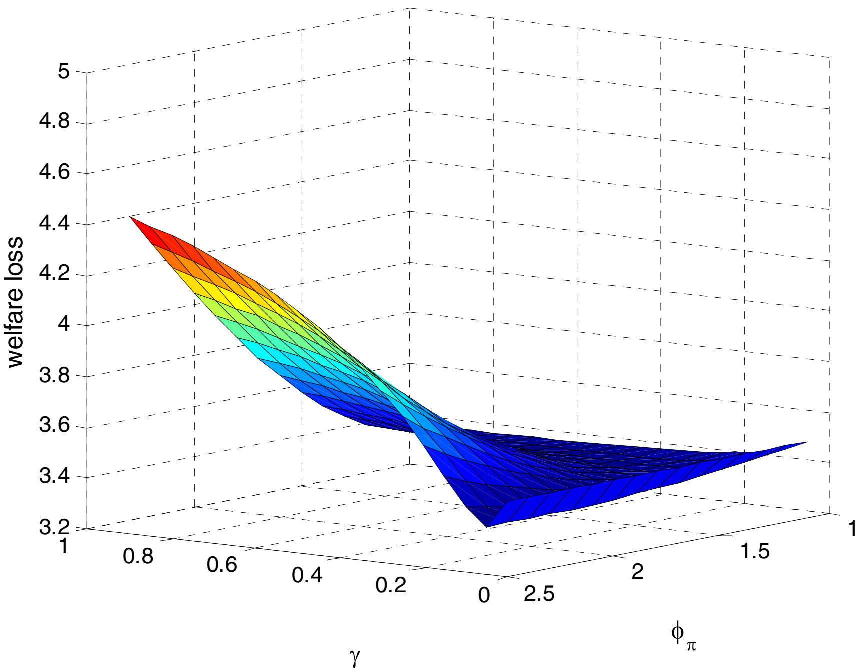

Figure 3: The welfare loss as a function of γ and ϕ_π for $\rho = 0.5$ and $\sigma = 1$

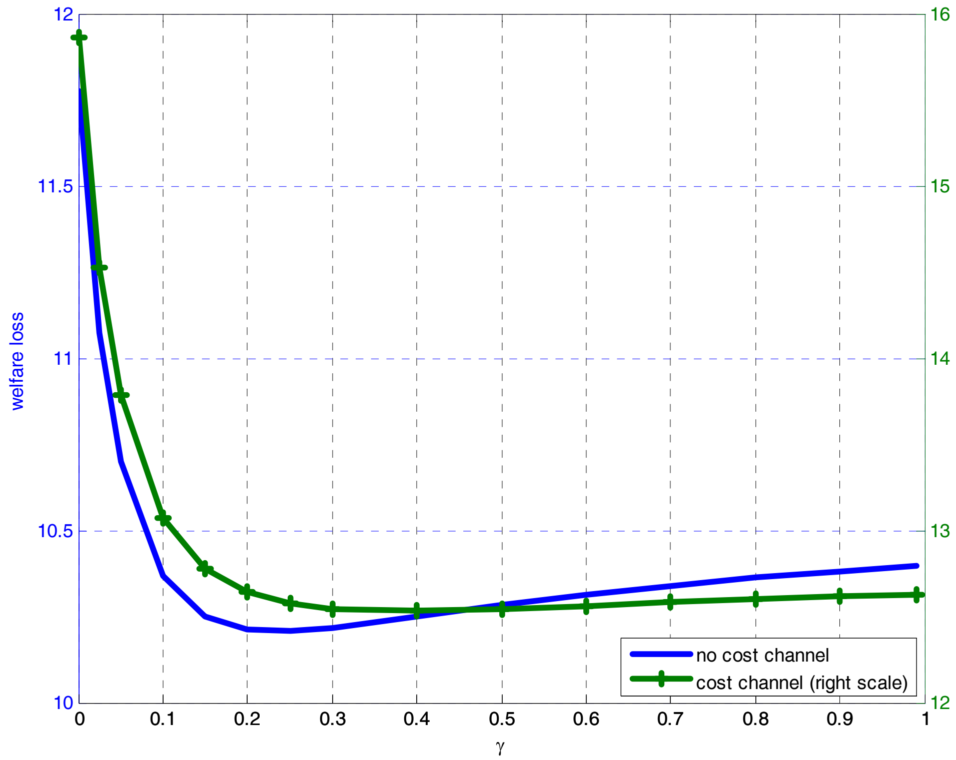

Figure 4: The welfare loss as a function of γ in the full model with persistent supply and demand shocks for $\rho = \varphi = 0.75$, $\phi_\pi = 1.8$ and $\phi_x = 0.3$. The size of the channel is $\phi = 0.8$.

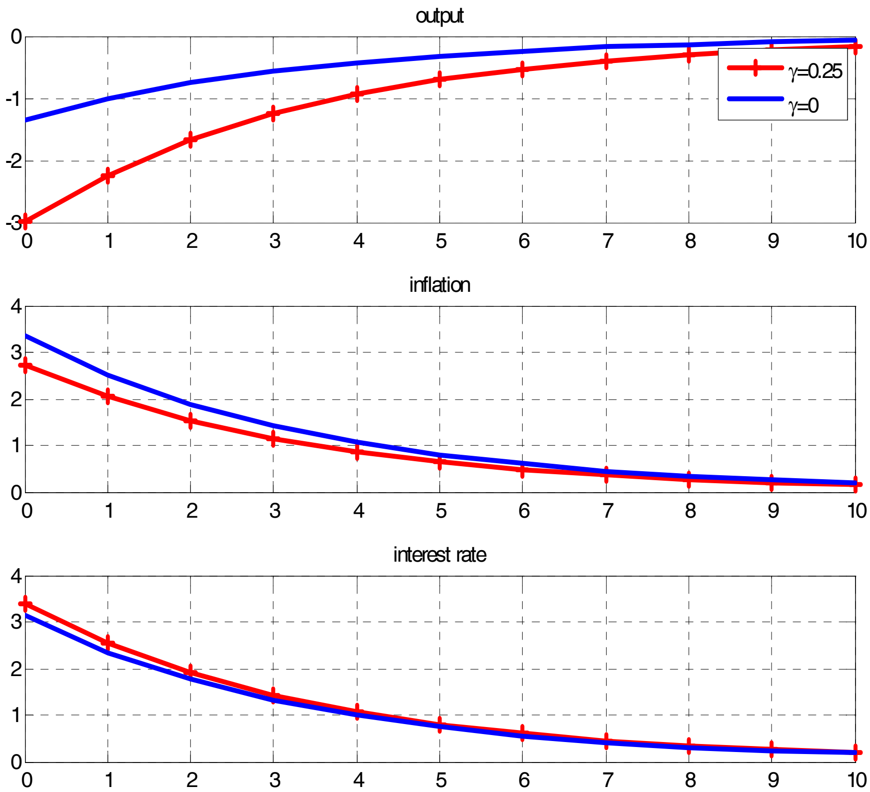

Figure 5: Impulse responses to a supply shock

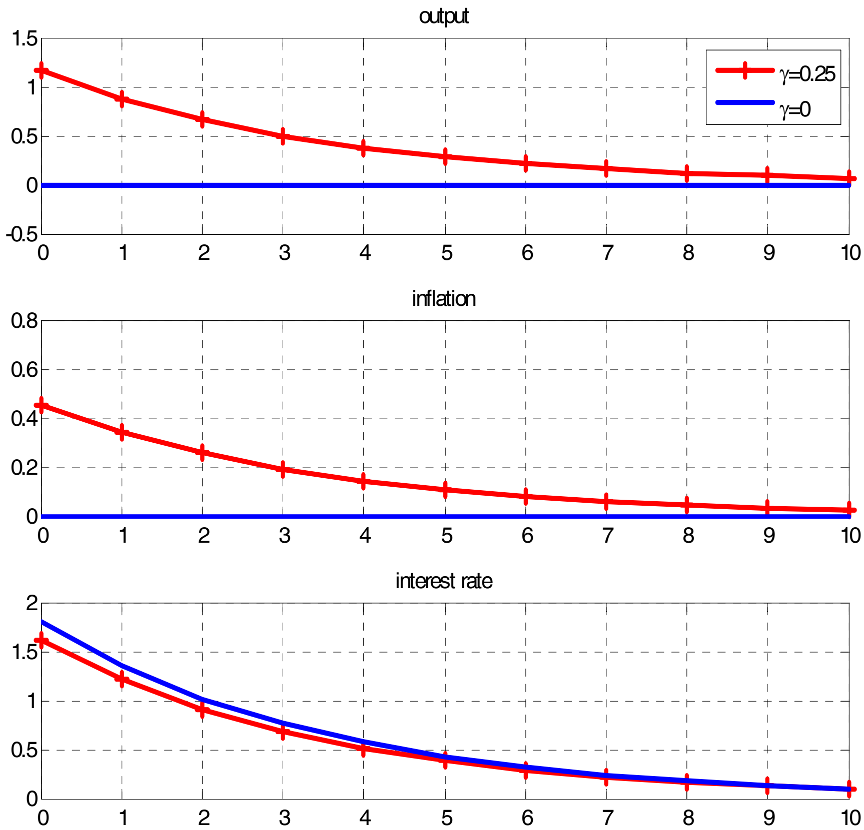

Figure 6: Impulse responses to a demand shock