Private News and Monetary Policy

Forward Guidance or (the Expected Virtue of Ignorance)*

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Abstract

When the central bank has information that can help the private sector predict the future better, should it communicate such information to the public? Not always. In a range of New Keynesian models, the central bank finds it optimal to commit to being secretive about news shocks. A lesson of our analysis for a central bank's communication strategy is that, while it is crucial that the central bank uses Odyssean forward guidance to communicate its policy action plan to the private sector, Delphic forward guidance that helps the private sector form more accurate forecasts of future shocks can be undesirable.

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1 Introduction

Central banks have been thought to possess private information about future economic conditions. Romer and Romer (2000) provide empirical evidence of asymmetric information between the central bank and private agents: "the Federal Reserve has considerable information about inflation beyond what is known to commercial forecasters.[1]" The presence of such superior information on the part of the central bank raises several questions. How should monetary policy be designed when the central bank has private information about future economic conditions? Does the central bank benefit from managing the private sector's expectations by utilizing such information?

This paper investigates whether central banks should reveal such *private news*, through communication or observable policy actions, by adding news about future economic conditions to an otherwise standard New Keynesian model in e.g. Woodford (2003). New Keynesian models are the best suited for our analysis because the central bank in the models can manage expectations of forward-looking agents by conveying its private news and because these models are widely used in central banks to guide policies. To focus on private news, we assume that contemporaneous shocks are perfectly observed by private agents. We also assume symmetric information among private agents in order to focus on information asymmetry between the central bank and the private sector.

Central banks' communication of their private news is of practical relevance. Campbell, Evans, Fisher, and Justiniano (2012) distinguish between *Delphic* forward guidance, which involves public statements about "a forecast of macroeconomic performance and likely or intended monetary policy actions based on the policymaker's potentially superior information about future macroeconomic fundamentals and its own policy goals", and *Odyssean* forward guidance that involves the policy-maker's commitment. They found empirical evidence that suggests that the forward guidance employed by the FOMC has "a substantial Delphic component". Although the importance of Odyssean forward guidance has been well established in the New Keynesian monetary policy literature, it is not yet established whether Delphic forward guidance is useful in New Keynesian models and this paper sheds light on this issue.

Our main theoretical result is that the central bank finds it optimal to commit to not revealing its superior information about news shocks at all, either directly through communication or indirectly through observable policy actions. In fact, the ex-ante loss for the central bank — the expected loss evaluated at time 0 before the central bank observes any private news — increases when the private sector becomes better-informed about future economic conditions, and an optimal commitment policy never utilizes the central bank's superior information. In other words, there exists an *expected virtue of ignorance*. This even holds even with simple New Keynesian models with endogenous state variables, where forward looking behavior becomes optimal for private agents. The environment we consider encapsulates the standard linear-quadratic one in which a central bank is benevolent and, therefore, information revelation can be harmful for social welfare.

[1] Fujiwara (2005) shows that central bank forecasts significantly affect those by professional forecasters.

The underlying mechanism is simple and operates through the forward-looking New Keynesian Phillips curve. Consider a simple New Keynesian model in which the central bank has preferences for stabilizing inflation and the output gap. When the private sector becomes better informed about future shocks, its inflation expectations vary with them and, from the ex-ante point of view, become more volatile. This increased volatility of inflation expectations acts as an additional source of disturbance in the New Keynesian Phillips curve, translates into higher variability of inflation and the output gap, and therefore is harmful to the central bank that aims to stabilize these variables.

Above-mentioned results are obtained in stylized models. It is not guaranteed whether *ignorance-is-bliss* about private news still holds even with a canonical DSGE model *a la* Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2003, 2007). Contrary to stylized models, there are multiple distortions and shocks so that the model can well explain the dynamics over business cycles. News about distortionary shocks may alleviate welfare loss stemming from existing inefficiencies through complex interactions among them. Advanced knowledge about efficient shocks can improve ex ante social welfare, as emphasized in a static framework by Angeletos and Pavan (2007) and in a dynamic setting by Fujiwara and Waki (2016). For this purpose, we simulate the canonical DSGE model with exogenous variation in private sector's information structure. Specifically, we assume that the private sector observes n-period ahead shocks and vary n. When all inefficiencies are shut down, social welfare increases (decreases) with n for news about efficient (distortionary) shocks. Welfare gain (loss) emerges with transparency about future efficient (distortionary) shocks. This result is consistent with findings in Angeletos and Pavan (2007) and Fujiwara and Waki (2016) . With all frictions and rigidities altogether, however, the relationship between social welfare and n becomes complex. More knowledge on future technological progress leads to lower ex ante welfare. It is hard to obtain such a simple policy prescription as ignorance-is-bliss with the canonical DSGE model. Welfare gains from revealing private news are, however, very small even if there exists any, and disclosure of news shocks is quite often detrimental to social welfare. Given these findings, no pressing need seems necessary for Delphic forward guidance, namely information revelation about future structural shocks.

It is also important to note that being secretive about news is optimal ex ante but may not be so ex post, i.e. after the central bank has observed particular realizations of news. Therefore, there is a time-inconsistency problem. Imagine that the economy is hit by a positive cost-push shock, which incentivizes sellers to set high prices with everything else being equal. Once the central bank observes a signal that a negative cost-push shock will likely hit in the future, it is tempted to convey that information to the private sector because it reduces the sellers' inflation expectations and discourages them from setting high prices. Time-inconsistency of commitment policy is well known in New Keynesian models, but our result is new in that it shows the possibility of time-inconsistency problem in the *communication* policy too.

This study therefore identifies an interesting property of a wide range of New Keynesian models. Precisely because price setters are forward-looking and there is a sticky-price friction, they set prices in response to news shocks. From the ex-ante point of view, inefficiency associated with price fluctuations is reduced by concealing news shocks from private agents. This implication provides a cautionary tale for central bank's communication strategies. The importance of *managing expectations* or forward guidance has been emphasized in the New Keynesian literature (Woodford, 2003), and also in real-world policy-making after many central banks in advanced economies reduced short-term nominal interest rates to the lowest possible level in response to the recent financial crisis.[2] Our result suggests that it may be even socially undesirable if the central bank, through communication, helps the private sector form more accurate forecast for future economic conditions. *Delphic* forward guidance based on private news can be harmful. The central bank should instead aim to conduct *Odyssean* forward guidance by communicating its state-contingent policy i.e. what it will do in response to these shocks after they materialize.

This paper is structured as follows. Section 2 provides the baseline setting and the main theorem about the undesirability of information revelation and discusses some extensions. In Section 3 we conduct numerical analysis. Section 4 concludes.

1.1 Related literature

Whether a central bank should disclose its private information to the public or not is not a new question, but our study is unique in its focus on the role of news shocks in a dynamic, forward-looking setting.

There has been a vast number of studies that focus on the role of the central bank's disclosure policy in coordinating actions of private agents who are heterogeneously informed about contemporaneous economic conditions, for example, Morris and Shin (2002) and Angeletos and Pavan (2007). They focus mainly on static settings.[3] Increased precision of a public signal can reduce welfare in these studies, but the reason is the coordination motives. In contrast, there is no dispersed information among private agents nor is there a need to coordinate their actions in our model, but information revelation is still detrimental to welfare.[4]

Stein (1989) and Moscarini (2007) are also important precursors of our research. In their model the central bank has private information about its policy goal but not about news shocks. By setting up a cheap-talk game (Crawford and Sobel, 1982), they show that, although full information revelation is desirable, only imperfect communication is possible in equilibrium, thereby providing a theory of imprecise announcement from policy-makers. Moscarini (2007) further shows that the more precise signal the central bank observes, the more information is revealed and the higher is the level of welfare. Our paper shows that their conclusion does not apply to news shocks and that information revelation is undesirable in the first place.

This paper is also related to the literature of news shocks, including Beaudry and Portier (2006, 2014), Jaimovich and Rebelo (2009), Fujiwara, Hirose, and Shintani

[2]Forward guidance is not necessarily a policy prescription under liquidity trap. Svensson (2014) states that "for many years, some central banks have used forward guidance as a natural part of their normal monetary policy." Its usefulness has been reported even in normal time.

[3]An exception is Hellwig (2005), who considers a dynamic general equilibrium model in which price setters are heterogeneously informed about the contemporaneous money supply.

[4]Svensson (2006) argues that the welfare-reducing property of increased precision of the public signal is rather limited to a small region of the parameter space in the model of Morris and Shin (2002). In our model, the undesirability of information revelation is a global property.

(2011) and Schmitt-Grohé and Uribe (2012). These papers largely focus on the role of news about future technology shocks in accounting for business cycle fluctuations and assume symmetric information between the central bank and the private sector. We depart from symmetric information to examine how the central bank should communicate superior information.

In this regard, Lorenzoni (2010) explores optimal monetary policy when aggregate fluctuations are driven by the private sector's uncertainty about the economy's fundamentals. Gaballo (2016) scrutinizes whether the central bank should release its information about future economic conditions in a flexible price OLG model. Walsh (2007) investigates whether there are gains from the announcement of the central bank's view on the state of the economy. Improvements in forecasts have ambiguous effects on the degree of transparency. Angeletos, Iovino, and La'O (2016) extend the theoretical framework in Angeletos and Pavan (2007) to the standard business-cycle models with or without nominal as well as real rigidities. They summarize how the gains from information revelation depends on the type of rigidities, the shock and the conduct of monetary policy. Contrary to our simple framework, however, information is dispersed across private agents in Lorenzoni (2010), Gaballo (2016), Walsh (2007), and Angeletos, Iovino, and La'O (2016). Our analysis is based on a standard model for monetary policy analysis where there is no information asymmetry among private agents, and therefore, the model is much simpler. Bianchi and Melosi (2014) compares transparency and no transparency when the monetary policy follows a Taylor rule whose coefficients change according to a Markov chain. Because they find welfare gains from transparency, we compare our paper with theirs in details in Section 2.7. Some numerical exercises in Wohltmann and Winkler (2008) are similar to ours. They, however, neither point out the intrinsic time-inconsistency problem nor distinguish between efficient and distortionary shocks.

It is crucial to differentiate efficient and inefficient shocks when considering optimal communication strategy. Angeletos and Pavan (2007) show that "if business cycles are driven primarily by shocks in markups or other distortions that induce a countercyclical efficiency gap, it is possible that providing markets with information that helps predict these shocks may reduce welfare." They make this point using a stylized, static model with dispersed information within the private sector, while we show that it is also possible for news shocks in the New Keynesian model without information asymmetry within the private sector. Using similar framework to this paper, Fujiwara and Waki (2016) investigate whether the fiscal authority should use forward guidance to reduce future policy uncertainty perceived by private agents. It is shown that "being transparent about future fiscal policy shocks that are distortionary can be detrimental to ex-ante social welfare, whereas conveying non-distortionary future policy shocks generally improves welfare." We will come back to this issue with numerical experiments in Section 3.3.

2 Theoretical results

Our baseline model is an extension of the simple New Keynesian model where the monetary policy trade-off is given by distortionary cost-push shock to the New Keynesian Phillips curve, and we assume that the central bank is better-informed about future cost-push shocks. The question we ask is, does the central bank find it beneficial to commit to making the private sector better-informed about future cost-push shocks? We find that the answer to this question is no, regardless of the way the central bank reveals information to the private sector. The optimal commitment policy never reveals or exploits superior information possessed by the central bank. This result holds even when the central bank possesses private news about the policy objective or the natural rate of interest with the binding zero lower bound of nominal interest rates.

In answering this question, we do not assume specific channels through which the private information of the central bank is conveyed to the private sector: the central bank may be able to send costless messages (as in e.g. Stein (1989) and Moscarini (2007)), or the private sector may infer the central bank's private information from central bank actions that depend on its private information (as in e.g. Cukierman and Meltzer (1986)).

Proofs are simple and based on Jensen's inequality, exploiting the linearity of the New Keynesian Phillips curve and the strict convexity of the loss function.[5] Therefore, the result of the desirability of secrecy about future fundamental shocks holds true in more general, linearized DSGE models without endogenous state variables.

2.1 Environment

We employ the standard analytical framework for optimal monetary policy as in Woodford (2003), Galí (2008) or Walsh (2010).

Stochastic processes for inflation $\{\pi_t\}_{t=0}^{\infty}$ and the output gap $\{x_t\}_{t=0}^{\infty}$ have to satisfy the aggregate supply relationship, or the New Keynesian Phillips curve:

$$\pi_t = \kappa x_t + \beta \mathbb{E}_t^P \pi_{t+1} + u_t, \tag{1}$$

where $\mathbb{E}_t^P$ denotes the expectation conditional on the information available to the private sector in period t, and u_t is a cost-push (mark-up) shock. The cost-push shock is distortionary, and creates the time-varying wedge between actual and efficient allocations.[6]

The central bank's ex-ante loss function is given by

$$\mathbb{E}[\sum_{t=0}^{\infty} \delta^t L(\pi_t, x_t)], \tag{2}$$

where L is a strictly convex, momentary loss function and $\delta \in (0, 1)$ is the discount factor. This loss function represents the idea that the central bank pursues some kind of "dual mandate" — the central bank benefits from stabilizing inflation and the output gap. This specification nests the standard linear-quadratic model with a benevolent central bank that minimizes the loss function which obtains as the second-order

[5] Linearity is stronger than we need. A sufficient condition for our result is that the constraint set of the Ramsey problem is convex.

[6] When instead non-distortionary shocks hit the economy, any distortion caused by such shocks can be eliminated by appropriate and instantaneous responses by the central bank.

approximation of the representative household's utility in a Calvo-type sticky-price model:

$$\mathbb{E}\left[\sum_{t=0}^{\infty}\beta^t\frac{1}{2}\left(\pi_t^2+\frac{\kappa}{\epsilon}x_t^2\right)\right], \tag{3}$$

where ϵ denotes the CES parameter for intermediate goods.[7]

For now, we assume that the only fundamental shock that hits the economy is the cost-push shock, $\{u_t\}_{t=0}^{\infty}$. We extend the model to incorporate other shocks in Section 2.6. Because our theoretical results do not require that the cost-push shock follows a particular shock process such as AR(1), we leave its process unspecified.[8] The private sector observes at least contemporaneous cost-push shocks, and thus is originally (i.e. before any information is revealed from the central bank) endowed with a filtration $\mathcal{F}=\{\mathcal{F}_t\}_{t=0}^{\infty}$ such that $\{u_t\}_{t=0}^{\infty}$ is adapted to it.[9] We do not rule out that the private sector also observes informative signals about future cost-push shocks. The central bank is endowed with a filtration that is finer than $\mathcal{F}$, which implies that the central bank has more information than the private sector, but its superior information is only about future shocks.

Note that the expectation in (2) is the unconditional one and thus the loss is evaluated before any shocks realize and before either the private sector or the central bank receives any information. In standard symmetric information cases, it is more common to use the expectation conditional on time-0 information, i.e. after the time-0 shocks have realized. All our theoretical results hold even if we replace the unconditional expectation with the conditional one given $\mathcal{F}_0$. Such a specification is justified under the assumption that the central bank evaluates its loss after the private sector and the central bank receive the common time-0 information but before the central bank receives any private news.

2.2 An illustrative, two-period model

We first use a stripped-down two-period model to illustrate that the central bank finds it optimal to commit to being secretive about private news. To focus on the effects of information provision, we eliminate the output gap by setting $\kappa=0$ in (1). Therefore, inflation is solely driven by exogenous shocks and the private sector's expectation about a future shock. Assuming $\beta=1$, the New Keynesian Phillips curve is given by $\pi_0=\mathbb{E}_0^P\pi_1+u_0$ and $\pi_1=u_1$. We assume that u_0 and u_1 have finite means and variances. The private sector observes u_0 before forming inflation expectations. The central bank is benevolent and minimizes the loss (3) with $(\beta,\kappa)=(1,0)$: $\mathbb{E}\left[\pi_0^2+\pi_1^2\right]/2$.

Substituting the New Keynesian Phillips curve into the loss function, the ex-ante

[7]This approximation obtains when the steady-state distortion associated with monopolistic competition is offset by a tax or subsidy, with x denoting the welfare relevant output gap.

[8]The only restriction is that the loss minimization problem which we introduce shortly must be well-defined. This rules out e.g. a shock process that grows too quickly.

[9]This assumption is not restrictive. In a micro-founded model, u_t is a shock to the firm's profit function (or more specifically to the elasticity of substitution). If we instead assume that price setters do not know the shock when setting prices, we should have $\mathbb{E}[u_t|\mathcal{F}_t]$ in place of u_t in the New Keynesian Phillips curve. Then the process $\{\mathbb{E}[u_t|\mathcal{F}_t]\}_{t=0}^{\infty}$ is $\mathcal{F}$-adapted.

loss can be written as

$$\frac{1}{2}\mathbb{E}\left[\{\mathbb{E}_0^P u_1 + u_0\}^2 + u_1^2\right] = \frac{1}{2}\mathbb{E}\left[\{\mathbb{E}_0^P u_1 + u_0\}^2\right] + \frac{1}{2}\mathbb{E}u_1^2.$$

Clearly, information revelation affects the first term on the right-hand side through the private sector's expectations of u_1. How does the welfare loss change when the private sector is made better-informed about u_1? Let $\mathbb{E}^O u_1$ be the conditional expectation of u_1 given the information with which the private sector is *originally* endowed, and $\mathbb{E}^I u_1$ be the conditional expectation given some *improved* information set of the private sector.

Perhaps surprisingly, the ex-ante loss is higher when the private sector is better-informed about u_1. To see this, note that

$$\mathbb{E}^I u_1 + u_0 = \underbrace{\left(\mathbb{E}^O u_1 + u_0\right)}_{\text{“original” term}} + \underbrace{\left(\mathbb{E}_0^I u_1 - \mathbb{E}^O u_1\right)}_{\text{“updating” term}} \tag{4}$$

and that the original and updating terms are orthogonal given the original information set, i.e. $\mathbb{E}^O\left[(\mathbb{E}^O u_1 + u_0)(\mathbb{E}^I u_1 - \mathbb{E}^O u_1)\right] = 0$. The orthogonality obtains because u_0 is in the original information set and because the law of iterated expectations implies $\mathbb{E}^O\left[\mathbb{E}^I u_1 - \mathbb{E}^O u_1\right] = 0$. Therefore,

$$\begin{aligned}
\mathbb{E}\left[\{\mathbb{E}^I u_1 + u_0\}^2\right] &= \mathbb{E}\left[\left\{(\mathbb{E}^O u_1 + u_0) + (\mathbb{E}^I u_1 - \mathbb{E}^O u_1)\right\}^2\right] \\
&= \mathbb{E}\left[(\mathbb{E}^O u_1 + u_0)^2\right] + \underbrace{\mathbb{E}\left[(\mathbb{E}^I u_1 - \mathbb{E}^O u_1)^2\right]}_{\geq 0} \\
&\quad + 2\underbrace{\mathbb{E}\left[\mathbb{E}^O\left\{(\mathbb{E}^O u_1 + u_0)(\mathbb{E}^I u_1 - \mathbb{E}^O u_1)\right\}\right]}_{= 0 \text{ (law of iterated expectations)}} \\
&\geq \mathbb{E}\left[(\mathbb{E}^O u_1 + u_0)^2\right].
\end{aligned}$$

The above inequality holds strictly if and only if $\mathbb{E}^I u_1 = \mathbb{E}^O u_1$ almost surely, i.e., the additional information does not improve inflation expectations meaningfully.

Therefore, the ex-ante loss strictly increases if the private sector becomes able to forecast future inflation more accurately with positive probability, i.e. $\mathbb{E}\left[(\mathbb{E}^I u_1 - \mathbb{E}^O u_1)^2\right] > 0$. This implies that the central bank wants to commit to not revealing any information about the future shock, u_1. The mechanism at work is quite simple. Future inflation varies with a future shock. When the private sector becomes better-informed about a future shock, its inflation expectations are updated, move with previously unavailable information, and thus become more volatile. The increased volatility of inflation expectations translates into higher variability of inflation through the New Keynesian Phillips curve. As we show in the next section, this mechanism is also at work in our general setting, in which the output gap is a choice variable of the central bank.

2.3 Committing to secrecy is ex-ante optimal in a general model

Now we turn to the general setting to demonstrate that information revelation is undesirable.

A benchmark is an optimal commitment policy when the private sector's filtration is fixed $\mathcal{F}$ and the central bank chooses inflation and the output gap processes that are $\mathcal{F}$-adapted. We say that $\{(\pi_t^*, x_t^*)\}_{t=0}^{\infty}$ is an *optimal secretive commitment policy* if it solves

$$\min_{\{(\pi_t, x_t)\}_{t=0}^{\infty}} \mathbb{E}[\sum_{t=0}^{\infty} \delta^t L(\pi_t, x_t)] \tag{5}$$

subject to

$$\pi_t = \kappa x_t + \beta \mathbb{E}[\pi_{t+1} | \mathcal{F}_t] + u_t, \tag{6}$$

and the constraint that

$$\text{the process } \{(\pi_t, x_t)\}_{t=0}^{\infty} \text{ is adapted to } \mathcal{F}. \tag{7}$$

Condition (7) guarantees that the private sector is unable to obtain more information than contained in $\mathcal{F}$ by observing the central bank's actions. Because of the strict convexity of the objective function and the linearity of the constraint, the optimal secretive commitment policy is unique (almost everywhere) if it exists. Hereafter, we assume that an optimal secretive commitment policy exists.

Our first result is that, taking the private sector's filtration as given, the central bank wants to commit to not using information that the private sector does not possess, i.e. condition (7) in the above problem does not bind.

Lemma 1 *Consider the above commitment problem with condition (7) being replaced by the condition that the process $\{(\pi_t, x_t)\}_{t=0}^{\infty}$ is adapted to a finer filtration $\mathcal{G}$ such that $\mathcal{F} \subset \mathcal{G}$. Then it has an $\mathcal{F}$-adapted solution.*

Proof is in Appendix A.1. Therefore, if gains from information revelation exist, they must arise from the improvement of the private sector's information.

Potentially, the effects of information revelation might depend crucially on the way we model information dissemination. Can the central bank use direct communication? If it can, is all the information it conveys verifiable? Do private agents infer true information from the central bank's actions? If so, do they observe the central bank's actions with noise? Surprisingly, information revelation always increases the central bank's ex-ante loss in our setting, regardless of how we specify the information transmission channel.

The irrelevance of the details of the information transmission mechanism follows from our second result: when the New Keynesian Phillips curve is satisfied with a finer filtration of the private sector, the central bank's loss is larger than that of the optimal secretive commitment policy. In the following, Lemma 2 establishes a weak inequality and Proposition 1 identifies a sufficient condition for a strict inequality.

Lemma 2 *Let $\mathcal{G} = \{\mathcal{G}_t\}_{t=0}^{\infty}$ be a filtration such that $\mathcal{F}_t \subset \mathcal{G}_t$ for all t. Then, for any process $\{(\pi_t, x_t)\}_{t=0}^{\infty}$ that is $\mathcal{G}$-adapted and satisfies*

$$\pi_t = \kappa x_t + \beta \mathbb{E}[\pi_{t+1} | \mathcal{G}_t] + u_t, \quad \forall t, \tag{8}$$

there is a process $\{(\tilde{\pi}_t, \tilde{x}_t)\}_{t=0}^{\infty}$ such that (i) it is adapted to $\mathcal{F}$, (ii) it satisfies

$$\tilde{\pi}_t = \kappa \tilde{x}_t + \beta \mathbb{E}[\tilde{\pi}_{t+1}|\mathcal{F}_t] + u_t, \quad \forall t, \tag{9}$$

and (iii)

$$\mathbb{E}[L(\pi_t, x_t)] \geq \mathbb{E}[L(\tilde{\pi}_t, \tilde{x}_t)], \quad \forall t. \tag{10}$$

Equality holds in (10) if and only if $(\pi_t, x_t) = (\tilde{\pi}_t, \tilde{x}_t)$ almost everywhere for all t.

Proof. Proof is by construction. Fix any $\{(\pi_t, x_t)\}_{t=0}^{\infty}$ that is adapted to $\mathcal{G}$ and satisfies (8). Let

$$(\tilde{\pi}_t, \tilde{x}_t) = (\mathbb{E}[\pi_t|\mathcal{F}_t], \mathbb{E}[x_t|\mathcal{F}_t]).$$

Then $\{(\tilde{\pi}_t, \tilde{x}_t)\}_{t=0}^{\infty}$ is adapted to $\mathcal{F}_t$. Taking the conditional expectation of (8) given $\mathcal{F}_t$, we obtain

$$\tilde{\pi}_t = \kappa \tilde{x}_t + \beta \mathbb{E}[\pi_{t+1}|\mathcal{F}_t] + u_t.$$

Because $\mathbb{E}[\pi_{t+1}|\mathcal{F}_t] = \mathbb{E}\left[\mathbb{E}[\pi_{t+1}|\mathcal{G}_t]|\mathcal{F}_t\right] = \mathbb{E}[\tilde{\pi}_{t+1}|\mathcal{F}_t]$, this implies (9).

Jensen's inequality implies

$$\mathbb{E}[L(\pi_t, x_t)] = \mathbb{E}\left[\mathbb{E}[L(\pi_t, x_t)|\mathcal{F}_t]\right] \geq \mathbb{E}\left[L(\mathbb{E}[\pi_t|\mathcal{F}_t], \mathbb{E}[x_t|\mathcal{F}_t])\right] = \mathbb{E}[L(\tilde{\pi}_t, \tilde{x}_t)],$$

for all t, and it follows that, because L is strictly convex, equality holds for all t if and only if $\{(\pi_t, x_t)\}_{t=0}^{\infty} = \{(\tilde{\pi}_t, \tilde{x}_t)\}_{t=0}^{\infty}$ almost everywhere. ■

An implication of Lemma 2 is that endowing the private sector with finer filtration never reduces the central bank's loss for *any* discount factor $\delta \in (0, 1)$ because (10) holds period by period. The reason is that fluctuations in a stochastic process adapted to a finer filtration can be, roughly speaking, reduced by taking the conditional expectation using a coarser filtration, and that the strictly convex loss function favors processes that fluctuate less. From the central bank's point of view, it is at best pointless to help the private sector learn more information.

We now identify a condition under which the central bank's loss under information revelation is strictly higher than that of the optimal secretive commitment policy.

Proposition 1 *Let $\mathcal{G} = \{\mathcal{G}_t\}_{t=0}^{\infty}$ be a filtration such that $\mathcal{F}_t \subset \mathcal{G}_t$ for all t. If the optimal secretive commitment policy satisfies*

$$\textit{Probability of } \left\{\mathbb{E}[\pi^*_{t+1}|\mathcal{G}_t] \neq \mathbb{E}[\pi^*_{t+1}|\mathcal{F}_t] \textit{ for some } t\right\} > 0, \tag{11}$$

then the loss from $\{(\pi^*_t, x^*_t)\}_{t=0}^{\infty}$ is strictly smaller than that from any $\mathcal{G}$-adapted processes $\{(\pi_t, x_t)\}_{t=0}^{\infty}$ that satisfy the New Keynesian Phillips curve in (8).

Proof is in Appendix A.1. When condition (11) holds, the optimal secretive commitment policy violates the New Keynesian Phillips curve in (8) with positive probability. Therefore a process that satisfies (8) cannot be equal to the optimal secretive policy almost everywhere, and its loss must be strictly higher than that of the optimal secretive policy.

Condition (11) is not strong. Suppose that the private sector only observes the contemporaneous u's, that the central bank observes future u's, and that the central bank is able to communicate credibly that information to the private sector. Let $\mathcal{G}$ be the filtration for the private sector after such communication. Then u_{t+1} is not $\mathcal{F}_t$-measurable but is $\mathcal{G}_t$-measurable. When the loss function is quadratic, the optimal secretive commitment policy linearly depends on a contemporaneous shock. This naturally implies $\mathbb{E}[\pi^*_{t+1}|\mathcal{G}_t] \neq \mathbb{E}[\pi^*_{t+1}|\mathcal{F}_t]$ because the left hand side depends on u_{t+1} but the right hand side does not.[10] Moreover, when condition (11) is not satisfied, the private sector is effectively not learning anything useful — new information it obtains doesn't help to forecast future inflation (under the optimal secretive commitment policy) any better.

2.3.1 Intuition

To obtain some intuition, let us assume that the central bank is benevolent and minimizes the loss in (3). Then the central bank benefits from stabilizing inflation and the output gap around zero.

As in Section 2.2, we can rewrite (8) as

$$\pi_t - \kappa x_t = \underbrace{\{\beta \mathbb{E}[\pi_{t+1}|\mathcal{F}_t] + u_t\}}_{\text{“original” term}} + \underbrace{\beta\{\mathbb{E}[\pi_{t+1}|\mathcal{G}_t] - \mathbb{E}[\pi_{t+1}|\mathcal{F}_t]\}}_{\text{“updating” term}}. \tag{12}$$

Observe that the benevolent central bank benefits from stabilizing the right-hand side around zero, because it can then stabilize inflation and the output gap around zero. The right-hand side consists of two terms, the "original" term and the "updating" term. The former collects the terms that are present even when the private sector's information is given by $\mathcal{F}$, and the latter captures how inflation expectations are updated when the information set is changed from $\mathcal{F}_t$ to $\mathcal{G}_t$. Therefore, taking the stochastic process $\{(\pi_t, x_t)\}_{t=0}^{\infty}$ as given, the updating term represents the effects of information revelation.

The decomposition in (12) implies that the presence of the updating term increases the variability of the right-hand side, and hence that the social loss increases with information revelation. To see this, note that the original term is $\mathcal{F}$-adapted because cost-push shocks are $\mathcal{F}$-adapted, whereas the updating term is orthogonal to $\mathcal{F}_t$. The variance of the right-hand side of (12) is thus the sum of the variances of the original and the updating terms, which is minimized when $\mathcal{F}_t = \mathcal{G}_t$. Roughly speaking, if $\mathcal{F}_t \subset \mathcal{G}_t$, the updating term effectively acts as an additional orthogonal disturbance term in the New Keynesian Phillips curve, which exacerbates the inflation-output tradeoff the central bank faces.

Figures 1 and 2 illustrate the point graphically. On the horizontal axis is $\pi_t - \kappa x_t$, which equals the sum of the discounted expected inflation and the mark-up shock, $\beta\mathbb{E}^P[\pi_{t+1}] + u_t$. We also draw the loss function L as a symmetric function around its minimizer. Figure 1 illustrates a situation where the private sector is endowed with $\mathcal{F}$ and the term $\beta\mathbb{E}[\pi_{t+1}|\mathcal{F}_t] + u_t$ can take on two values that are symmetric around the minimizer of L, with equal probability. Then it is straightforward that the ex-ante loss is at the level indicated in the figure. In Figure 2, the private sector is better informed, and is endowed with $\mathcal{G}$ with $\mathcal{F} \subset \mathcal{G}$. How is $\beta\mathbb{E}[\pi_{t+1}|\mathcal{G}_t] + u_t$ distributed?

[10] More generally, when $\mathcal{F}_{t+1} \subset \mathcal{G}_t$ for all t, we have $\mathbb{E}[\pi^*_{t+1}|\mathcal{G}_t] = \pi^*_{t+1}$, which does not equal $\mathbb{E}[\pi^*_{t+1}|\mathcal{F}_t]$ unless π^*_{t+1} is also $\mathcal{F}_t$-measurable.

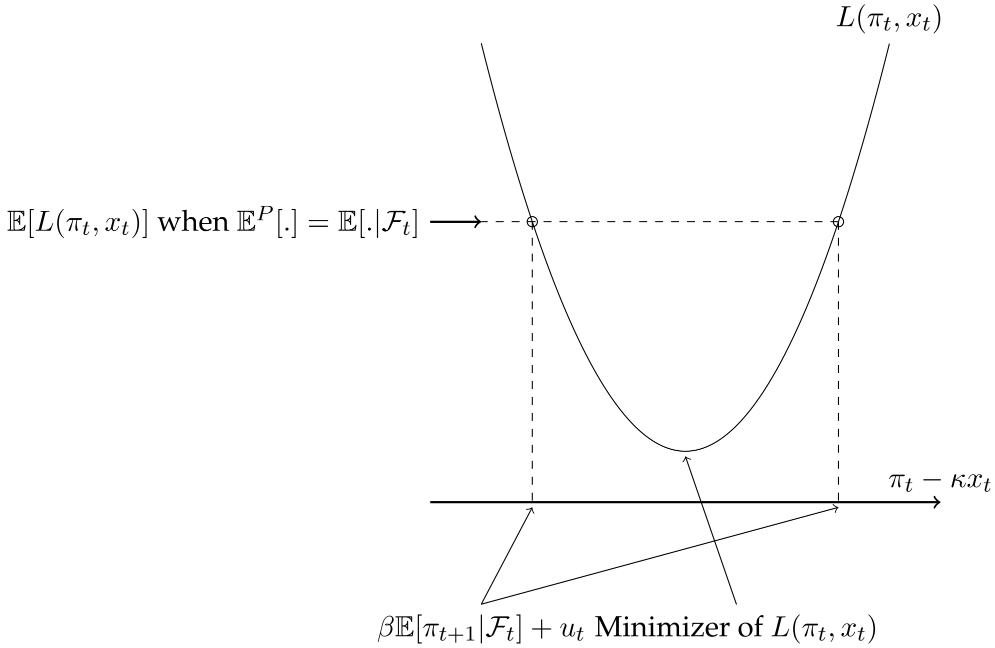

Figure 1: The inflation vs. the output gap trade-off when the private sector is uninformed

Because its conditional mean given $\mathcal{F}_t$ equals $\beta\mathbb{E}[\pi_{t+1}|\mathcal{F}_t] + u_t$, it must be distributed around $\beta\mathbb{E}[\pi_{t+1}|\mathcal{F}_t] + u_t$. Figure 2 depicts such a situation, where $\beta\mathbb{E}[\pi_{t+1}|\mathcal{G}_t] + u_t$ is distributed symmetrically around $\beta\mathbb{E}[\pi_{t+1}|\mathcal{F}_t] + u_t$. The ex-ante loss is larger when the private sector is better informed than when it is less informed. This implies that the distribution of $\pi_t - \kappa x_t$ when the private sector is better informed is a mean-preserving spread of the distribution when the private sector is less informed. Because the loss function is convex, a mean-preserving spread is undesirable.

2.3.2 Where do the gains from better information go?

If the private sector obtains more information, it may appear that the private agents — both the household and goods producers — must not lose anything because they can still choose not to use additional information. This assertion is incorrect because the price setters' incentives are not perfectly aligned with the household's (i.e. social welfare) or with the central bank's. Price setters in a Calvo model do not internalize the inefficiency associated with price dispersion and their profit-maximizing responses to news shocks increase the expected inefficiency.

To see this, consider a benevolent central bank that minimizes the loss (3). Ideally, it wants to conduct policy so that both inflation and the output gap are always zero. For any given process of inflation and any information the household has, the central bank can indeed conduct policy so that the output gap is always zero.[11] However, the price setters have incentives to deviate from price stability even if the output gap is fully stabilized at zero, when a mark-up shock and inflation expectations deviate

[11] The central bank can do this by choosing the process of the nominal interest rates so that the real rates are always equal to the natural rates.

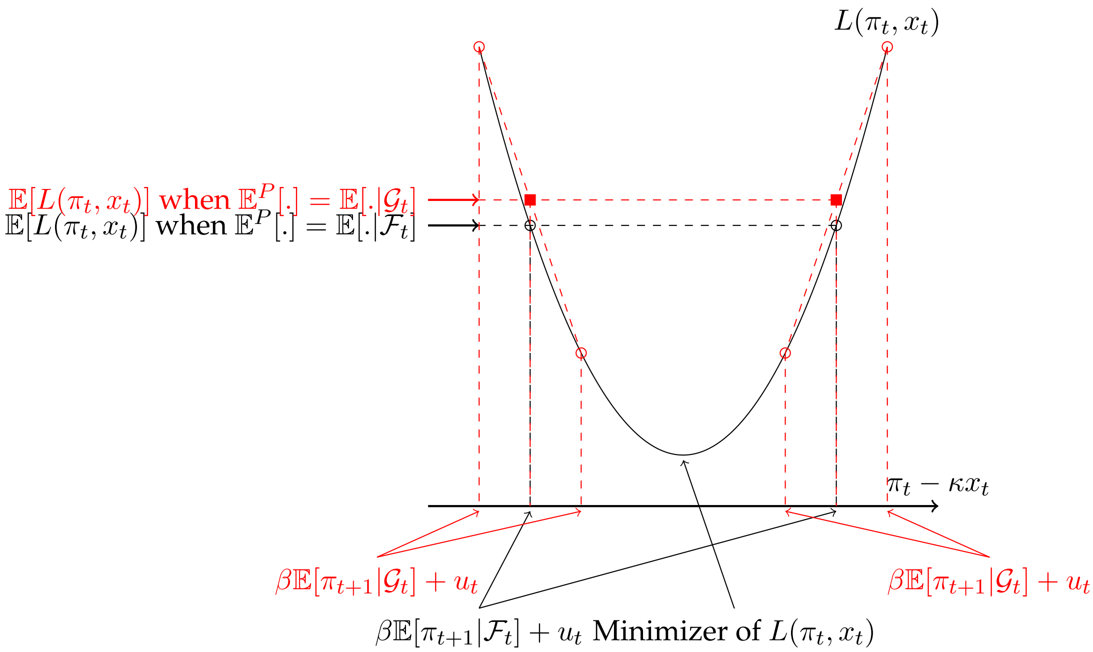

Figure 2: The inflation vs. the output gap trade-off when the private sector is better-informed

from zero. In this sense, the price setters' incentives are not aligned with the social objective.[12] When the price setters have more information about future shocks, they tailor their current prices based on additional information and achieve higher profits.[13] However, as a result, prices then tend to move with future shocks and social welfare decreases.[14]

2.4 Time-inconsistency of secrecy

Importantly, the optimal secretive commitment policy is time-inconsistent for two reasons. One reason is standard in the New Keynesian literature — the optimal commitment policy depends on history which the optimal discretionary policy ignores. The other reason is unique to the present setting — commitment to secrecy is by itself time-inconsistent.

To see this, consider the two-period model in Section 2.2. For simplicity, we make additional assumptions. First, u_0 and u_1 are i.i.d. and have a symmetric distribution around 0. Second, the private sector is originally completely uninformed and, therefore, $\mathbb{E}[\pi_1|\mathcal{F}_0] = 0$. Third, the central bank observes u_1 perfectly at time 0. As shown

[12]This is the reason why the optimal commitment policy problem has to take the New Keynesian Phillips curve, which summarizes the price setters' incentives, as a constraint.

[13]The price setters take certain prices as given, e.g. the aggregate nominal price, the real wage, etc. Taking these prices as given, the profits of the price setters weakly increase with information they possess. Because these objects change in an equilibrium when all firms change their prices using additional information, the price setters' equilibrium profits may not increase.

[14]In other words, it is crucial that there are shocks that generate inefficient fluctuations. This is related to the findings in Angeletos and Pavan (2007) and Fujiwara and Waki (2016).

in Section 2.2, the central bank finds it optimal to commit to secrecy from the ex-ante point of view, i.e. before observing private news about u_1.

Now consider the ex-post welfare loss, evaluated *after* the central bank observes its private news, when $u_0 \neq 0$ and $u_1 = -u_0$. When the private sector is left completely uninformed, the conditional loss given the central bank's information is

$$\frac{1}{2}(\pi_0^2 + \pi_1^2) = \frac{1}{2}\{(\mathbb{E}u_1 + u_0)^2 + u_1^2\} = \frac{1}{2}(u_0^2 + u_1^2).$$

When the private sector perfectly learns u_1, the conditional loss is

$$\frac{1}{2}(\pi_0^2 + \pi_1^2) = \frac{1}{2}\{(u_1 + u_0)^2 + u_1^2\} = \frac{1}{2}u_1^2 < \frac{1}{2}(u_0^2 + u_1^2).$$

Hence, the central bank may benefit ex-post from credibly revealing its superior information. This gives rise to a time-inconsistency problem.

2.5 Undesirability of information revelation without commitment

Can information revelation be beneficial when the central bank is unable to commit to a state-contingent action plan but is able to commit to information revelation policy? To answer this question, we first define an equilibrium under discretion *for a given information structure*. Although it is conventional to focus on a Markov perfect equilibrium when considering discretionary policy, we do not require a Markov property here.

Definition 1 *Let $\mathcal{G} = \{\mathcal{G}_t\}_{t=0}^{\infty}$ be a filtration such that $\{u_t\}_{t=0}^{\infty}$ is $\mathcal{G}$-adapted. A $\mathcal{G}$-adapted stochastic process $\{(\pi_t, x_t)\}_{t=0}^{\infty}$ is a $\mathcal{G}$-discretionary policy equilibrium if and only if, for all t, (π_t, x_t) solves $\min_{(\pi,x)} L(\pi, x)$ subject to $\pi = \kappa x + \beta \mathbb{E}[\pi_{t+1}|\mathcal{G}_t] + u_t$.*

Because L is continuous and strictly convex, a $\mathcal{G}$-discretionary policy equilibrium is $\mathcal{G}$-adapted. The next proposition shows that, when the loss function is quadratic, for any $\mathcal{G}$-discretionary policy equilibrium we can find an $\mathcal{F}$-discretionary policy equilibrium that achieves (weakly) lower ex-ante loss. In this sense, information revelation is undesirable even without commitment.

Proposition 2 *Suppose that L is quadratic: $L(\pi, x) = (\pi^2 + bx^2)/2$ with $b > 0$. Let $\mathcal{G} = \{\mathcal{G}_t\}_{t=0}^{\infty}$ and be a filtration such that $\mathcal{F}_t \subset \mathcal{G}_t$ for all t. Then the following holds.*

1. *For any $\mathcal{G}$-discretionary policy equilibrium $\{(\pi_t, x_t)\}_{t=0}^{\infty}$, there exists an $\mathcal{F}$-discretionary policy equilibrium $\{(\tilde{\pi}_t, \tilde{x}_t)\}_{t=0}^{\infty}$ such that $\mathbb{E}[L(\pi_t, x_t)|\mathcal{F}_t] \geq \mathbb{E}[L(\tilde{\pi}_t, \tilde{x}_t)|\mathcal{F}_t]$ (hence $\mathbb{E}[L(\pi_t, x_t)] \geq \mathbb{E}[L(\tilde{\pi}_t, \tilde{x}_t)]$) for all t. Equality holds if and only if $\{(\pi_t, x_t)\}_{t=0}^{\infty} = \{(\tilde{\pi}_t, \tilde{x}_t)\}_{t=0}^{\infty}$ almost everywhere.*

2. *Let $\{(\pi_t^*, x_t^*)\}_{t=0}^{\infty}$ be the best $\mathcal{F}$-discretionary policy equilibrium, i.e. it minimizes the loss among all $\mathcal{F}$-discretionary policy equilibria. If condition (11) holds, then the best $\mathcal{G}$-discretionary policy equilibrium yields strictly larger minimized loss than $\{(\pi_t^*, x_t^*)\}_{t=0}^{\infty}$.*

When is it reasonable to assume that the central bank can commit to secrecy but cannot commit to a state-contingent policy? This assumption can be justified if, every period, the central bank chooses whether to observe a piece of private news or not. This is a situation in which private news can be observed by the central bank only after it does some "research." In such an environment, the central bank is effectively able to commit to secrecy by choosing not to do research, even if it is unable to commit to future policy actions.

Even when the central bank is unable to commit to not observing the private news, if the private news is not verifiable, no-revelation can be an equilibrium outcome. One way to set up a game with communication is to introduce a cheap-talk stage in which the central bank sends a message to the private sector at the beginning of each period. Because in cheap-talk games there is always a "babbling" equilibrium, in which no information is transmitted, the best $\mathcal{F}$-discretionary policy equilibrium we analyzed above must also be an equilibrium in such a game with cheap talk, and therefore it remains the best equilibrium.[15] In contrast, if the private news is verifiable, then the central bank is tempted to reveal it when the news is good and, as a result, the above $\mathcal{F}$-discretionary policy equilibrium will not be reached.

2.6 Extensions

Commitment to secrecy is optimal even if private news is about shocks other than cost-push shocks. We now consider two cases: one in which private news is about the natural rate of interest with the binding zero lower bound of nominal interest rates and another in which it is about the policy objective.

2.6.1 A New Keynesian model with the zero lower bound

Consider a model along the lines of Eggertsson and Woodford (2003) and Adam and Billi (2006), in which the zero lower bound on nominal interest rates can bind when a large, negative shock to the natural rate of interest hits the economy. Due to the non-negativity constraint on nominal interest rates,

$$i_t \geq 0, \tag{13}$$

we have to explicitly take into account the dynamic IS equation:

$$x_t = \mathbb{E}_t^P x_{t+1} - \frac{1}{\sigma}\{i_t - \mathbb{E}_t^P \pi_{t+1} - r_t^n\}. \tag{14}$$

In addition to the cost-push shock $\{u_t\}_{t=0}^{\infty}$, the natural rate of interest $\{r_t^n\}_{t=0}^{\infty}$ is also an $\mathcal{F}$-adapted stochastic process. Note, however, that we assume neither that the economy is at the zero lower bound at time 0, nor that the natural rate follows a two-state Markov chain with its steady-state value as the absorbing state. Therefore, this model allows for the zero lower bound to bind multiple times and for the central bank

[15] In the babbling equilibrium, the central bank sends a message independently from its private information, and the private sector never updates its belief in response to the received message. These strategies are mutually best response.

to act differently when it foresees that the zero bound will bind or that it will cease to bind in the near future.

An optimal secretive commitment policy is $\{(\pi_t^*, x_t^*, i_t^*)\}_{t=0}^{\infty}$ that minimizes the loss function (5) subject to the New Keynesian Phillips curve in (6), the non-negativity constraint in (13), and the dynamic IS equation in (14). The following proposition immediately follows.

Proposition 3 *Let $\mathcal{G} = \{\mathcal{G}_t\}_{t=0}^{\infty}$ be a filtration such that $\mathcal{F}_t \subset \mathcal{G}_t$ for all t. If the optimal secretive commitment policy $\{(\pi_t^*, x_t^*, i_t^*)\}_{t=0}^{\infty}$ satisfies condition (11) or*

$$\textit{Probability of}\left\{\mathbb{E}[x_{t+1}^*|\mathcal{G}_t] + \frac{1}{\sigma}\mathbb{E}[\pi_{t+1}^*|\mathcal{G}_t] < \mathbb{E}[x_{t+1}^*|\mathcal{F}_t] - \frac{1}{\sigma}\{i_t^* - \mathbb{E}[\pi_{t+1}^*|\mathcal{F}_t]\}\textit{ for some } t\right\} > 0, \tag{15}$$

then the loss from $\{(\pi_t^*, x_t^*, i_t^*)\}_{t=0}^{\infty}$ is strictly smaller than that from any $\mathcal{G}$-adapted processes $\{(\pi_t, x_t, i_t)\}_{t=0}^{\infty}$ that satisfy the New Keynesian Phillips curve in (8), the dynamic IS equation:

$$x_t = \mathbb{E}[x_{t+1}|\mathcal{G}_t] - \frac{1}{\sigma}\{i_t - \mathbb{E}[\pi_{t+1}|\mathcal{G}_t] - r_t^n\},$$

and the non-negativity constraint in (13).

Condition (15) identifies the situation in which expectations in the dynamic IS equation change so much that even lowering the nominal rate to zero is not sufficient to maintain the output gap at x_t^*.

This proposition implies that, from the ex-ante point of view, the central bank should be secretive even if the zero lower bound is already binding at time 0 and if it may, for example, receive private news that a negative natural rate shock disappears in near future or that a future cost-push shock is positive. This might sound contradicting with the literature, which has shown that raising inflation expectation can be welfare-improving at the zero lower bound, but it is not. From the ex-post point of view, once the central bank observes a good news — short duration of a negative natural rate shock or a positive future cost-push shock — that raises inflation expectations, it is beneficial if the private sector is also informed about the news. However, from the ex-ante point of view, it is possible that bad news is observed and the continuation loss increases in that event. Therefore, it is on average better to leave the private sector uninformed.

2.6.2 Private news about the central bank's future policy goals

Delphic forward guidance can be used to communicate information not only about future cost-push shocks but also about the central bank's objective in the future.[16] Let $\{\theta_t\}_{t=0}^{\infty}$ be an exogenous stochastic process. The central bank's loss is now given by

$$\mathbb{E}\sum_{t=0}^{\infty}\delta^t L(\pi_t, x_t, \theta_t).$$

[16] Jensen (2002) conducts similar analysis, but puts emphasis on the central bank's reaction. Contrary to our study, whether the central bank has commitment technology or not leads to qualitatively different implications on transparency.

A quadratic example such as

$$L(\pi, x, \theta) = \frac{1}{2}\left[(\pi - \theta)^2 + bx^2\right], \quad b \geq 0, \tag{16}$$

is used elsewhere in the literature, e.g. Stein (1989), Moscarini (2007), Athey, Atkeson, and Kehoe (2005), and Waki, Dennis, and Fujiwara (2015).

Note that Lemma 2 and Proposition 1 hold true in this augmented model, under the assumption that $\{\theta_t\}_{t=0}^{\infty}$ is $\mathcal{F}$-adapted i.e. the private sector observes contemporaneous θ.[17] This assumption is useful to isolate the effects of revealing private news about future monetary policy objectives. Under this assumption, revealing future monetary policy goals is therefore undesirable.

When $\{\theta_t\}_{t=0}^{\infty}$ is not $\mathcal{F}$-adapted but adapted to the central bank's filtration, then the central bank generally faces a trade-off: there are gains from making period-t actions contingent on θ_t, but that can reveal to the private sector some information about θ_t and possibly about future θ's, which is detrimental to welfare.[18] Therefore, secrecy is not in general optimal. In Appendix A.2, we provide an example in which θ is i.i.d. and the central bank possesses private information about the contemporaneous θ, and show that, when the central bank is unable to commit, a unique Markov perfect equilibrium features full information revelation. The optimal discretionary policy in that example thus features full disclosure of private information.[19] Stein (1989) considers a model in which there is a forward-looking constraint (specifically, uncovered interest parity) and the central bank has private information that determines its future action. In a cheap-talk game he finds that full information revelation is desirable but impossible due to the central bank's inability to commit. This is in contrast to our result that, regardless of the central bank's ability to commit, it is desirable not to disclose any private information to the private sector. The reason for this difference is again that the private information in Stein (1989) is not a news shock. Details on this point are shown in Appendix A.3.

In contrast to Moscarini (2007), the precision of the private information possessed by the central bank is irrelevant for this result. He finds that, under discretion, the competence of a central bank, measured by the precision of the private signal the central bank receives about a contemporaneous shock to its objective, implies improved welfare. A crucial difference is that his result is about a contemporaneous private shock, i.e. θ_t is not $\mathcal{F}_t$-measurable, while ours is about private news.

Waki, Dennis, and Fujiwara (2015) consider a monetary-policy delegation problem in a New Keynesian model, when the contemporaneous shock is private information to the central bank and influences the central bank's loss as in (16), and the central

[17] This condition guarantees

$$\mathbb{E}[\mathbb{E}[L(\pi_t, x_t, \theta_t)|\mathcal{F}_t]] \geq \mathbb{E}[L(\mathbb{E}[\pi_t|\mathcal{F}_t], \mathbb{E}[x_t|\mathcal{F}_t], \theta_t)],$$

which is necessary to show Lemma 2.

[18] This holds even if the central bank only observes a noisy signal about contemporaneous θ.

[19] This is in contrast to Moscarini (2007) and Stein (1989) in which full information disclosure is never an equilibrium in a cheap-talk game. The result of Moscarini (2007) does not hold in our model because he uses a static Phillips curve in which cheap-talk can affect inflation expectations. In Appendix A.3 we discuss the model in Stein (1989) in details.

bank is unable to commit. Their paper differs from ours in that the central bank does not possess private news in their model, and their focus is on the optimal legislation to be imposed on the central bank's choice.

2.7 A three-equation New Keynesian model

So far we have considered situations in which monetary policy is chosen optimally. Now we show that the central bank may want to commit to secrecy even when it follows a Taylor rule. Consider the three-equation New Keynesian model with the New Keynesian Phillips curve (1), the dynamic IS equation (14), and the Taylor rule:

$$i_t = \phi_t^\pi \pi_t + \phi_t^x x_t + \eta_t, \quad \forall t, \tag{17}$$

where i_t is the (net) nominal interest rate at t. We allow the Taylor rule coefficients to change stochastically and assume that contemporaneous shocks are known to the private sector, i.e. $\{(\phi_t^\pi, \phi_t^x, \eta_t)\}$ is an $\mathcal{F}$-adapted process. Stochastic processes of inflation, the output gap, and the nominal interest rate constitute an equilibrium if they satisfy (1), (14), and (17).

Let $\mathcal{F}$ and $\mathcal{G}$ be two filtrations as before, and $\{(\pi_t, x_t, i_t)\}_{t=0}^\infty$ be an equilibrium when $\mathbb{E}_t^P[.] = \mathbb{E}[.|\mathcal{G}_t]$. Defining $\tilde{\pi}_t = \mathbb{E}[\pi_t|\mathcal{F}_t]$, $\tilde{x}_t = \mathbb{E}[x_t|\mathcal{F}_t]$, and $\tilde{i}_t = \mathbb{E}[i_t|\mathcal{F}_t]$ for all t, it is straightforward to check that $\{(\tilde{\pi}_t, \tilde{x}_t, \tilde{i}_t)\}_{t=0}^\infty$ is an equilibrium when $\mathbb{E}_t^P[.] = \mathbb{E}[.|\mathcal{F}_t]$. Jensen's inequality implies that

$$\mathbb{E}[L(\pi_t, x_t)] = \mathbb{E}\left[\mathbb{E}[L(\pi_t, x_t)|\mathcal{F}_t]\right] \geq \mathbb{E}\left[L(\mathbb{E}[\pi_t|\mathcal{F}_t], \mathbb{E}[x_t|\mathcal{F}_t])\right] = \mathbb{E}[L(\tilde{\pi}_t, \tilde{x}_t)].$$

Therefore, for any equilibrium in which the private sector knows more than $\mathcal{F}$, there is an equilibrium under secrecy that achieves weakly lower ex-ante loss to the central bank.[20]

Bianchi and Melosi (2014) use this model with a Taylor rule that has a lagged nominal interest rate. In their model the Taylor rule coefficients change with the policy regime that switches between three regimes (one active, and two passive with different persistence). Under the no-transparency policy, the private sector is unable to distinguish between the two passive regimes and is unsure about the persistence of the current passive regime. Under the transparency policy, whenever the policy switches to a passive regime, the private sector is informed about the exact end date of the passive regime. This is a particular kind of communication about private news the central bank receives, and the authors argue that the steady-state welfare improves under transparency.

Because the model in Bianchi and Melosi (2014) has a lagged nominal interest rate in the Taylor rule, we investigate numerically whether incorporating the lagged nominal rate in the monetary policy rule makes information revelation beneficial, using the three-equation model with constant coefficients: $(\phi_t^\pi, \phi_t^x) = (\phi^\pi, \phi^x)$. As shown in Appendix A.4, the lagged interest rate itself does not overturn the desirability of secrecy, suggesting that the welfare improving property of transparency in Bianchi and Melosi (2014) may depend crucially on their use of the steady-state welfare. Because

[20] Again, as long as condition (11) is satisfied, the ex-ante loss is strictly higher when the private sector is better informed.

we are interested in whether it is beneficial for the central bank to commit to secrecy, ex-ante or time-0 expected loss is a more natural criterion.

3 Numerical results

Now we examine how the optimal policy changes when the private sector becomes better informed about future disturbances. For this purpose, we numerically solve for the optimal policy, under the assumption that the private sector observes the n-period ahead shocks. In our notation, $\mathcal{F}$ is the filtration generated by the shock process $\{u_t\}_{t=0}^{\infty}$, and we consider for each n a situation in which the private sector is endowed with a filtration $\mathcal{G}^n$ with $\mathcal{G}_t^n = \mathcal{F}_{t+n}$ for all t.

We examine New Keynesian models in the linear-quadratic framework. We begin with a simple problem by minimizing loss function subject to the aggregate supply condition and then proceed to the linear-quadratic problem with endogenous state variables, in particular, one with endogenously accumulated capital analyzed in Edge (2003) and Takamura, Watanabe, and Kudo (2006).[21]

We also investigate whether secrecy remains to be optimal policy in the canonical DSGE model, which used for forecasting and policy simulation in many policy institutions. Contrary to the previous experiments, the canonical DSGE model, based on Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2003, 2007), incorporates multiple distortions and shocks. Multiple distortions will lead to complex relationship among distortions, which may be alleviated by the announcement of future distortionary shocks. Also, private agents can have more smoothed consumption plan by knowing future technological developments.

3.1 Standard linear-quadratic New Keynesian model

The central bank minimizes the quadratic loss in (3) subject to the New Keynesian Phillips curve in (1), where $\mathbb{E}_t^P \pi_{t+1}$ is set to $\mathbb{E}[\pi_{t+1}|\mathcal{G}_t^n]$. The first-order condition implies the standard optimal targeting rule under commitment:

$$\pi_t = -\frac{1}{\varepsilon}\left(x_t - x_{t-1}\right). \tag{18}$$

Optimal targeting rule under discretion is also standard and is given by

$$\pi_t = -\frac{1}{\varepsilon} x_t. \tag{19}$$

The New Keynesian Phillips curve (1) together with the targeting rule in (18) or (19) determine optimal allocations and prices. Although (18) and (19) are identical to those in the model in which the private sector does not observe future shocks, the optimal policy depends on anticipated future shocks because the New Keynesian Phillips curve does.

[21] Appendix A.5 show the results from backward price indexation (Steinsson, 2003).

Throughout the numerical experiments, we use the unconditional social loss as welfare metric:[22]

$$\mathbb{L} = \text{var}\left(\pi_t\right) + \frac{\kappa}{\varepsilon}\text{var}\left(x_t\right). \tag{20}$$

Parameters are calibrated as in Table 1. Parameters σ, η, ε and θ denote the in-

Table 1: Parameter Values

Parameters	Values	Explanation
β	.99	Subjective discount factor
σ	1	Inverse of intertemporal elasticity of substitution
η	1	Inverse of Frisch elasticity
ε	6	Elasticity of substitution among differentiated products
θ	.75	Calvo parameter

verse of the intertemporal elasticity of substitution, the inverse of Frisch elasticity, the elasticity of substitution among differentiated products, and the Calvo parameter. $1-\theta$ is the probability of re-optimization of prices. The standard deviation of the cost-push shock is set to 1%. Parameter κ is related to structural parameters as: $\kappa \equiv (1-\theta)(1-\beta\theta)(\sigma+\eta)/\{\theta(1+\eta\varepsilon)\}$.

3.1.1 Results

Figure 3 displays how unconditional losses under commitment and under discretion change with n (shown on the horizontal axis).

The case with $n = 0$ corresponds to the situation in which the private sector only observes the contemporaneous cost-push shock. The social loss is minimized at $n = 0$ under both commitment and discretion, as we have shown theoretically.

The right panel displays the difference in social loss between commitment and discretion. The relative welfare loss from discretionary monetary policy is larger when cost-push shocks in the more distant future becomes observable by the private sector. The intuition behind this result is simple. When the private sector observes more future cost-push shocks, it is desirable, from the ex-ante point of view, for the central bank to reduce the dependence of future inflation on cost-push shocks that are foreseen, because this dependence acts as a disturbance to the New Keynesian Phillips curve. Such a reduction is possible when the central bank can commit, but is impossible when the central bank is unable to commit. Therefore the loss under discretion increases faster than the loss under commitment, as n increases. This finding reiterates the importance of commitment in New Keynesian models.

Differences in responses of inflation and the output gap under commitment and under discretion can be most transparently analyzed by looking at impulse responses to an anticipated, future cost-push shock.

Figure 4 draws impulse responses to an anticipated positive 1% cost-push shock. In each panel, the period when the cost-push shock materializes corresponds to 0 on the x-axis. We display the responses to the news shock from $n = 0$ to 4. The left two

[22] The difference between the unconditional and the conditional losses is minuscule. This is because the discount factor is set close to unity. We thus only report the unconditional loss hereafter.

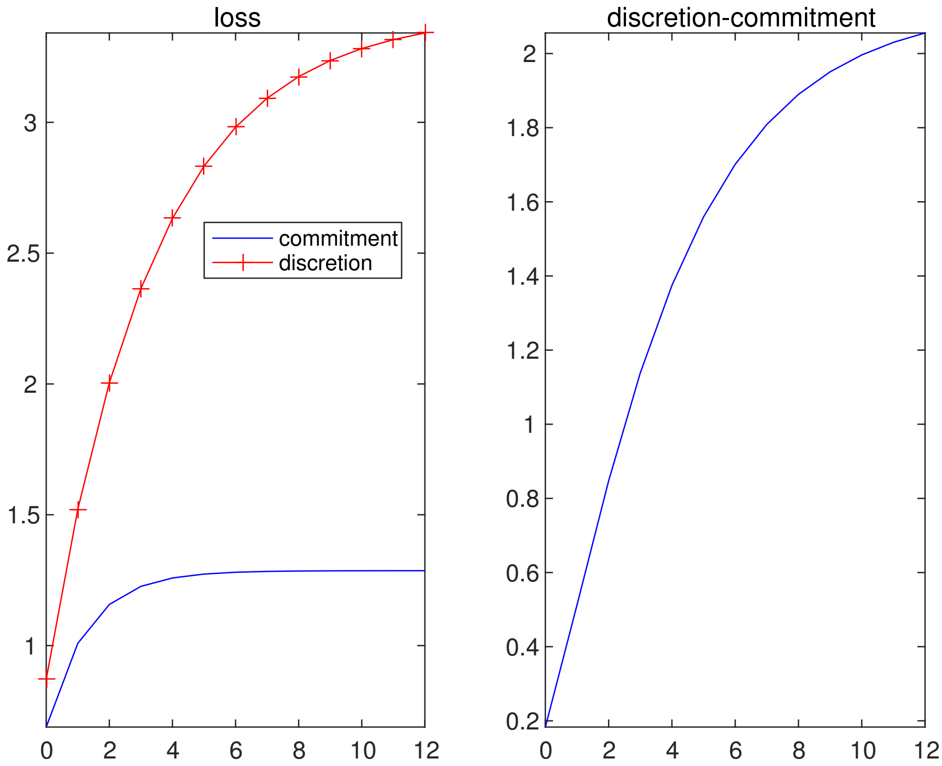

Figure 3: Loss under Commitment and Discretion

panels depict the responses of inflation and the output gap under discretion, and the right panels depict those under commitment.

Responses under discretion offer an intuitive explanation as to why there is no gain from revealing private news. Observe that, irrespective of whether a shock is anticipated or not, responses after the materialization of shocks are identical. Under optimal discretionary policy, revealing future cost-push information only results in additional fluctuations before the realization of the shock, and therefore is undesirable.

In contrast, under commitment, the central bank can lower the inflation response upon the materialization of a shock, which is undesirable when the private sector foresees future shocks because it disturbs the New Keynesian Phillips curve, by altering the inflation responses after the materialization and the output gap responses. It is clear in Figure 4 that the size of the inflation response in the period when the shock is realized decreases with n. Because the New Keynesian Phillips curve must be satisfied, lower contemporaneous inflation response can be achieved only by moving future inflation and the output gap further in the negative direction, which is inefficient. Figure 5 clarifies this point by showing the sum of the squared impulse responses of each variable before (left panels), upon (middle panels), and after (right panels) the materialization of the shock, respectively, as functions of n.

For the output gap, they are weighted by κ/ϵ as in the loss function. The loss from the output gap response monotonically increases with n in all panels. The loss

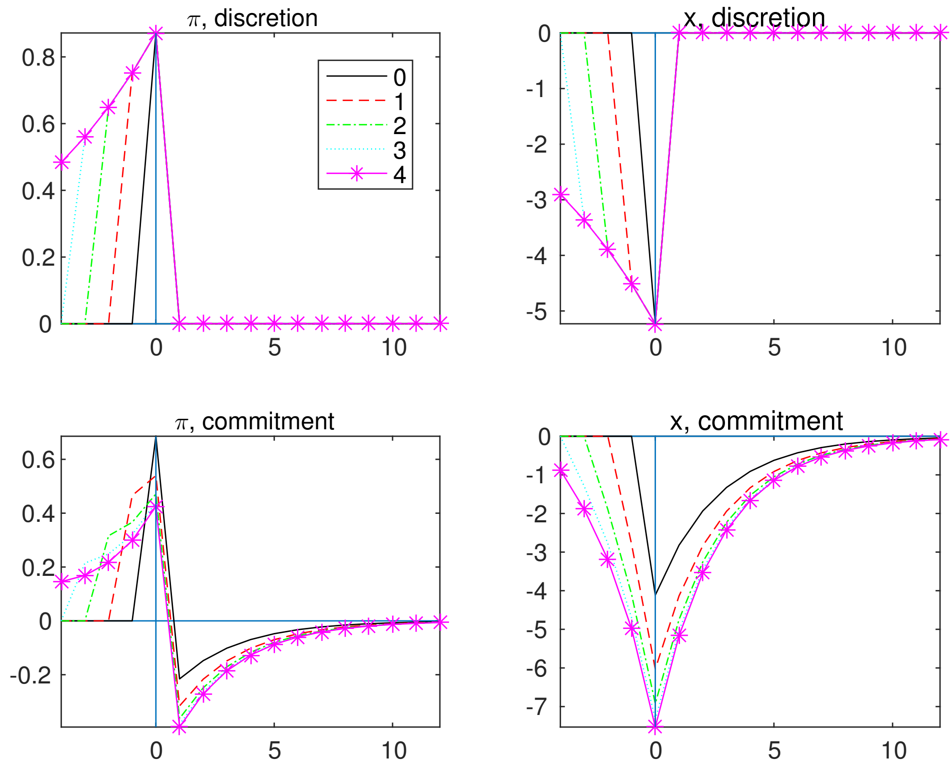

Figure 4: Impulse Responses: Discretion vs. Commitment

from inflation upon the materialization of the shock decreases monotonically but the loss after materialization monotonically increases with n. The loss from the inflation response before the materialization of the shock is not monotone in n, probably because, if the news is about a sufficiently distant future, the central bank can somewhat smooth its negative effects on inflation. One can observe in Figure 4 that inflation response before the materialization of a shock becomes smoother as n increases.

3.2 Endogenous Capital

Next, we examine the linear quadratic model with endogenous capital accumulation in Edge (2003) and Takamura, Watanabe, and Kudo (2006). The model is a straightforward extension of the New Keynesian model to the endogenous capital formation subject to the convex capital adjustment cost: $\bar{I}_t = I\left(\bar{K}_{t+1}/\bar{K}_t\right)\bar{K}_t$, where $I\left(1\right) = \delta$, $I'\left(1\right) = 1$, and $I''\left(1\right) = \varepsilon_{\psi}$. Variables with upper bars denote level variables, while those without it are log deviations from their steady state values.

The benevolent central bank's loss function is derived as a second-order approxi-

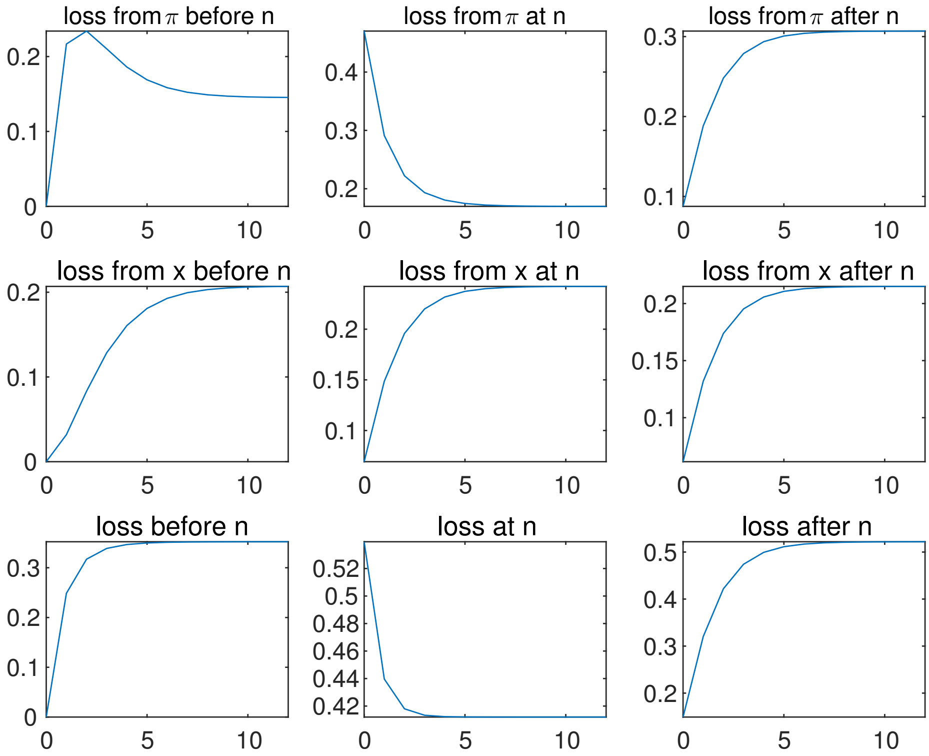

Figure 5: Sum of the squared impulse responses before, upon, and after the materialization of the shock

mation of the representative household's utility:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\begin{array}{l} (\sigma+\omega) Y_t^2 + \sigma k^2 \left[K_{t+1} - (1-\delta) K_t\right]^2 \\ +\varepsilon_\psi k \left(K_{t+1} - K_t\right)^2 + \rho_k k \left[\beta^{-1} - (1-\delta)\right] K_t^2 \\ -2\sigma k Y_t \left[K_{t+1} - (1-\delta) K_t\right] - 2(\omega - \eta) Y_t K_t \\ + \left[\theta\varepsilon\{\rho_k + (\rho_y - \omega)\eta\epsilon\}/\{\rho_k (1-\theta)(1-\beta\theta)\}\right] \pi_t^2 \end{array} \right],$$

subject to the New Keynesian Phillips curve:

$$\pi_t = \beta \mathbb{E}_t^p \pi_{t+1} + \frac{(1-\theta)(1-\beta\theta)}{\theta\psi} \left[(\omega+\sigma) Y_t - \sigma k K_{t+1} + \{\sigma k (1-\delta) - \omega + \eta\} K_t\right] + u_t,$$

and the resource constraint:

$$0 = Y_t + \frac{\rho_y \left[1 - \beta(1-\delta)\right] - \sigma\beta(1-\delta)}{\sigma} \mathbb{E}_t^P Y_{t+1} + \frac{k\sigma(1-\delta) + \varepsilon_\psi}{\sigma} K_t$$
$$- \frac{\sigma k + \varepsilon_\psi (1+\beta) + \sigma\beta k (1-\delta)^2 + \rho_k \left[1 - \beta(1-\delta)\right]}{\sigma} K_{t+1} + \frac{\beta\left[\sigma k (1-\delta) + \varepsilon_\psi\right]}{\sigma} \mathbb{E}_t^P K_{t+2},$$

where Y_t denotes output.[23]

[23]We will also show impulse responses of real marginal costs MC_t and investment I_t, which are

Parameters are taken from Woodford (2005) and Takamura, Watanabe, and Kudo (2006) as in Table 2. Other parameters are defined as the function of structural param-

Table 2: Parameter Values: Endogenous Capital

Parameters	Values	Explanation
β	.99	Subjective discount factor
σ	1	Inverse of intertemporal elasticity of substitution
η	.11	Inverse of Frisch elasticity
ε	23/3	Elasticity of substitution among differentiated products
θ	.75	Calvo parameter
δ	.12/4	Depreciation rate
ϕ_h	4/3	Reciprocal of the elasticity of the production function with respect to labor input
ε_ψ	3	Capital adjustment cost parameter
ω_p	.33	Negative of the elasticity of the marginal product

eters: $\rho_y := \eta\phi_h + \omega_p\phi_h/(\phi_h - 1)$, $\rho_k := \rho_y - \eta$, $k := (1-\phi_h^{-1})/\{\beta^{-1} - (1-\delta)\}$, $\omega := \omega_\omega + \omega_p$, $\omega_\omega := \eta\phi_h$, and $\psi := 1 + \varepsilon(\rho_y - \omega)\eta/\rho_k$.

3.2.1 Results

Figure 6 compares the impulse responses for different n's. The responses of inflation and marginal cost are qualitatively similar to the model without capital, noting that the marginal cost is proportional to the output gap in the canonical model. The response of marginal cost is magnified as n increases, and the inflation response upon realization of a shock is reduced. However, notice that it takes much longer for the impulse response of the marginal cost to come close to zero. This is due to the fact that marginal costs depend on capital that adjusts only slowly over time. The top-left panel shows that it takes a long time for capital to return to the steady-state level even if n is low, and that the response of capital increases as n increases. This slow-moving property of marginal costs keeps the inflation response away from zero, before and after the realization of a shock.

Figure 7 compares the unconditional loss $\mathbb{L}^K$:

$$\mathbb{L}^K = (\sigma+\omega)\,\mathrm{var}(Y_t) + \sigma k^2 \mathrm{var}(I_t) + \varepsilon_\psi k \mathrm{var}(\Delta K_t) + \rho_k k\left[\beta^{-1} - (1-\delta)\right]\mathrm{var}(K_t) - 2\sigma^{-1}k\mathrm{cov}(Y_t, I_t) - 2(\omega-\eta)\,\mathrm{cov}(Y_t, K_t) + \frac{\theta\varepsilon\left[\rho_k + (\rho_y - \omega)\eta\varepsilon\right]}{\rho_k(1-\theta)(1-\beta\theta)}\mathrm{var}(\pi_t)\,. \quad (21)$$

and each of its components weighted by parameters for different values of n. Again the unconditional loss is increasing in n, which is consistent with our theoretical re-

given by:

$$MC_t = (\omega+\sigma)\,Y_t - \sigma k K_t + \left[\sigma k(1-\delta) - \omega + \eta\right]K_{t-1},$$

and

$$I_t = k\left[K_{t+1} - (1-\delta)\,K_t\right].$$

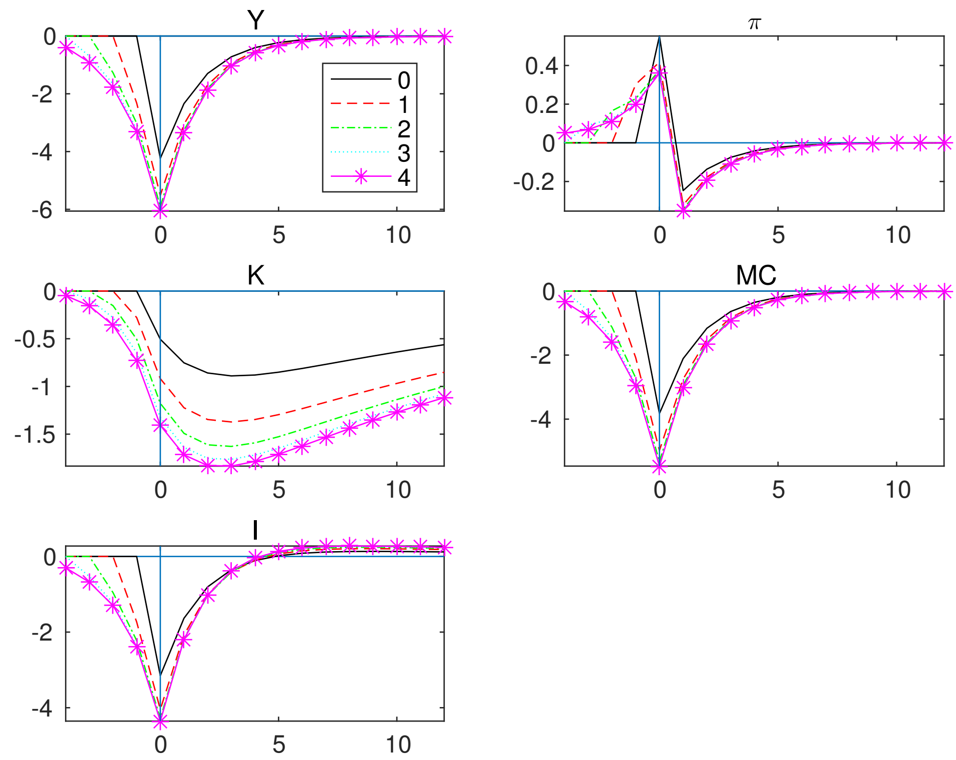

Figure 6: Impulse Responses: Endogenous Capital

sults; i.e., there is an expected virtue of ignorance. Results are similar to those obtained from the standard New Keynesian model as well as those from the model with price indexation examined in Appendices A.5.

3.3 A canonical DSGE model

Over a range of New Keynesian models, we have observed that helping the private sector form more accurate forecasts of future shocks is undesirable. In this subsection, we examine whether secrecy remains to be optimal policy in a canonical DSGE model based on Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2003, 2007).[24]

There exist several fundamental differences from previous experiments. First, there are multiple distortions: price and wage rigidities, and the external habit in consumption. These distortions can be further exaggerated by non-optimal monetary policy following the Taylor type rule and real rigidities embedded in the model. In this economy, price stability does not constitute optimal monetary policy. There is a policy tradeoff: central banks must take the right balance among remedies on these distortions. Information revelation of future shocks will likely affect distortions asymmetrically. It may reduce inefficencies caused by some of distortions. Thus, gains from transparency about future shocks may arise.

[24]Derivation is in Appendix A.6.

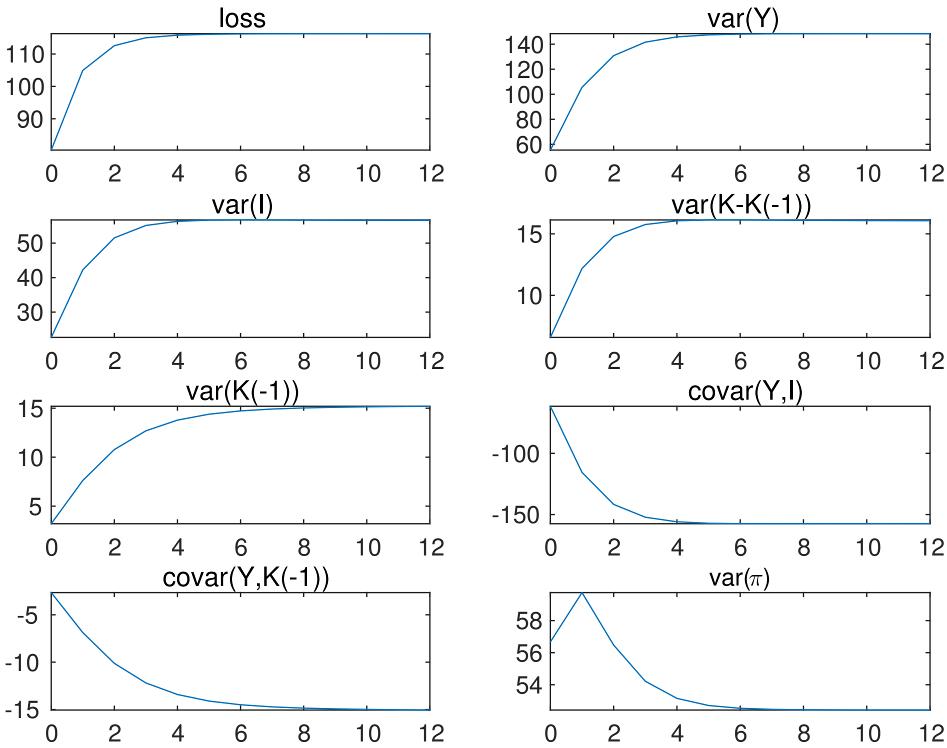

Figure 7: Terms in the Loss Function: Endogenous Capital

Second, there are multiple shocks: the technology shock, the wage markup shock and the monetary policy shock, in addition to the cost-push shock, whose implications are intensively examined so far. A notable difference from previous experiments is the inclusion of the technology shock. Fujiwara and Waki (2016) show that news about future distortionary shocks deteriorates the ex-ante welfare, but information revelation on future efficient shocks is beneficial to the ex-ante welfare. The technology shock is an efficient shock if there is no distortion in the economy. In the canonical DSGE model examined here, however, contains multiple inefficiencies. Even the technology shock can create distortions, which may lead to the optimality of secrecy even with efficient shocks.

Evaluation is based on the the ex-ante welfare. We first compute the policy function of the second-orderly approximated system around the deterministic steady states. The ex-ante welfare conditional on information at time $t-1$ is given by

$$\mathbb{E}V_0^n = \mathbb{E}f\left(S_{-1}, e_0, e_1, e_2, ..., e_n\right).$$

e_0 is a contemporaneous shock, while $e_1, e_2, ..., e_n$ are news shocks with n as news horizon. Note that expectations of these shocks are zero but variances, which matter with higher order approximation, are non-zero. Welfare costs are measured in consumption equivalent variation (CEV) relative to when $n = 0$.[25] Parameters are set following

[25]Details are shown in Appendix A.6.

Table 3: Parameter Values

Parameters	Values	Explanation
β	.9983	Subjective discount factor
σ	1.72	Inverse of intertemporal elasticity of substitution
η	2.23	Inverse of Frisch elasticity
ϵ	10	Elasticity of substitution among differentiated products
θ	.4	Calvo parameter for price
δ	.025	Depreciation rate
s''	4.82	Investment growth adjustment cost
b	.38	Consumption habit
α	.21	Capital share
θ_h	.26	Calvo parameter for wage
γ	.18	Price indexation
γ_h	.51	Wage indexation
ϵ_h	10	Elasticity of substituion among differentiated labor
ρ	.75	Policy inertia
ϕ^{π}	2.1	Policy reaction to inflation rates
ϕ^{y}	.17	Policy reaction to output growth
ρ_z	.98	AR(1) parameter for technology shock
ρ_u	.86	AR(1) parameter for price markup shock
ρ_μ	.96	AR(1) parameter for wage markup shock
ρ_η	.36	AR(1) parameter for monetary policy shock
σ_z	.0043	Standard deviation of technology shock
σ_u	.0014	Standard deviation of price markup shock
σ_μ	.0022	Standard deviation of wage markup shock
σ_η	.0016	Standard deviation of monetary policy shock

Fujiwara, Hirose, and Shintani (2011) as in Table 2.

In order to understand the role of each friction and real rigidity, we examine 6 cases with different parameter settings. In Case 6, parameters are set as in Table 2, but in other 5 cases, some frictions and rigidities are shut down as follows: Case 1 ($b = s'' = \rho_\eta = 0$, $\theta = 0.01$, $\phi^{\pi} = \infty$); Case 2 ($b = \rho_\eta = 0$, $\theta = 0.01$, $\phi^{\pi} = \infty$); Case 3 ($\rho_\eta = 0$, $\theta = 0.01$, $\phi^{\pi} = \infty$); Case 4 ($\rho_\eta = 0$, $\phi^{\pi} = \infty$); Case 5 ($b = s'' = \rho_\eta = 0$). Case 1 corresponds to the standard Real Business Cycle Model. In Case 2, investment growth adjustment costs are added to Case 1. There are no frictions in Cases 1 and 2. In Case 3, external habit formation in consumption is introduced. Then, sticky wages are further added in Case 4. All three distortions: external habit, and price as well as wage stickiness, are present in Case 5. The difference between Case 5 and 6 is policy inertia. Monetary policy reacts to shocks only contemporaneously in Case 5. In Case 6, monetary policy demonstrates significant history dependence.

3.3.1 Results

Figure 8 displays how conditional welfare changes with n (shown on the horizontal axis). Let us first explain Case1 where there is neither distortion nor real rigidity.

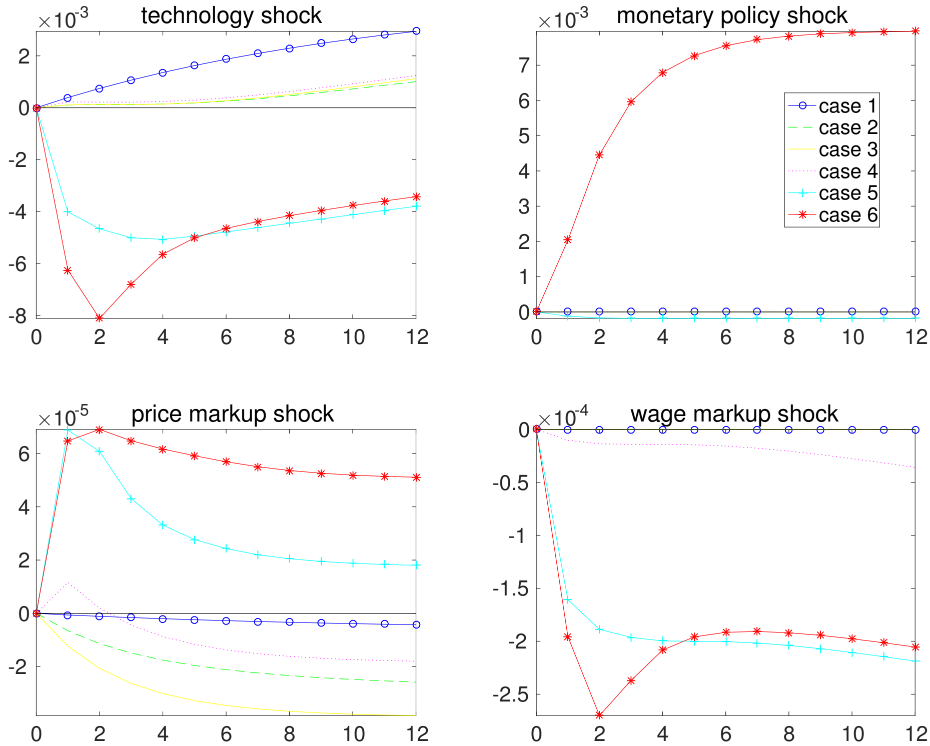

Figure 8: Welfare Costs in CEV by News Horizon (%)

Welfare increases with n for the technology shock, but it decreases for the markup shock. The central bank can increase (decrease) social welfare by announcing future technological (markup) developments when it notices them. In other words, Delphic forward guidance about efficiency (distortionary) shocks is beneficial (detrimental) to social welfare. Gains from disclosing future efficient shocks are properties that are reported in Angeletos, Iovino, and La'O (2016) and Fujiwara and Waki (2016). Angeletos, Iovino, and La'O (2016) find it optimal to disclose contemporaneous efficient shocks for hegerogeneously informed agents. Fujiwara and Waki (2016) report that revealing future government expenditure is beneficial in a simple model with homogeneously informed private agents. Qualitatively equivalent results are obtained in Cases 2 to 4, although inefficiencies stemming from external habit and/or sticky wages are present in Cases 3 and 4.

On the other hand, the existence of inefficiencies displays the different pictures in Cases 5 and 6. With sticky wages and prices altogether, however, complicated and non-monotonic relationships between welfare gains and n emerge. There, revealing future technological progresses can deteriorate social welfare. With the presence of distortions, even efficient shocks create inefficiencies. For example, a technology shock can cause inefficient markup fluctuations. Consequently, it becomes a non-trivial task to offer central banks general and simple policy prescriptions for information strategy about private news when realistic frictions and rigidities are present.

Simulations here illustrate that welfare gains from revealing private news are very small even if there exists any, and disclosure of news shocks is quite often detrimental to social welfare. Given these two facts, we can conclude that no pressing need is necessary for Delphic forward guidance, namely information revelation about future structural shocks. This result is still contrary to the common view which tends to appraise transparency about future shocks.[26]

4 Conclusion

How should monetary policy be designed when the central bank has private information about future economic conditions? We show that when the central bank has a dual-mandate-type objective function it finds it undesirable to disclose private news to help the private sector form more accurate forecasts of the future. Being secretive about private news constitutes optimal monetary policy when the central bank receives such information. This result also casts doubt on the usefulness of Delphic forward guidance, if it is based on private news about future shocks. Our result also implies that, in a wide class of New Keynesian models, if information acquisition is costly for the central bank, there is no incentive to collect information that would help it forecast the future better than the private sector.

We have identified a class of New Keynesian models in which information revelation is only harmful to the central bank. There are mechanisms that are absent in the models in this paper but are likely to counteract the negative effects of information revelation. For example, when the representative household is not an expected utility maximizer but instead has a preference for early resolution of uncertainty, then there can be a direct, positive effect on social welfare from revealing information regarding future shocks to the household. If price setters receive idiosyncratic, noisy private signals regarding future shocks, then the resulting price distribution can be more dispersed than it would be when they have homogeneous information. Providing a public signal may improve welfare because it may reduce the price dispersion through a reduction in the dispersion of inflation expectations, which is the source of inefficiency in the New Keynesian model. It would be interesting to examine whether these mechanisms can more than offset the mechanism identified in the present paper, for a set of reasonable parameter values. It is also interesting to examine the optimal time-consistent communication policy in the present setting. They are left for our future research. In an accompanying paper (Fujiwara and Waki, 2016), we investigate whether Delphic forward guidance can be useful for the conduct of fiscal policy and show that it can be harmful for ex-ante welfare to convey more accurate information about future distortionary taxes.

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[26] Hirose and Kurozumi (2017) find that anticipated monetary policy disturbances play a larger role in monetary policy transmission mechanism after 1999 and conclude that this is "consistent with the rise in the academic views on central banking as management of expectations."

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A Appendix

A.1 Proofs

Proof. [Proof of Lemma 1] Consider the following *relaxed* problem:

$$\min_{\{(\pi_t,x_t)\}_{t=0}^{\infty}} \mathbb{E}[\sum_{t=0}^{\infty} \delta^t L(\pi_t, x_t)] \tag{22}$$

subject to (6) and the constraint that the process $\{(\pi_t, x_t)\}_{t=0}^{\infty}$ is adapted to $\mathcal{G}$ with $\mathcal{F} \subset \mathcal{G}$. Let $\{(\pi_t, x_t)\}_{t=0}^{\infty}$ be a solution. Define $\{(\tilde{\pi}_t, \tilde{x}_t)\}_{t=0}^{\infty}$ by

$$(\tilde{\pi}_t, \tilde{x}_t) = (\mathbb{E}[\pi_t|\mathcal{F}_t], \mathbb{E}[x_t|\mathcal{F}_t])$$

for all t. Then $\{(\tilde{\pi}_t, \tilde{x}_t)\}_{t=0}^{\infty}$ is $\mathcal{F}$-adapted, and is in the constraint set in the relaxed problem. Moreover, Jensen's inequality implies

$$\mathbb{E}[L(\pi_t, x_t)] = \mathbb{E}\left[\mathbb{E}[L(\pi_t, x_t)|\mathcal{F}_t]\right] \geq \mathbb{E}[L(\tilde{\pi}_t, \tilde{x}_t)].$$

Therefore $\{(\tilde{\pi}_t, \tilde{x}_t)\}_{t=0}^{\infty}$ must be a solution to the above problem too. Because the solution to this problem is unique almost everywhere, we can without loss of generality use the $\mathcal{F}$-adapted version, $\{(\tilde{\pi}_t, \tilde{x}_t)\}_{t=0}^{\infty}$, as the solution. ■

Proof. [Proof of Proposition 1] Let $\{(\pi_t, x_t)\}_{t=0}^{\infty}$ be a $\mathcal{G}$-adapted process which satisfies (8), and define $\{(\tilde{\pi}_t, \tilde{x}_t)\}_{t=0}^{\infty}$ as in Lemma 2. If $\{(\pi_t, x_t)\}_{t=0}^{\infty}$ is not $\mathcal{F}$-adapted, then it follows that

$$\mathbb{E}[\sum_{t=0}^{\infty} \delta^t L(\pi_t, x_t)] > \mathbb{E}[\sum_{t=0}^{\infty} \delta^t L(\tilde{\pi}_t, \tilde{x}_t)] \geq \mathbb{E}[\sum_{t=0}^{\infty} \delta^t L(\pi_t^*, x_t^*)].$$

If $\{(\pi_t, x_t)\}_{t=0}^{\infty}$ is $\mathcal{F}$-adapted, then $\{(\pi_t^*, x_t^*)\}_{t=0}^{\infty} \neq \{(\pi_t, x_t)\}_{t=0}^{\infty}$, because $\{(\pi_t^*, x_t^*)\}_{t=0}^{\infty}$ does not satisfy (8) under the stated conditions while $\{(\pi_t, x_t)\}_{t=0}^{\infty}$ does. Because the an optimal secretive commitment policy is almost-everywhere unique, it follows that

$$\mathbb{E}[\sum_{t=0}^{\infty} \delta^t L(\pi_t, x_t)] = \mathbb{E}[\sum_{t=0}^{\infty} \delta^t L(\tilde{\pi}_t, \tilde{x}_t)] > \mathbb{E}[\sum_{t=0}^{\infty} \delta^t L(\pi_t^*, x_t^*)].$$

■

Proof. [Proof of Proposition 2] Let $\{(\pi_t, x_t)\}_{t=0}^{\infty}$ be a $\mathcal{G}$-discretionary policy equilibrium. Then, for all t, it satisfies the first-order necessary and sufficient condition for the problem $\min_{\pi,x} L(\pi, x)$ subject to $\pi = \kappa x + \beta \mathbb{E}[\pi_{t+1}|\mathcal{G}_t] + u_t$, which is summarized by

$$(\pi_t, x_t) = \left(\frac{b/\kappa}{\kappa + b/\kappa} \{\beta \mathbb{E}[\pi_{t+1}|\mathcal{G}_t] + u_t\}, -\frac{1}{\kappa + b/\kappa} \{\beta \mathbb{E}[\pi_{t+1}|\mathcal{G}_t] + u_t\} \right).$$

Define $\{(\tilde{\pi}_t, \tilde{x}_t)\}_{t=0}^{\infty}$ as in Lemma 2. Then it satisfies

$$(\tilde{\pi}_t, \tilde{x}_t) = \left(\frac{b/\kappa}{\kappa + b/\kappa} \{\beta \mathbb{E}[\tilde{\pi}_{t+1}|\mathcal{F}_t] + u_t\}, -\frac{1}{\kappa + b/\kappa} \{\beta \mathbb{E}[\tilde{\pi}_{t+1}|\mathcal{F}_t] + u_t\} \right),$$

implying that $\{(\tilde{\pi}_t, \tilde{x}_t)\}_{t=0}^{\infty}$ is a $\mathcal{F}$-discretionary policy equilibrium. It follows from Jensen's inequality that $\mathbb{E}[L(\pi_t, x_t)] \geq \mathbb{E}[L(\tilde{\pi}_t, \tilde{x}_t)]$ for all t. Because L is quadratic, equality holds if and only if $\{(\pi_t, x_t)\}_{t=0}^{\infty} = \{(\tilde{\pi}_t, \tilde{x}_t)\}_{t=0}^{\infty}$ almost everywhere. This proves the part 1. The proof of the part 2 is the same as that of Proposition 1 and thus is omitted. ■

A.2 Private information about contemporaneous shocks

Here we provide an example in which the central bank possesses private information about *contemporaneous* θ and the optimal policy does not involve secrecy. For simplicity, we abstract from other shocks, from news shocks, and from imperfect knowledge of the central bank, and assume that the central bank perfectly observes only θ_t in period t while the private sector is completely uninformed, i.e. it observes neither θ itself nor any noisy signals. We further assume that θ_t is i.i.d. with mean zero, that the central bank is unable to commit, and that the loss function is given by (16). We focus on a Markov perfect equilibrium in which the central bank uses a time-invariant strategy that depends only on the current realization of θ.

Let (π^*, x^*, π^{e*}) with $(\pi^*, x^*) : \Theta \to \mathbb{R}^2$ and $\pi^{e*} \in \mathbb{R}$ be a Markov perfect equilibrium. A simple observation is that the private sector's inflation expectation is unaffected even if the central bank reveals some information about contemporaneous θ. The central bank's strategy $(\pi^*, x^*) : \Theta \to \mathbb{R}^2$ must solve

$$\min_{(\pi,x)} \frac{1}{2}\mathbb{E}_\theta[(\pi(\theta) - \theta)^2 + bx(\theta)^2]$$

subject to $\pi(\theta) = \kappa x(\theta) + \beta\pi^{e*}$ for all θ. This implies, for all θ,

$$(\pi^*(\theta), x^*(\theta)) = \left(\frac{b/\kappa}{\kappa + b/\kappa}\beta\pi^{e*} + \frac{\kappa}{\kappa + b/\kappa}\theta, -\frac{1}{\kappa + b/\kappa}(\theta - \beta\pi^{e*})\right).$$

Rational expectations imply $\pi^{e*} = 0$, and thus

$$(\pi^*(\theta), x^*(\theta)) = \left(\frac{\kappa}{\kappa + b/\kappa}\theta, -\frac{1}{\kappa + b/\kappa}\theta\right).$$

This shows that the optimal discretionary policy exploits the central bank's private information.

A.3 Comparison to Stein (1989) – Role of private news

Here we demonstrate that the reason for this difference is that the private information in Stein (1989) is not a news shock, by rewriting his model as a two-period New Keynesian model. The central bank's loss function is

$$\mathbb{E}[(\pi_0 - \theta)^2 + (\pi_1(\theta) - \theta)^2 + \pi_1(\theta)^2].$$

where θ is private information to the central bank, and has mean 0 and variance σ_θ^2. The central bank is unable to commit and chooses π_1 as a function of θ, implying the best response of $\pi_1(\theta) = \theta/2$. The inflation rate in period 0 is determined by the New Keynesian Phillips curve: $\pi_0 = \mathbb{E}^P[\pi_1(\theta)]$. This setting is not nested by our setting.

It is then straightforward to calculate the losses under full and no information revelation. Full revelation implies $\pi_0 = \pi_1(\theta)$, and the loss is $(3/4)\sigma_\theta^2$. No revelation implies $\pi_0 = 0$, and the loss is $(3/2)\sigma_\theta^2$, which is bigger than the loss under full-revelation.

Desirability of full revelation in Stein's model is due to the assumption that θ is constant over time, i.e., θ is not a news shock. Because of this property, it is desirable that π_0 varies positively with θ, which is achieved when full information is revealed. Without this property, we can easily show that no revelation is better than full revelation. Consider, for example, an alternative loss function where θ only affects the period 1 loss: $\mathbb{E}[\pi_0^2 + (\pi_1(\theta) - \theta)^2 + \pi_1(\theta)^2]$. Then no revelation results in the loss of $(1/2)\sigma_\theta^2$ while full revelation results in the loss of $(3/2)\sigma_\theta^2$. The undesirability of information revelation also holds true if the loss function is hit by two shocks that are independent over time, as $\mathbb{E}[(\pi_0 - \theta_0)^2 + (\pi_1(\theta_1) - \theta_1)^2 + \pi_1(\theta_1)^2]$. Revealing θ_0 is irrelevant for welfare because inflation in period 0 is pinned down by $\pi_0 = \mathbb{E}^P[\theta_1/2]$ and thus is independent of θ_0.

A.4 A three-equation model with a lagged interest rate

Because Bianchi and Melosi (2014) find steady-state welfare gains from transparency using the Taylor rule with a lagged nominal interest rate, now we incorporate the lagged policy rate to the Taylor rule in a three equation model to examine its welfare consequences. The Taylor rule is now

$$i_t = \rho i_{t-1} + (1-\rho)\left(\phi_\pi \pi_t + \phi_x x_t\right) + \eta_t, \quad 0 < \rho < 1.$$

Structural parameters are the same as in Table 1 and we use $(\rho, \phi_\pi, \phi_x) = (0.6, 1.6, 0.3)$.

Figure 9 reports how the ex-ante loss varies with n, for the mark-up shock case and for the monetary shock case. In both cases, welfare loss is increasing in n, and therefore revealing information about future shocks is detrimental to welfare. This pattern does not change with ρ, and higher values for ρ (e.g. $\rho = 0.9$) produce the same pattern. Although the model considered here is not identical to Bianchi and Melosi (2014), the above result suggests that the lagged nominal interest rate in the Taylor rule by itself does not have significant implications for the welfare consequences of information revelation.

A.5 Indexation

We turn to the setting with backward price indexation, employing the analytical framework used in Steinsson (2003). In Steinsson (2003), a fraction ω of price setters are assumed to set prices P_t^B following a simple rule: $P_t^B = P_{t-1}^* (1 + \pi_{t-1}) \exp(x_{t-1})^\gamma$, where P_{t-1}^* denotes an index of the prices set in $t-1$ and the parameter $\gamma \in [0,1)$ controls how strongly their price-setting decision depends on past demand conditions. Among the remaining $(1-\omega)$ fraction of price setters, the $(1-\theta)$ fraction are randomly given an opportunity to optimize their prices while the θ fraction reset their prices according to the steady-state inflation.

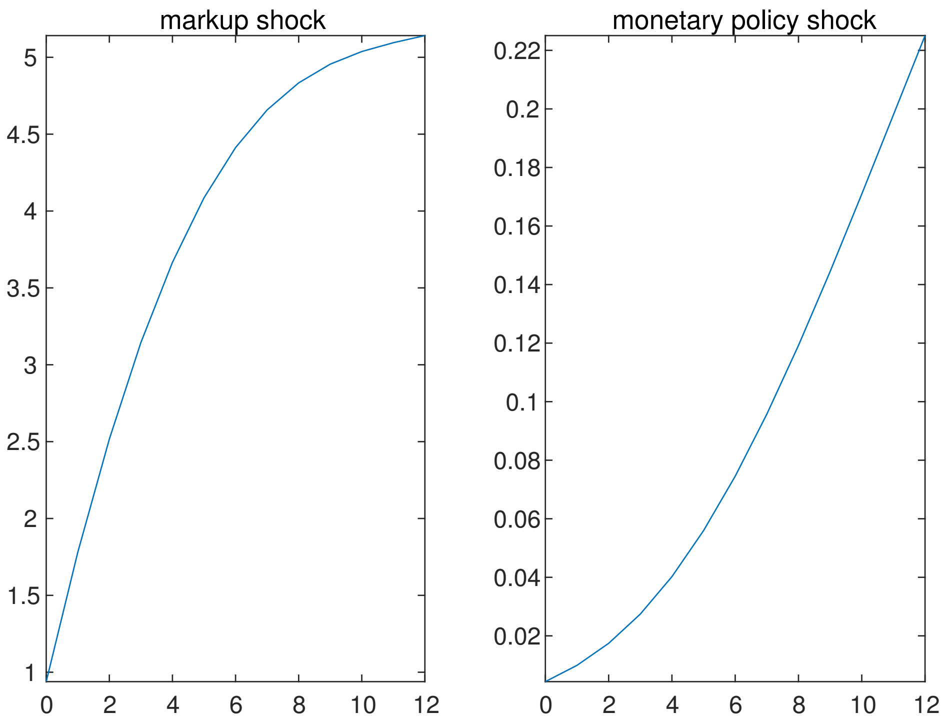

Figure 9: Welfare loss vs. n in the three equation model with a lagged interest rate

Steinsson (2003) derives the following linear-quadratic commitment problem: the central bank minimizes

$$\frac{1}{2}\mathbb{E}_0\sum_{t=0}^{\infty}\beta^t\left[\begin{array}{c}\pi_t^2+\frac{(1-\theta)(1-\beta\theta)(\sigma+\eta)}{\theta(1+\eta\varepsilon)\varepsilon}x_t^2\\ +\frac{\omega}{(1-\omega)\theta}\Delta\pi_t^2+\frac{(1-\theta)^2\omega\gamma^2}{(1-\omega)\theta}x_{t-1}^2-\frac{2(1-\theta)\omega\gamma}{(1-\omega)\theta}\Delta\pi_t x_{t-1}\end{array}\right],$$

subject to the hybrid New Keynesian Phillips curve:

$$\begin{aligned}\pi_t &= \frac{\beta\theta}{\omega(1-\theta+\beta\theta)+\theta}\mathbb{E}_t^P\pi_{t+1}+\frac{\omega}{\omega(1-\theta+\beta\theta)+\theta}\pi_{t-1}\\ &\quad+\frac{(1-\theta)(1-\omega)(1-\beta\theta)(\sigma+\eta)-\omega\beta\theta\gamma(1+\eta\varepsilon)}{[\omega(1-\theta+\beta\theta)+\theta](1+\eta\varepsilon)}x_t\\ &\quad+\frac{\omega\gamma(1-\theta)}{\omega(1-\theta+\beta\theta)+\theta}x_{t-1}+u_t.\end{aligned}$$

We set $\omega=.5$ and $\gamma=.052$ as in Steinsson (2003).

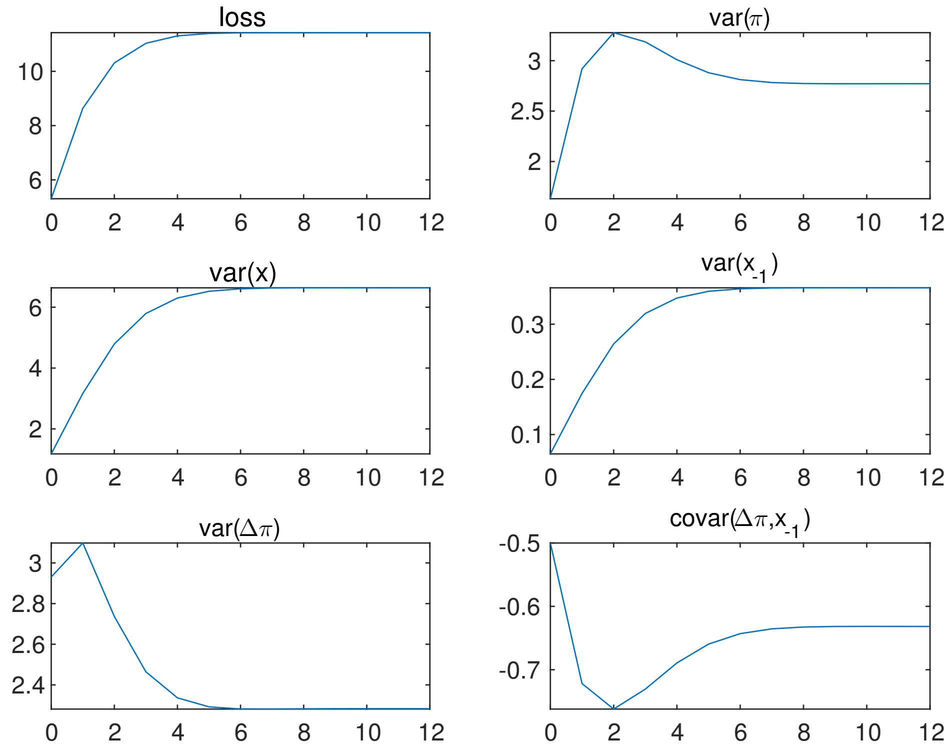

Figure 10: Terms in the Loss Function: Indexation

A.5.1 Results

Figure 10 illustrates how the unconditional loss $\mathbb{L}^S$:

$$\mathbb{L}^S = \text{var}(\pi_t) + \frac{(1-\theta)(1-\beta\theta)(\sigma+\eta)}{\theta(1+\eta\varepsilon)\varepsilon}\text{var}(x_t) + \frac{\omega}{(1-\omega)\theta}\text{var}(\Delta\pi_t) \tag{23}$$
$$+ \frac{(1-\theta)^2\omega\gamma^2}{(1-\omega)\theta}\text{var}(x_{t-1}) - \frac{2(1-\theta)\omega\gamma}{(1-\omega)\theta}\text{cov}(\Delta\pi_t, x_{t-1}),$$

and its components weighted by parameters change with n.

The unconditional loss is the smallest at $n = 0$, consistent with our theoretical result. As in the simple New Keynesian model, we observe that variations in inflation (and inflation difference) are reduced as n is increased from $n = 2$, at the cost of higher variability in other terms; in particular, that of the output gap. Even with price indexation, "ignorance is bliss" remains the optimal monetary policy.Figure 11 draws similar impulse responses to those in Figure 4 but with indexation.

Similarly to the case with the standard New Keynesian model, when the private sector observes future cost-push shocks, the central bank finds it optimal to smooth inflation rates and difference in inflation rates to reduce their negative effects on the New Keynesian Phillips curve, and this is accompanied by higher variability of the output gap. When $\gamma = 0$, this model becomes similar to the standard model with price

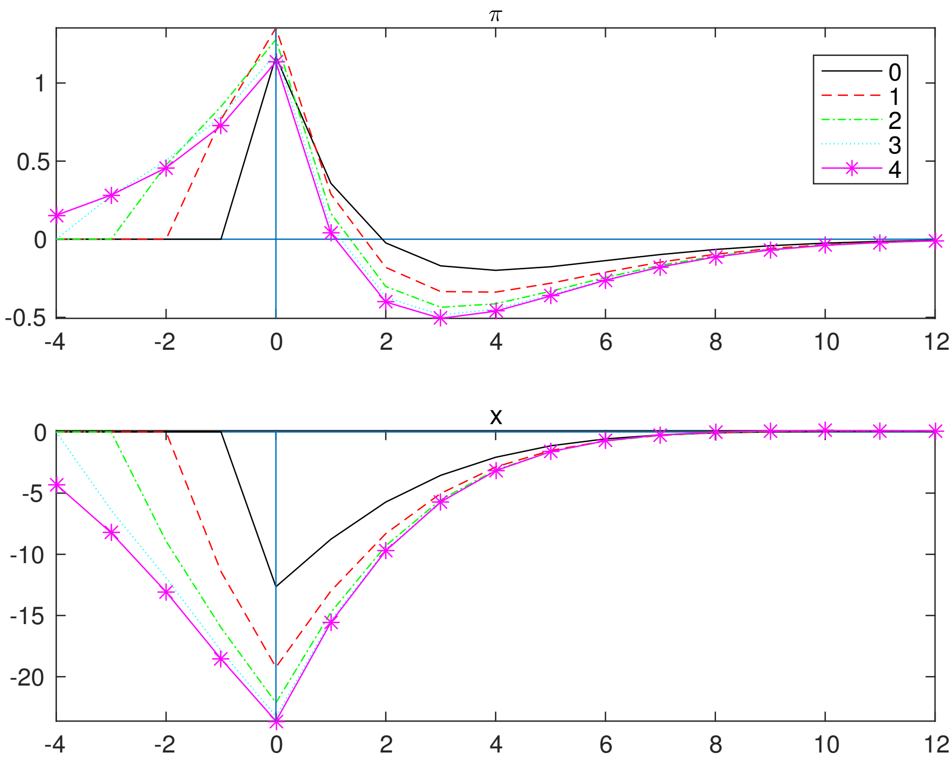

Figure 11: Impulse Responses: Indexation

indexation in Woodford (2003), and the quasi-difference of inflation, $\pi_t - (\omega/\theta)\pi_{t-1}$, behaves in a similar way as inflation behaves in the simple New Keynesian model. Therefore we plot the quasi-difference of inflation in the rightmost panel in Figure 11. One can see that the impulse response presented here is qualitatively the same as that of π in the simple model.

A.6 A canonical DSGE model

The model examined in this paper is based on Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2003, 2007).

A.6.1 Consumers

A representative household maximizes welfare:

$$V_t = \mathbb{E}_t \sum_{i=0}^{\infty} \beta^i \left[u\left(C_t\right) - v\left(h_t\right) \right],$$

subject to

$$
\begin{aligned}
A_{t+1} + P_t \left(C_t + I_t\right) &\leq W_t h_t + \left(1 + r_{t-1}^n\right) A_t + P_t r_t^K K_t + \Pi_t - T_t, \\
K_{t+1} &= (1-\delta) K_t + \left[1 - S\left(I_t, I_{t-1}\right)\right] I_t.
\end{aligned}
$$

C_t, h_t, A_t, P_t, W_t, r_t^n, r_t^K, Π_t, and T denote consumption, hours worked, amount of financial assets, consumer price, nominal wage, nominal interest rates, cost of capital, aggregate profits and lump-sum tax (transfer), respectively.

A.6.2 Labor union

A union collects the homogeneous labor supplied from households. It then differentiates labor services denoted by l and offers wages to firms. It maximizes

$$
\mathbb{E}_t \sum_{i=0}^{\infty} \theta_h^i m_{t,t+i} \Pi_{t+i}^U,
$$

subject to

$$
\begin{aligned}
\Pi_t^U &= \left[W_t\left(l\right) - \frac{W_t}{1+\tau_t^h}\right] h_{t+i}\left(l\right), \\
h_t\left(h\right) &= \left[\frac{W_t\left(h\right)}{W_t}\right]^{-\varepsilon_h} h_t, \\
W_{t+i}\left(h\right) &= W_t^* \prod_{n=1}^{i} \pi_{t+n-1}^{\gamma_h}.
\end{aligned}
$$

$m_{t,t+i}$, Π_t^U, τ_t^h, and π_t denote the stochastic discount factor, the profit of labor union, subsidy to the union, and (gross) consumer price inflation rates respectively. W_t^* denotes the optimal nominal wage set at time t. θ_h^i, ε_h and γ_h are Calvo parameter for staggered nominal wage, elasticity of substitution among differentiated labor, and degree of nominal wage indexation on past inflation rates.

A.6.3 Intermediate goods producer

Intermediate-goods producer f maximizes the profit $\Pi_{j,t}^F$:

$$
\mathbb{E}_t \sum_{i=0}^{\infty} \theta^i m_{t,t+i} \Pi_{t+i}^I\left(j\right),
$$

subject to

$$\begin{aligned}\Pi_t^I(f) &= (1+\tau_t) P_t(f) Y_t(f) - P_t MC_t Y_t(f), \\ Y_t(f) &= \left[\frac{P_t(f)}{P_t}\right]^{-\varepsilon} Y_t, \\ P_{t+i}(f) &= P_t^* \prod_{n=1}^{i} \pi_{t+n-1}^{\gamma}.\end{aligned}$$

τ_t and Y_t denotes subsidy to intermediate good producers and output, respectively. W_t^* denotes the optimal price set at time t. t. γ is degree of price indexation on past inflation rates. The second constraint is the downward sloping demand curve which can be derived from the cost minimization problem by the below-mentioned final good producer. Real marginal cost MC_t is given as the Lagrange multiplier in the total cost minimization problem:

$$\min_{h_t, K_t} \frac{W_t}{P_t} h_t + r_t^K K_t,$$

subject to the production technology:

$$Y_t = K_t^{\alpha} \left[\exp(z_t) h_t\right]^{1-\alpha}.$$

z_t denotes the technology shock. α is the capital share.

A.6.4 Final good producer

A final good producer minimizes the total cost $\int_0^1 P_t(f) Y_t(f) \mathrm{d}f$ subject to the aggregating technology:

$$Y_t = \left[\int_0^1 Y_t(f)^{\frac{\theta-1}{\theta}} \mathrm{d}f\right]^{\frac{\theta}{\theta-1}}.$$

A.6.5 Aggregate conditions and others

The central bank set nominal interest rates following the Taylor type rule:

$$r_t^n = \rho r_{t-1}^n + (1-\rho)\left[\phi^{\pi}(\pi_t - 1) + \phi^y \left(\frac{Y_t}{Y_{t-1}} - 1\right)\right] + \eta_t,$$

where ρ denotes the degree of policy inertia. Regarding the fiscal policy, the balanced budget is assumed:

$$T_t = \tau P_t Y_t + \tau^h W_t h_t,$$

where both τ and τ^h denote steady state subsidy rates. The aggregate profit is given by

$$\Pi_t = \Pi_t^U + \Pi_t^I.$$

The resource constraint is given by

$$C_t + I_t = Y_t.$$

We assume following functional forms:

$$\begin{aligned}
u(C_t) &:= \frac{\left(C_t - b\bar{C}_{t-1}\right)^{1-\sigma}}{1-\sigma}, \\
v(h_t) &:= \frac{h_t^{1+\eta}}{1+\eta}, \\
S(I_t, I_{t-1}) &:= S''\left[\frac{1}{2}\left(\frac{I_t}{I_{t-1}}\right)^2 - \left(\frac{I_t}{I_{t-1}}\right) + \frac{1}{2}\right].
\end{aligned}$$

b defines the degree of external habit and $\bar{C}_{t-1}$ is taken as given when maximizing welfare at time t.

A.6.6 System of equations

We have 19 equations for 19 endogenous variables: Y_t, λ_t, π_t, w_t, q_t, r_t^K, I_t, MC_t, K_t, $\bar{F}_t$, $\bar{K}_t$, C_t, Δ_t, $\pi_{W,t}$, $\bar{F}_t^h$, $\bar{K}_t^h$, Δ_t^h, and r_t^n

$$K_{t+1} = (1-\delta)K_t + \left\{1 - S''\left[\frac{1}{2}\left(\frac{I_t}{I_{t-1}}\right)^2 - \left(\frac{I_t}{I_{t-1}}\right) + \frac{1}{2}\right]\right\} I_t,$$

$$Y_t = C_t + I_t,$$

$$\lambda_t = \left(C_t - bC_{t-1}\right)^{-\sigma},$$

$$\lambda_t = \beta \mathbb{E}_t \frac{R_t}{\pi_{t+1}} \lambda_{t+1},$$

$$q_t = \beta \mathbb{E}_t \frac{\lambda_{t+1}}{\lambda_t}\left[r_{t+1}^K + q_{t+1}(1-\delta)\right],$$

$$\begin{aligned}
1 &= q_t\left\{1 - S''\left[\frac{1}{2}\left(\frac{I_t}{I_{t-1}}\right)^2 - \left(\frac{I_t}{I_{t-1}}\right) + \frac{1}{2}\right]\right\} - q_t S''\left(\frac{I_t}{I_{t-1}} - 1\right)\frac{I_t}{I_{t-1}} \\
&\quad + \beta \mathbb{E}_t \frac{\lambda_{t+1}}{\lambda_t} q_{t+1} S''\left(\frac{I_{t+1}}{I_t} - 1\right)\left(\frac{I_{t+1}}{I_t}\right)^2,
\end{aligned}$$

$$w_t = (1-\alpha)\exp(z_t)^{1-\alpha} MC_t K_t^{\alpha} h_t^{-\alpha},$$

$$r_t^K = \alpha \exp(z_t)^{1-\alpha} MC_t K_t^{\alpha-1} h_t^{1-\alpha},$$

$$\bar{F}_t = 1 + \theta\beta \mathbb{E}_t \frac{\lambda_{t+1} Y_{t+1}}{\lambda_t Y_t} \pi_{t+1}^{\varepsilon} \pi_t^{\gamma} \bar{F}_{t+1},$$

$$\bar{K}_t = \exp(u_t) MC_t + \theta\beta \mathbb{E}_t \frac{\lambda_{t+1} Y_{t+1}}{\lambda_t Y_t} \pi_{t+1}^{1+\varepsilon} \bar{K}_{t+1},$$

$$\bar{K}_t = \left[\frac{1-\theta \left(\frac{\pi_{t-1}^{\gamma}}{\pi_t} \right)^{1-\varepsilon}}{1-\theta} \right]^{\frac{1}{1-\varepsilon}} \bar{F}_t,$$

$$Y_t = \frac{K_t^{\alpha} \left[\exp(z_t) h_t \right]^{1-\alpha}}{\Delta_t},$$

$$\Delta_t = (1-\theta) \left[\frac{1-\theta \left(\frac{\pi_{t-1}^{\gamma}}{\pi_t} \right)^{1-\varepsilon}}{1-\theta} \right]^{\frac{\varepsilon}{\varepsilon-1}} + \theta \left(\frac{\pi_t}{\pi_{t-1}^{\gamma}} \right)^{\varepsilon} \Delta_{t-1},$$

$$\pi_{W,t} = \frac{w_t}{w_{t-1}} \pi_t,$$

$$\bar{K}_t^h = \left[\frac{1-\theta_h \left(\frac{\pi_{t-1}^{\gamma_h}}{\pi_{W,t}} \right)^{1-\varepsilon_h}}{1-\theta_h} \right]^{\frac{1}{1-\varepsilon_h}} \bar{F}_t^h,$$

$$\bar{F}_t^h = w_t + \theta_h \beta \mathbb{E}_t \frac{\lambda_{t+1} N_{t+1} \pi_{t+1}}{\lambda_t N_t} \left(\frac{\pi_t^{\gamma_h}}{\pi_{W,t+1}} \right)^{1-\varepsilon_h} \bar{F}_{t+1}^h,$$

$$\bar{K}_t^h = \exp(\mu_t) \frac{N_t^{\eta}}{\lambda_t} + \theta_h \beta \mathbb{E}_t \frac{\lambda_{t+1} N_{t+1} \pi_{t+1}}{\lambda_t N_t} \left(\frac{\pi_{W,t+1}}{\pi_t^{\gamma_h}} \right)^{\varepsilon_h} \bar{K}_{t+1}^h,$$

$$\Delta_t^h = (1-\theta_h) \left[\frac{1-\theta_h \left(\frac{\pi_{t-1}^{\gamma_h}}{\pi_{W,t}} \right)^{1-\varepsilon_h}}{1-\theta_h} \right]^{\frac{\varepsilon_h}{\varepsilon_h-1}} + \theta_h \left(\frac{\pi_{W,t}}{\pi_{t-1}^{\gamma_h}} \right)^{\varepsilon_h} \Delta_{t-1}^h,$$

and

$$r_t^n = \rho r_{t-1}^n + (1-\rho) \left[\phi^{\pi} (\pi_t - 1) + \phi^{y} \left(\frac{Y_t}{Y_{t-1}} - 1 \right) \right] + \eta_t.$$

w_t and λ_t denote real wage W_t/P_t and the marginal utility of consumption, respectively. is equity price defined as the ratio of Lagrange multiplier on the first over that on the last constraint in the household optimization problem. Δ_t and Δ_t^h denote relative price dispersion terms for prices and wages, defined as

$$\Delta_t \quad : \quad = \int_0^1 \left[\frac{P_t(f)}{P_t} \right]^{-\varepsilon} \mathrm{d}f,$$

$$\Delta_t^W \quad : \quad = \int_0^1 \left[\frac{W_t(l)}{W_t} \right]^{-\varepsilon_h} \mathrm{d}l.$$

$\bar{F}_t$, $\bar{K}_t$, $\bar{F}_t^h$, and $\bar{K}_t^h$ are auxiliary variables. Price and wage markup shocks are defined as

$$\exp(u_t) \quad : \quad \frac{\varepsilon}{(1+\tau_t)(\varepsilon-1)},$$

$$\exp(\mu_t) \quad : \quad = \frac{\varepsilon_h}{\left(1+\tau_t^h\right)(\varepsilon_h-1)}.$$

All shocks are assumed to follow AR(1) processes:

$$
\begin{aligned}
z_t &= \rho_z z_{t-1} + \omega_{z,t}, \\
u_t &= \rho_u u_{t-1} + \omega_{u,t}, \\
\mu_t &= \rho_\mu \mu_{t-1} + \omega_{\mu,t}, \\
\eta_t &= \rho_\eta \eta_{t-1} + \omega_{\eta,t},
\end{aligned}
$$

where

$$
\begin{aligned}
\omega_{z,t} &\sim N\left(0, \sigma_z^2\right), \\
\omega_{u,t} &\sim N\left(0, \sigma_u^2\right), \\
\omega_{\mu,t} &\sim N\left(0, \sigma_\mu^2\right), \\
\omega_{\eta,t} &\sim N\left(0, \sigma_\eta^2\right).
\end{aligned}
$$

A.6.7 Welfare cost

We first define the welfare with news horizon being n:

$$
V_t^n = \mathbb{E}_t \sum_{i=1}^{\infty} \beta^i u\left(c_{t+1}^n, h_{t+1}^n\right).
$$

Then, the welfare cost in consumption unit relative to the case when $n = 0$ is given by

$$
\begin{aligned}
V_t^n &= \mathbb{E}_t \sum_{t=0}^{\infty} \beta^t u\left[\left(1+\lambda_c\right) C_t^0, \left(1+\lambda_c\right) C_{t-1}^0, h_t^0\right] \\
&= \frac{\left(1+\lambda_c\right)^{1-\sigma}\left[C_t^0 - bC_{t-1}^0\right]^{1-\sigma}}{1-\sigma} - \frac{\left(h_t^0\right)^{1+\eta}}{1+\eta} + \beta \mathbb{E}_t \left[\frac{\left(1+\lambda_c\right)\left[C_{t+1}^0 - bC_t^0\right]^{1-\sigma}}{1-\sigma} - \frac{\left(h_{t+1}^0\right)^{1+\eta}}{1+\eta}\right] \ldots \\
&= \left(1+\lambda_c\right)^{1-\sigma} UC_t^0 + V_t^0 - UC_t^0,
\end{aligned}
$$

where we define

$$
UC_t = \sum_{t=0}^{\infty} \beta^t \frac{\left(C_t^0 - bC_{t-1}^0\right)^{1-\sigma}}{1-\sigma}.
$$

Thus,

$$
\lambda_c = \left(\frac{V_0^a - V_0^r + UC_t^0}{UC_t^0}\right)^{\frac{1}{1-\sigma}} - 1.
$$