# Transparency in Monetary Policy, Signaling, and Heterogeneous Information*

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**Abstract**

In this paper we examine whether publishing the information underlying the central bank's decisions is socially desirable. We show that opacity may lead to the same equilibrium as transparency. However, additional equilibria may emerge under opacity with adverse consequences for welfare. Moreover, we explore the extent to which the central bank can use communication as a substitute for monetary policy when its hands are tied due to long lags between monetary-policy implementation and its effects on inflation and output. In this case, transparency has ambiguous effects. It reduces output variance and the distortions stemming from heterogeneous information. However, transparency generally raises the variance of inflation. On balance, transparency is plausible to be socially desirable. We also argue that a conflict of interests may arise between society and the central bank with regard to transparency.

Keywords: monetary policy, transparency, signaling, heterogeneous information.

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# 1 Introduction

In the course of the recent years, central banks' approaches to communication have been undergoing a paradigm shift. While traditionally tight-lipped, central banks nowadays stress the importance of communicating openly with the public. In particular, central banks explain their decisions and the underlying assessments of economic developments carefully. For example, it has become common practice to justify monetary-policy decisions in press conferences. Some central banks also make details about the decision-making process public.[1]

In this paper, we propose a model to evaluate whether this paradigm shift is socially desirable. In particular, we consider an economy inhabited by a central bank and a continuum of monopolistically competitive firms with heterogeneous information. While a certain fraction of firms do not change their prices due to either price or information stickiness, the remainder of the firms re-adjust the prices of their outputs. Each of these firms observes an idiosyncratic signal about a demand shock.

We adopt the commonly accepted notion of substantial lags between the implementation of monetary policy and its maximum effects.[2] Consequently, some information obtained by the central bank may concern the near future, which cannot be influenced by conventional monetary policy measures. Then communication may be used as a substitute for these measures.

More specifically, we assume that the central bank acquires private information about demand at two points in time. Some information is available at the time when the central bank makes its decision regarding monetary policy. Additional information is discovered by the central bank after it has made its decision.

Accordingly, two types of transparency can be studied in our model. First, the central bank can publish the information underlying its decision. Henceforth we will refer to this kind of transparency as "decision transparency". Second, the central bank can

[1] For an interesting overview of central bank's communication practices, see Eijffinger and Geraats (2006).

[2] See Svensson (1999), among others.

publish the information it has received after locking in a particular course of monetary policy. We refer to this communication practice as "post-decision transparency".[3] We show that this distinction is crucial for the evaluation of the economic consequences of transparency.

Interestingly, in the absence of decision transparency private firms can always infer the respective information from the policy implemented by the central bank. Even so, decision opacity may be socially harmful. Two types of equilibria exist in this case. First, a fundamental equilibrium may occur, which involves the same outcomes as the equilibrium under decision transparency. Second, there are additional equilibria in which the central bank may have to incur large policy swings in order to signal the correct information. The policy swings result in large variances of output and inflation and thus, in turn, in large social losses. These detrimental additional equilibria can be eliminated by decision transparency.

With respect to post-decision transparency, i.e. the publication of information concerning the near future, which cannot be affected directly by the central bank, our results are ambiguous. First, post-decision transparency reduces the distortions arising from heterogeneous information; this is socially desirable. Second, post-decision transparency generally reduces output variance; in this sense communication actually serves as a substitute for conventional policy measures. Third, post-decision transparency increases social losses in terms of inflation variance. This is a consequence of the effect that publishing information about demand shocks widens the gap between the prices chosen by the firms that re-adjust their prices and the prices of the other firms.

On balance, post-decision transparency will be desirable from a social point of view if one of two conditions is met. First, society will always benefit from transparency if it values output stabilization sufficiently highly. Second, we identify a range of plausible parameter values ensuring that post-decision transparency is beneficial, irrespective of the relative significance of the output target in the social loss function.

[3] Decision transparency corresponds to economic transparency and post-decision transparency is equivalent to operational transparency in the taxonomy introduced by Geraats (2002).

We refrain from giving a detailed overview over the literature on transparency in monetary policy, which has been surveyed by Geraats (2002), Hahn (2002), and Blinder et al. (2008). Here we discuss only the papers most closely related to this analysis. In our paper, we consider heterogeneity of information across agents, which is often assumed away to simplify the analysis.[4] A notable exception is Morris and Shin (2002), who demonstrate that making the principal's signal publicly available induces agents to overreact to public information; this may be socially detrimental.[5] In our framework, complementarities in price setting also make agents react more strongly to public information compared to private information. However, this effect is socially beneficial because disregarding idiosyncratic information reduces distortionary relative price differences.

In our paper, we explore the possibility that agents attempt to infer the central bank's private information from its monetary-policy decision. Thus our papers belongs to the class of signaling models in monetary policy (see Gersbach and Hahn (2007, 2009), Sibert (2002, 2003, 2009), and Vickers (1986)). In Sibert (2009), the central bank has private information about both its desire to boost output through surprisingly high inflation and about the current efficiency of such a policy. In the present paper, the central bank has private information about demand shocks.

The paper is organized as follows. In Section 2 we lay out our model. We derive the solution if the central bank publishes the information underlying its decision in Section 3. In Section 4, we analyze the case where the central bank keeps this information secret. Welfare is considered in Section 5; here we also explore the potential merits of communication as a substitute for monetary policy. We discuss several extensions to our model and issues related to the robustness of our results in Section 6. Section 7 concludes.

[4]In a recent contribution, Berentsen and Strub (2009) study monetary policy in a framework with agents who have different utility functions. However, they do not analyze transparency.

[5]Svensson (2006) argues that for plausible parameter values transparency is beneficial in Morris and Shin's model.

# 2 Model

We consider a yeoman farmer model of price-setting under monopolistic competition presented, for example, in Rotemberg and Woodford (1997) and Woodford (2003), chapter 3. The economy is populated by a large number of agents denoted by $i$, uniformly distributed on the interval $[0; 1]$. Each agent produces a differentiated good using only his own labor. He sells his good and buys the other agents' goods from the proceeds.

Firms, i.e. consumer-producers, choose the prices $p_{ti}$ for their outputs in each period $t = 1, 2, \ldots$. The following price-setting equation can be derived from the respective microeconomic optimization problem (the details can be found in Woodford (2003), chapter 3):

$$p_t^* = p_t + \alpha y_t. \tag{1}$$

The (log) optimal price $p_t^*$ depends on the (log) aggregate price level $p_t$, which reflects strategic complementarities.[6] It also depends on (log) aggregate output $y_t$, which is common in macroeconomic models (see, e.g., Romer (2005), chapter 6). The optimal price may depend on aggregate output, because aggregate output affects the costs of inputs, such as the real wage, or because of diminishing returns. The positive parameter $\alpha$ determines how strongly output variations influence the firm's optimal price. In the following, we will often omit the time index $t$ when there is no danger of confusion.

We adopt the notion of sticky information, which has been introduced by Mankiw and Reis (2002). They argue that some firms may act on the basis of outdated information. The reason may be that information processing is costly and the benefits from always being well-informed may not be very large. More specifically, we assume that only a fraction $\lambda$ of firms update their information, while the remaining firms use outdated information. Without loss of generality, we arrange firms such that $[0; \lambda]$ corresponds to the set of firms updating their information. The interval $]\lambda; 1]$ comprises the firms using outdated information.

[6] We neglect the firm index for the optimal price $p_t^*$, because this price is identical for all firms.

It would be equivalent to consider sticky prices, which is the standard assumption in New Keynesian models. In particular, we could assume that all firms can freely choose their prices at the beginning of the period. Later, after additional information has become available, only a fraction $\lambda$ of firms could change their prices. The remaining firms would be stuck with the prices they have chosen at the beginning of the period.

In order to keep the model tractable, we adopt the assumption frequently used in the literature, namely that output is affected through a quantity equation[7]

$$y_t = m_t - p_t + \varepsilon_t, \tag{2}$$

where $m_t$ denotes (log) money, which is the central bank's instrument. In addition, we have introduced a demand shock $\varepsilon_t$ which is a normally distributed shock with expected value 0 and variance $\sigma_\varepsilon^2$. For simplicity, we consider shocks that are not correlated over time and identical for all firms in each period $t$.

The shock $\varepsilon_t$ is not known with certainty by the central bank when it conducts its monetary policy. Price-setters also have only imperfect information about $\varepsilon_t$ when they choose their prices. More specifically, the central bank receives a signal $s_{CB,0}$ before choosing $m$. This signal is normally distributed with variance $\sigma_{CB,0}^2$ and mean $\varepsilon_t$. In addition, the central bank obtains another signal $s_{CB,1}$ after it has adopted monetary policy. This signal is drawn from a normal distribution with variance $\sigma_{CB,1}^2$ and mean $\varepsilon_t$. Each individual price setter receives a normally distributed signal $s_i$ with variance $\sigma_i^2$ and mean $\varepsilon_t$. The precision of all firms' signals is identical, i.e. $\sigma_i^2$ is identical across firms. All variances are common knowledge; and all signals are independent from each other, conditional on $\varepsilon_t$. These assumptions imply, in particular, that the signals of price setters are different in general.

In Appendix A, we demonstrate that the following social loss function can be derived from microeconomic foundations

$$L_{SOC} = \pi_t^2 + a_{SOC} y_t^2 + b_{SOC} \operatorname*{Var}_{i \in [0,\lambda]} p_{ti}, \tag{3}$$

[7]See, e.g., Mankiw and Reis (2002).

where $a_{SOC}$ and $b_{SOC}$ are positive parameters and $\pi_t := p_t - p_{t-1}$ denotes the inflation rate. $\operatorname{Var}_{i\in[0,\lambda]} p_{ti}$ is the variance of the prices of agents on the interval $[0;\lambda]$, which comprises those agents who update their information.

Equation (3) encompasses the standard loss function that depends only on deviations of inflation from its target and from deviations of output from the natural level. The term $a_{SOC}y_t^2$ reflects the costs stemming from deviations of output from its socially optimal level. The terms $\pi_t^2$ and $b_{SOC} \operatorname{Var}_{i\in[0,\lambda]} p_{ti}$ capture the distortions arising from price dispersion in period $t$. First, the average price chosen by firms in $[0;\lambda]$ differs from the prices selected by firms in $]\lambda;1]$. This leads to losses proportional to $\pi_t^2$. Second, the firms in $[0;\lambda]$ choose different prices because of heterogeneous information. This results in the term proportional to $\operatorname{Var}_{i\in[0,\lambda]} p_{ti}$ in the social loss function. In Appendix A, we demonstrate that

$$b_{SOC} = \frac{\lambda^2}{1-\lambda}. \tag{4}$$

In principle, $a_{SOC}$ can also be pinned down by the parameters of the underlying yeoman-farmer model.

The central bank chooses $m_t$ to minimize the central bank loss function

$$L_{CB} = \pi_t^2 + a_{CB}y_t^2 + b_{CB} \operatorname*{Var}_{i\in[0,\lambda]} p_{ti}, \tag{5}$$

where $a_{CB}$ and $b_{CB}$ are weakly positive parameters. Parameter $a_{CB}$ describes the degree of the central bank's conservatism. If $a_{CB}$ is very high, then the central bank cares very much about output stabilization compared to inflation stabilization. This form of loss function implies that the central bank targets an inflation rate of 0 and the natural rate of output. We have included the term $b_{CB} \operatorname{Var}_{i\in[0,\lambda]} p_{ti}$ in (5) to make the central bank's loss function formally equivalent to the social loss function. However, the central bank cannot affect $\operatorname{Var}_{i\in[0,\lambda]} p_{ti}$ by its choice of $m_t$. Thus we can neglect this term when we calculate the central bank's optimal choice of monetary policy and set $b_{CB}$ to zero.

The sequence of events in every period $t$ is as follows:

1. All price-setters choose their default prices.

2. Nature draws the demand shock $\varepsilon$.
3. The central bank learns the value of $s_{CB,0}$.
4. Depending on the transparency regime (decision transparency or decision opacity), the central bank may or may not make $s_{CB,0}$ public.
5. The central bank selects $m$, which is publicly observable.
6. The central bank learns the value of $s_{CB,1}$.
7. Depending on the transparency regime (post-decision transparency or post-decision opacity), the central bank may or may not make $s_{CB,1}$ public.
8. Each firm in $[0;\lambda]$ privately observes the value of its signal $s_i$.
9. Firms in $[0;\lambda]$ choose their prices. The remaining firms leave their prices at the respective default levels.

# 3 Transparency of Information Underlying Monetary Policy

In this section we assume that the central bank publishes the information underlying its monetary-policy decision, i.e. $s_{CB,0}$. Moreover, we assume for the moment that the central bank also makes $s_{CB,1}$ public. As a first step, we specify each firm's estimate of $\varepsilon$:[8]

$$\mathbb{E}_i[\varepsilon] = \gamma_{CB,0}s_{CB,0} + \gamma_{CB,1}s_{CB,1} + \gamma_i s_i, \tag{6}$$

where we have introduced

$$\gamma_{CB,0} := \frac{\frac{1}{\sigma^2_{CB,0}}}{\frac{1}{\sigma^2_{CB,0}} + \frac{1}{\sigma^2_{CB,1}} + \frac{1}{\sigma^2_i} + \frac{1}{\sigma^2_\varepsilon}}, \tag{7}$$

$$\gamma_{CB,1} := \frac{\frac{1}{\sigma^2_{CB,1}}}{\frac{1}{\sigma^2_{CB,0}} + \frac{1}{\sigma^2_{CB,1}} + \frac{1}{\sigma^2_i} + \frac{1}{\sigma^2_\varepsilon}}, \tag{8}$$

$$\gamma_i := \frac{\frac{1}{\sigma^2_i}}{\frac{1}{\sigma^2_{CB,0}} + \frac{1}{\sigma^2_{CB,1}} + \frac{1}{\sigma^2_i} + \frac{1}{\sigma^2_\varepsilon}}. \tag{9}$$

[8] See DeGroot (1970).

If a firm has no information about the shock, it will always expect $\mathbb{E}[y] = 0$ and $\mathbb{E}[p] = p_{-1}$, where we use $p_{-1}$ to denote the price level of the previous period. This results from the observations that the central bank pursues an inflation target of zero and that demand shocks are zero on average. We can conclude from this that all firms choose their default prices equal to $p_{-1}$ at the beginning of the period. Using (1), (2) and (6), firm $i$'s price can be stated as

$$\begin{aligned} p_i &= \mathbb{E}_i[p] + \alpha(m - \mathbb{E}_i[p] + \mathbb{E}_i[\varepsilon]) \\ &= \alpha m + (1-\alpha)\left(\lambda \mathbb{E}_i[p_j] + (1-\lambda)p_{-1}\right) + \alpha\left(\gamma_{CB,0}s_{CB,0} + \gamma_{CB,1}s_{CB,1} + \gamma_i s_i\right), \end{aligned} \tag{10}$$

where $\mathbb{E}_i[p_j]$ is firm $i$'s expectation about the price chosen by an arbitrary other firm $j$ in $[0;\lambda]$. As we wish to focus on the case where there are complementarities in price setting, we assume $\alpha < 1$ for the remainder of the paper (see also Branch et al. (2009)). According to (10), this assumption guarantees that firm $i$'s price choice is a positive function of the other firms' prices.

We conjecture that $p_i$ can be written as

$$p_i = \psi_m m + \psi_{CB,0}s_{CB,0} + \psi_{CB,1}s_{CB,1} + \psi_i s_i + p_{-1}, \tag{11}$$

where $\psi_m$, $\psi_{CB,0}$, $\psi_{CB,1}$, and $\psi_i$ are coefficients left to be determined. Inserting (11) into (10), applying $\mathbb{E}_i[s_j] = E_i[\varepsilon]$, and equating coefficients gives

$$\psi_m = \frac{\alpha}{1-\lambda(1-\alpha)}, \tag{12}$$

$$\psi_{CB,0} = \frac{\alpha\gamma_{CB,0}}{(1-\lambda(1-\alpha))(1-\gamma_i\lambda(1-\alpha))}, \tag{13}$$

$$\psi_{CB,1} = \frac{\alpha\gamma_{CB,1}}{(1-\lambda(1-\alpha))(1-\gamma_i\lambda(1-\alpha))}, \tag{14}$$

$$\psi_i = \frac{\alpha\gamma_i}{1-\gamma_i\lambda(1-\alpha)}. \tag{15}$$

We assume that an appropriate law of large numbers holds and thus the average signal $s_i$ is identical to $\varepsilon$.[9] Consequently, with the help of (11) the aggregate price level can be written as $\lambda$ times the average price chosen by the firms in $[0;\lambda]$ plus $1-\lambda$ times $p_{-1}$, which is the price selected by the other firms in $]\lambda;1]$:

$$p = \lambda\left(\psi_m m + \psi_{CB,0}s_{CB,0} + \psi_{CB,1}s_{CB,1} + \psi_i\varepsilon\right) + p_{-1} \tag{16}$$

[9]See Judd (1985) and Uhlig (1996) for accounts how a law of large numbers can be stated for a continuum of IID random variables.

As a next step, we compute the central bank's optimal choice of $m$. Minimizing (5) subject to (16) and applying $\pi_t = p_t - p_{t-1} = p - p_{-1}$ yields the following first-order condition:

$$\mathbb{E}_{CB,0}\left[\lambda\psi_m p + a_{CB}(1-\lambda\psi_m)(m - p + \varepsilon)\right] = 0 \tag{17}$$

$\mathbb{E}_{CB,0}$ denotes the central bank's expectations after observing $s_{CB,0}$ but not $s_{CB,1}$. Utilizing (17) and $\mathbb{E}_{CB,0}[s_{CB,1}] = \mathbb{E}_{CB,0}[\varepsilon] = \hat{\gamma}_{CB,0}s_{CB,0}$ where

$$\hat{\gamma}_{CB,0} := \frac{1/\sigma^2_{CB,0}}{1/\sigma^2_{CB,0} + 1/\sigma^2_{\varepsilon}}, \tag{18}$$

we obtain

$$m = -\hat{\gamma}_{CB,0}s_{CB,0} + p_{-1}. \tag{19}$$

This result is highly plausible. The central bank chooses $m$ so as to eliminate the expected impact of the demand shock on output, which amounts to $\mathbb{E}_{CB,0}[\varepsilon] = \hat{\gamma}_{CB,0}s_{CB,0}$. Using $\mathbb{E}_{CB,0}[\varepsilon] = \mathbb{E}_{CB,0}[s_{CB,1}] = \hat{\gamma}_{CB,0}s_{CB,0}$ and $\hat{\gamma}_{CB,0}\psi_m = \psi_{CB,0} + (\psi_{CB,1} + \psi_i)\hat{\gamma}_{CB,0}$, which can be readily verified, (2) and (16), respectively, can be simplified to

$$\begin{aligned} \mathbb{E}_{CB,0}[\pi] &= 0, \\ \mathbb{E}_{CB,0}[y] &= 0. \end{aligned}$$

Hence because demand shocks involve no tradeoff between stabilizing output and inflation, the central bank can choose its instrument in a way such that both output and inflation are identical to their targets in expected terms. Equations (11)-(16) and (19) give a complete characterization of the equilibrium if the central bank publishes the information underlying its monetary-policy decision.

So far, we have derived the solution if the central bank operates under both decision transparency and post-decision transparency. It is crucial to note that it is straightforward to construct the solution under decision transparency and post-decision opacity. We simply have to set $\sigma^2_{CB,1} \to \infty$. In this case, the signal $s_{CB,1}$ published by the central bank becomes completely uninformative, which corresponds to post-decision opacity.

# 4 Opacity of Information Underlying Monetary Policy

While we have assumed so far that the central bank publishes the information that it has used to reach its decision, we consider in the following the case where the central bank keeps this information secret. Nevertheless the firms may be able to infer this information from the policy of the central bank. Consequently, the analysis of the present scenario corresponds to a signaling game. Like in the previous section, we initially adopt the assumption that $s_{CB,1}$ is public. By taking $\sigma^2_{CB,1}$ to infinity, the case where the central bank is completely silent with respect to both $s_{CB,0}$ and $s_{CB,1}$ is readily constructed.

We conjecture that the central bank's policy is a linear function of its signal $s_{CB,0}$:

$$m = \phi^O s_{CB,0} + p_{-1} \tag{20}$$

If $\phi^O = 0$ held, the equilibrium would correspond to a pooling equilibrium. Although it is somewhat tedious, it is immediate to show that such an equilibrium cannot exist.[10] Therefore we will consider $\phi^O \neq 0$ in the following. Particularly, we will determine possible values for the coefficient $\phi^O$. Moreover, we will show that for these values $m = \phi^O s_{CB,0} + p_{-1}$ actually corresponds to an optimal behavior of the central bank.

Importantly, firms can derive $s_{CB,0}$ by using (20). Thus the optimal price set by a firm is given by (11)-(15) with $s_{CB,0} = (m - p_{-1})/\phi^O$, i.e.

$$p_i = \psi_m m + \psi_{CB,0}\frac{m - p_{-1}}{\phi^O} + \psi_{CB,1}s_{CB,1} + \psi_i s_i + p_{-1}. \tag{21}$$

Analogously to (16), the price level under decision opacity is

$$p = \lambda\left(\psi_m m + \psi_{CB,0}\frac{m - p_{-1}}{\phi^O} + \psi_{CB,1}s_{CB,1} + \psi_i\varepsilon\right) + p_{-1}. \tag{22}$$

According to (22), the impact of a marginal change in $m$ is different from the respective effect in the scenario considered in the previous section because a change in $m$ also

[10]Intuitively, because the normal distribution extends to the entire range of real numbers, the central bank's estimate of the shock can be arbitrarily large. For extremely large expected shocks, the central bank will always find it beneficial to deviate from $m = p_{-1}$.

influences the firms' estimate of the central bank's signal $s_{CB,0}$. This observation constitutes the main difference between the scenario where the central bank distributes the information that led to its decision and the one where this information is kept private.

In Appendix B, we demonstrate that two solutions for $\phi^O$ exist, which correspond to two different equilibria:

$$\phi^O_{fund} = -\hat{\gamma}_{CB,0} \tag{23}$$

$$\phi^O_{add} = -\frac{\lambda\psi_m - a_{CB}(1-\lambda\psi_m)}{\lambda^2\left(\psi_m\right)^2 + a_{CB}(1-\lambda\psi_m)^2}\lambda\psi_{CB,0} \tag{24}$$

We label the first solution, $\phi^O_{fund}$, fundamental because it is identical to the solution when the central bank is transparent about its signal $s_{CB,0}$ (compare (19)). The additional solution $\phi^O_{add}$, however, arises only if the central bank withholds its information about $s_{CB,0}$.

We summarize our findings in the following proposition:

**Proposition 1**

*If the central bank does not publish its private information about $s_{CB,0}$, two equilibria exist. In both equilibria, the firms choose their prices in line with* (21)*. In the fundamental equilibrium, the central bank pursues the same policy as in the case where it publishes $s_{CB,0}$, i.e. $m = -\hat{\gamma}_{CB,0}s_{CB,0} + p_{-1}$. In the additional equilibrium, the central bank chooses $m = \phi^O_{add}s_{CB,0} + p_{-1}$, where $\phi^O_{add}$ is given by* (24).

While we have focused on the case with decision opacity and post-decision transparency in this section, the results for a combination of decision opacity and post-decision opacity can be easily obtained by taking $\sigma^2_{CB,1}$ to infinity. Having derived the equilibria for all transparency regimes considered in this paper, we now turn to an analysis of welfare.

# 5 Welfare

With respect to the fundamental equilibrium, the welfare consequences of the publication of $s_{CB,0}$ are clear because the fundamental equilibrium is identical to the solution under decision transparency. However, it is unclear as yet whether the additional equilibrium leads to lower or higher social losses over and against the scenario with decision transparency. This question is addressed in this section. Moreover, we examine the impact of post-decision transparency on welfare.

## 5.1 Additional Equilibrium vs. Fundamental Equilibrium

The following proposition, which is proved in Appendix C, compares the fundamental equilibrium and the additional equilibrium with respect to welfare.

**Proposition 2**

*The additional equilibrium always leads to higher expected values of* $\pi_t^2 + b_{SOC}\,\mathrm{Var}_{i\in[0,\lambda]}\,p_{ti}$ *and* $y_t^2$. *Consequently, the additional equilibrium unequivocally involves lower welfare.*

In a fundamental equilibrium, the central bank behaves exactly as it would if it published the information that forms the basis of its decision. Consequently, it chooses $m$ so as to exactly offset the expected impact of the shock $\varepsilon$ on output.

In an additional equilibrium, the central bank does not behave in the same manner as in the scenario where it publishes information in tandem with its monetary-policy decision. If it did, the firms would form an incorrect estimate of the central bank's signal and therefore opt for grossly inaccurate prices. Thus the central bank is forced to select money growth rates that stabilize the consequences of demand shocks for output and inflation inefficiently. As a result, the additional equilibrium is socially harmful irrespective of the relative weight society attaches to output stabilization ($a_{SOC}$).

Thus we arrive at the important conclusion that the central bank should always publicize the information that led to its decision. If it does not, the public will be able to derive the information from the policy chosen by the central bank anyway. However, the central bank is more constrained in this case as it always has to take into account the impact its policy has on private expectations. This effect leads to inefficient outcomes of monetary policy.

## 5.2 Publishing Information the Central Bank Obtains after its Decision

In the following, we assume that the central bank behaves socially optimally with respect to decision transparency and publishes $s_{CB,0}$. The next step is to evaluate whether transparency of the information $s_{CB,1}$, which the central bank receives after it has chosen monetary policy, is desirable. This can be achieved by comparing the solutions obtained under decision transparency for $\sigma^2_{CB,1} \to \infty$ with the solution for a finite value of $\sigma^2_{CB,1}$.

In particular, it will be useful to examine hypothetical marginal decreases in $\sigma^2_{CB,1}$, which correspond to marginal improvements in the quality of signal $s_{CB,1}$. First, post-decision transparency will be beneficial if marginal improvements in the quality of $s_{CB,1}$ are always desirable. Second, studying marginal increases in signal quality may be interesting in its own right because small changes in signal quality can be interpreted as small improvements in transparency.[11] Formally, this can be modeled by increasing $\sigma^2_{CB,1}$ above its minimum level, which is given by the precision of the central bank's information.

We examine the three components of the social loss function (3) separately, namely $\pi_t^2$, $y_t^2$, and $\mathrm{Var}_{i\in[0,\lambda]}\, p_{ti}$. In Appendix D, we analyze the impact that improving the quality of $s_{CB,1}$ has on the variance of the prices chosen by the firms that update their information:

**Proposition 3**

*The ex-ante expected value of* $\mathrm{Var}_{i\in[0,\lambda]}\, p_{ti}$ *decreases for any marginal reduction in* $\sigma^2_{CB,1}$.

[11] Transparency is modeled as a continuous rather than a dichotomous variable by Cukierman and Meltzer (1986) and Faust and Svensson (2002), among others.

This has the immediate consequence that the publication of the central bank's signal $s_{CB,1}$ is always desirable in terms of $\text{Var}_{i\in[0,\lambda]}\, p_{ti}$. Intuitively, if the central bank publishes $s_{CB,1}$, this additional source of information will induce firms to pay less attention to their own heterogeneous signals when they choose their prices. This leads to a reduction in $\text{Var}_{i\in[0,\lambda]}\, p_{ti}$.

It is instructive to relate this finding to Morris and Shin (2002), who identify a socially harmful overreaction of agents to public signals. In our paper, firms respond to the different sources of information according to (11). More specifically, the coefficients $\psi_i$, $\psi_{CB,0}$, and $\psi_{CB,1}$ (see (13)-(15)) measure how strongly the different sources of information influence firms' behavior. Suppose for the moment that all signals $s_i$, $s_{CB,0}$, and $s_{CB,1}$ had the same variance and were equally precise accordingly. This would imply $\gamma_i = \gamma_{CB,0} = \gamma_{CB,1} =: \gamma$. As a consequence,

$$\begin{aligned} \psi_{CB,0} &= \psi_{CB,1} = \frac{\alpha\gamma}{(1-\lambda(1-\alpha))(1-\gamma\lambda(1-\alpha))}, \\ \psi_i &= \frac{\alpha\gamma}{1-\gamma\lambda(1-\alpha)}. \end{aligned}$$

Importantly, $\psi_{CB,0} = \psi_{CB,1} > \psi_i$. Thus the responses of firms to the public signals $s_{CB,0}$ and $s_{CB,1}$ are stronger compared to their responses to the private signals. Because each individual firm knows that the other firms also incorporate information about $s_{CB,0}$ and $s_{CB,1}$ into their prices, the complementarities in price setting induce a more pronounced reaction to these pieces of information than to the idiosyncratic signals $s_i$. However, this stronger response to publicly available signals is not socially harmful as in Morris and Shin (2002) because heterogeneous prices are distortionary in our framework.

As a next step we examine the expected value of $\pi_t^2$.

**Proposition 4**

*The ex-ante expected value of $\pi_t^2$ is increasing for any marginal reduction in $\sigma_{CB,1}^2$.*

The proof is given in Appendix E.

We obtain as a corollary that publishing $s_{CB,1}$ always leads to a reduction in welfare in terms of inflation variance, as the absence of post-decision transparency can be modeled by letting $\sigma^2_{CB,1} \to \infty$.

The proposition follows from the observation that the expected value of $\pi_t^2$ corresponds to the distortions accruing from the difference between the average prices of the firms in $[0;\lambda]$ and in $]\lambda;1]$. Recall that the firms in $]\lambda;1]$ do not re-adjust their prices. By contrast, the firms in $[0;\lambda]$ adapt their prices in line with the available information. The more precise this information is, the more strongly is these firms' response to demand shocks. This effect is responsible for the larger expected value of $\pi_t^2$ if the central bank publishes $s_{CB,1}$.

Having analyzed the impacts of post-decision transparency on the two terms capturing relative price distortions separately, we evaluate the respective impact on the sum of these two terms. Accordingly, we study how $\pi_t^2 + b_{SOC} \operatorname{Var}_{i\in[0,\lambda]} p_{ti}$ with $b_{SOC} = \lambda^2/(1-\lambda)$ (see (4)) is affected by post-decision transparency. For this purpose, we introduce a range of plausible parameter values. Usually values of $\alpha \approx 0.1$ are considered in the literature (see Mankiw and Reis (2002), among others). Additionally, we assume $\gamma_i < \gamma_{CB,0} + \gamma_{CB,1}$, which, loosely speaking, implies that the precision of an individual firm's signal is lower than the precision of a combination of both signals of the central bank.[12] This inequality can be combined with $\gamma_i < 1 - \gamma_{CB,0} - \gamma_{CB,1}$ to yield $\gamma_i < 1/2$. Finally, we introduce the assumption $\lambda \leq 0.8$, which implies that no more than 80% of firms adjust their prices in each period. For this range of parameter values, we use numerical simulations to show

**Numerical Finding 1**

*For* $\alpha = 0 \ldots 0.2$, $\lambda = 0 \ldots 0.8$, *and* $\gamma_i = 0 \ldots 0.5$, *post-decision transparency involves a lower value of* $\pi_t^2 + \lambda^2/(1-\lambda) \operatorname{Var}_{i\in[0,\lambda]} p_{ti}$ *than post-decision opacity.*

Thus for an important range of parameter values the reduction in $b_{SOC} \operatorname{Var}_{i\in[0,\lambda]} p_{ti}$ induced by post-decision transparency outweighs the increase in the expected value of

[12] Romer and Romer (2000) and Peek et al. (2003) find empirical support for the hypothesis that central banks are better-informed than private agents.

$\pi_t^2$. Equivalently, post-decision transparency reduces the distortions associated with relative price distortions.

Finally, we turn to the impact post-decision transparency has on the deviations of output from potential output. In Appendix F we show

**Proposition 5**
*If $\gamma_i < \frac{1}{1+\alpha}$, then a marginal reduction in $\sigma^2_{CB,1}$ leads to a reduction in the ex-ante expected value of $y^2$.*

Hence improving the precision of the information obtained by the central bank after it has made its decision reduces output variance if the condition specified in the proposition holds.

Even for arbitrary values of $\alpha$ with $0 < \alpha < 1$, $\gamma_i < \frac{1}{1+\alpha}$ is likely to be fulfilled. Recall that $\gamma_i < 1/2$ is plausible to hold because the central bank's information is unlikely to be inferior to the information of an individual firm. We note that $1/2 < 1/(1+\alpha)$, irrespective of the value of $\alpha \in ]0;1[$. Consequently, proposition 5 can be applied for $\gamma_i < 1/2$.

To sum up, we have demonstrated that publishing information after the central bank has made its monetary-policy decision has ambiguous effects on welfare. First, it lowers the distortions stemming from heterogeneous information by causing price setters to ascribe less significance to their heterogeneous signals. Second, post-decision transparency drives the prices of the firms who update their information away from the prices of the other firms. This effect is socially harmful. Third, publicizing information that becomes available after monetary policy has been conducted reduces output variance. In this sense, transparency can serve as a substitute for stabilization policy.

Post-decision transparency is definitely desirable from an overall perspective if at least one of the following two conditions is fulfilled. First, it is desirable if society attaches a high significance to output stabilization. Then the term $y^2$ dominates social losses. This term is unequivocally lowered by post-decision transparency under the plausible assumption $\gamma_i < \frac{1}{1+\alpha}$. Second, post-decision transparency is socially beneficial for the parameter range considered in Numerical Finding 1. Only if both requirements are not met is it possible for post-decision transparency to be harmful.

## 6 Extensions and Robustness

In this section we discuss possible extensions to our framework and the robustness of our results. We focus on the following issues: the nature of shocks, endogenous attentiveness, and the potential conflict between the central bank and society with respect to transparency.

**Nature of shocks** While in our paper we have considered demand shocks, it is easily verified that our findings extend to a framework with shocks to the natural level of output. Such a re-interpretation of our model is interesting because there is no universally agreed upon method of measuring current natural output, which plausibly results in very different estimates of its size.

**Endogenous attentiveness** Two recent contributions study endogenous attentiveness, i.e. models where information processing is costly and price setters choose optimally whether they update their information (see Reis (2006) and Branch et al. (2009)). One could also extend the framework in this paper along these lines. Transparency is likely to increase the benefits from information processing and thus firms' overall attentiveness. Interestingly, the complementarities in price setting will translate into complementarities in information acquisition. Information acquisition will involve negative externalities because the decision of an individual agent to gather information reduces the profits of uninformed agents. These negative externalities tend to cause the fraction of firms that readjust their prices to be higher than the socially optimal value. However, if this effect is not particularly strong, our findings would extend to such a framework.[13]

[13] Akerlof and Yellen (1985) argue that the costs of adjusting prices, despite having substantial economic effects, are very small. Thus the costs of adjusting prices or of acquiring information may not be directly relevant for the function describing aggregate welfare.

**Potential conflict of interests** Suppose the central bank could determine freely its transparency degree. Would it deliver the optimal degree of transparency in our model? While it would be optimal for the central bank to provide an analysis of the information underlying its decisions if its interests were accurately described by the loss function (5) (and thus there were no additional motives for opacity), a discrepancy may arise between the socially optimal level of post-decision transparency and the one preferred by the central bank. For example, let us assume that the central bank's weight on the output target is identical to the respective weight in the social loss function, i.e. $a_{CB} = a_{SOC}$. Moreover, as no central bank is endowed with an objective of eliminating relative price distortions in addition to the objective of stabilizing inflation, we can plausibly assume $b_{CB} = 0$. In this case, the central bank disregards one of the benefits of post-decision transparency, namely the reduction of distortionary price variation. If the central bank neglects this effect, it will generally select a transparency degree that is too low compared to the socially optimal level. This potential conflict of interests is further exacerbated by the fact that most central bankers are more conservative than society, i.e. put a higher emphasis on inflation stabilization vis-à-vis output stabilization. Because post-decision transparency ameliorates deviations of output from its target, while raising inflation variance, conservative central bankers' choice of transparency may be biased towards opacity.

Hence our model may shed some light on the observation that many central banks became more transparent only as a result of substantial outside pressure. For example, the Federal Reserve fended off early attempts to force it to release more information (see Goodfriend (1986)). Similarly, the European Central Bank was under heavy criticism in its start-up period for being opaque (see Buiter (1999), among others). Since then it has become gradually more transparent.

# 7 Conclusions

In this paper we have examined the costs and benefits of central-bank transparency in the presence of heterogeneous information. We have shown that central banks should always publish the information underlying their decisions because withholding this information may lead to additional equilibria with adverse consequences for the variance of output and inflation.

In addition, we have argued that central banks may not be able to affect the economy in the very short term due to long time lags between policy implementation and its impact on output and prices. Then communication may be used as an alternative means of influencing these economic variables. On the positive side, communication reduces the distortions arising from heterogeneous information and can be used to stabilize output. On the negative side, communicating the central bank's private information may lead to a larger inflation variance. Overall, society will benefit from post-decision transparency if it puts sufficient emphasis on output stabilization. Moreover, we have identified a range of plausible parameter values for which post-decision transparency is beneficial irrespective of the weight on output stabilization in the social loss function.

Despite the potential benefits of transparency for society, central bankers may have incentives to choose a degree of post-decision transparency that is too low compared to the social optimum. First, while central bankers are usually concerned with the level of inflation, they may not take into account the additional beneficial effects of transparency arising from the reduction of relative price distortions. Second, conservative central bankers, which place lower emphasis on output stabilization than society, may not fully internalize the socially desirable impact of transparency on output.

# A Derivation of (3)

Woodford (2002) shows that optimal monetary policy involves a minimization of a weighted average of the variance of prices and the variance of output. We apply this result and derive an expression for the variance of prices in the context of our model.

The prices of the firms in $[0;\lambda]$ can be written as the sum of a common and an idiosyncratic part, i.e.

$$p_i = \overline{p} + p_{-1} + \mu_i, \tag{25}$$

where $\overline{p}$ is the difference between the average price of the firms in $[0;\lambda]$ and $p_{-1}$. Additionally, $(\mu_i)_{i=0}^1$ are the idiosyncratic components of $(p_i)_{i=0}^1$, which satisfy $\int_{i=0}^{\lambda} \mu_i \, di = 0$. Using the fact that the firms in $]\lambda;1]$ choose $p_{-1}$, which implies $p = \lambda(\overline{p} + p_{-1}) + (1-\lambda)p_{-1}$ and thus $\overline{p} = (p - p_{-1})/\lambda$, (25) can be stated as

$$\begin{aligned} p_i &= \frac{p - p_{-1}}{\lambda} + p_{-1} + \mu_i \\ &= \frac{\pi}{\lambda} + p_{-1} + \mu_i. \end{aligned} \tag{26}$$

Applying (26) and $\int_{i=0}^{\lambda} \mu_i \, di = 0$, the variance of prices in our model can be written as

$$\begin{aligned} \operatorname*{Var}_{i\in[0;1]} p_i &= \int_{i=0}^{\lambda} (p_i - p)^2 \; di + \int_{\lambda}^{1} (p_{-1} - p)^2 \; di \\ &= \int_{i=0}^{\lambda} \left(\frac{\pi}{\lambda} + p_{-1} - p + \mu_i\right)^2 \; di + (1-\lambda)\pi^2 \\ &= \int_{i=0}^{\lambda} \left(\frac{\pi}{\lambda} - \pi\right)^2 \; di + \int_{i=0}^{\lambda} \mu_i^2 \, di + (1-\lambda)\pi^2 \\ &= \lambda\left(\frac{1}{\lambda} - 1\right)^2 \pi^2 + \lambda \operatorname*{Var}_{i\in[0,\lambda]} p_i + (1-\lambda)\pi^2 \\ &= \frac{1-\lambda}{\lambda}\pi^2 + \lambda \operatorname*{Var}_{i\in[0,\lambda]} p_i. \end{aligned}$$

Finally, we explain how this expression for $\operatorname{Var}_{i\in[0;1]} p_i$ relates to the respective expression found in the literature on models with pre-determined prices and homogeneous information. Because the central bank targets an inflation rate of zero, we have concluded in the course of our analysis that $\mathbb{E}[p] = p_{-1}$, where $\mathbb{E}[p]$ denotes ex-ante expectations, i.e. expectations that are formed before information about $\varepsilon$ is available. $\mathbb{E}[\pi] = 0$, which is equivalent to $\mathbb{E}[p] = p_{-1}$, yields the following expression for $\operatorname{Var}_{i\in[0;1]} p_i$:

$$\operatorname*{Var}_{i\in[0;1]} p_i = \frac{1-\lambda}{\lambda}(\pi - \mathbb{E}[\pi])^2 + \lambda \operatorname*{Var}_{i\in[0,\lambda]} p_i \tag{27}$$

The first summand of this expression can also be found in Woodford (2002), p. 19, for a model with predetermined prices. The second term is unique to this model and is a consequence of the price differences caused by heterogeneous information.

Equation (27) implies that social losses depend on the difference of the price level from the expected price level, because $(\pi - \mathbb{E}[\pi])^2 = (p - \mathbb{E}[p])^2$ enters the social loss function. As a consequence, infinitely many paths of the price level are equivalent with respect to welfare.

However, we have singled out one of the expected paths of the price level by assuming that the central bank targets an inflation rate of 0, which implies $\mathbb{E}[p] = p_{-1}$. The assumption that the central bank chooses this particular path, which involves zero expected inflation, can be justified by introducing some (possibly very small) costs of inflation that are not captured by our model.

Hence, the social loss function can be written as (3) with $b_{SOC} = \frac{\lambda^2}{1-\lambda}$. In principle, parameter $a_{SOC}$ could also be derived from the structural parameters of the underlying yeoman farmer model.

□

# B Derivation of (23) and (24)

In this appendix, we derive the optimal policy of the central bank under the assumption that $s_{CB,0}$ remains secret. Minimizing (5) subject to (2) and (22) results in the first-order condition:

$$\mathbb{E}_{CB,0}\left[\lambda\left(\psi_m + \frac{\psi_{CB,0}}{\phi^O}\right)(p - p_{-1}) + a_{CB}\left(1 - \lambda\left(\psi_m + \frac{\psi_{CB,0}}{\phi^O}\right)\right)(m - p + \varepsilon)\right] = 0.$$

Rearranging terms yields

$$\begin{aligned}&\left[\lambda\left(\psi_m+\frac{\psi_{CB,0}}{\phi^O}\right)-a_{CB}\left(1-\lambda\left(\psi_m+\frac{\psi_{CB,0}}{\phi^O}\right)\right)\right]\mathbb{E}_{CB,0}[p]\\&-\lambda\left(\psi_m+\frac{\psi_{CB,0}}{\phi^O}\right)p_{-1}+a_{CB}\left(1-\lambda\left(\psi_m+\frac{\psi_{CB,0}}{\phi^O}\right)\right)(m+\mathbb{E}_{CB,0}[\varepsilon])=0.\end{aligned}\tag{28}$$

In equilibrium,

$$\mathbb{E}_{CB,0}[p]=\lambda\left(\psi_m\phi^O+\psi_{CB,0}+(\psi_{CB,1}+\psi_i)\hat{\gamma}_{CB,0}\right)s_{CB,0}+p_{-1}\tag{29}$$

must hold, which follows from (22), $m=\phi^O s_{CB,0}+p_{-1}$, and $\mathbb{E}_{CB,0}[\varepsilon]=\hat{\gamma}_{CB,0}s_{CB,0}$. It is readily verified that

$$\hat{\gamma}_{CB,0}\psi_m=\psi_{CB,0}+(\psi_{CB,1}+\psi_i)\hat{\gamma}_{CB,0}.\tag{30}$$

Using (30), (29) can be simplified further to

$$\mathbb{E}_{CB,0}[p]=\lambda\psi_m(\phi^O+\hat{\gamma}_{CB,0})s_{CB,0}+p_{-1}.\tag{31}$$

Together with $\mathbb{E}_{CB,0}[\varepsilon]=\hat{\gamma}_{CB,0}s_{CB,0}$, (31) enables us to rewrite (28) as

$$\begin{aligned}&\left[\lambda\left(\psi_m+\frac{\psi_{CB,0}}{\phi^O}\right)-a_{CB}\left(1-\lambda\left(\psi_m+\frac{\psi_{CB,0}}{\phi^O}\right)\right)\right]\left[\lambda\psi_m(\phi^O+\hat{\gamma}_{CB,0})s_{CB,0}+p_{-1}\right]\\&-\lambda\left(\psi_m+\frac{\psi_{CB,0}}{\phi^O}\right)p_{-1}+a_{CB}\left(1-\lambda\left(\psi_m+\frac{\psi_{CB,0}}{\phi^O}\right)\right)\left[\left(\phi^O+\hat{\gamma}_{CB,0}\right)s_{CB,0}+p_{-1}\right]=0,\end{aligned}$$

which, in turn, simplifies to

$$\begin{aligned}&\left[\lambda\left(\psi_m+\frac{\psi_{CB,0}}{\phi^O}\right)-a_{CB}\left(1-\lambda\left(\psi_m+\frac{\psi_{CB,0}}{\phi^O}\right)\right)\right]\lambda\psi_m(\phi^O+\hat{\gamma}_{CB,0})s_{CB,0}\\&\qquad+a_{CB}\left(1-\lambda\left(\psi_m+\frac{\psi_{CB,0}}{\phi^O}\right)\right)\left(\phi^O+\hat{\gamma}_{CB,0}\right)s_{CB,0}=0.\end{aligned}$$

As this equality must hold for all realizations of $s_{CB,0}$, we obtain

$$\left[\lambda^2\psi_m\left(\psi_m+\frac{\psi_{CB,0}}{\phi^O}\right)+a_{CB}\left(1-\lambda\left(\psi_m+\frac{\psi_{CB,0}}{\phi^O}\right)\right)(1-\lambda\psi_m)\right](\phi^O+\hat{\gamma}_{CB,0})=0.$$

Multiplying by $\phi^O$ yields a quadratic equation in $\phi^O$:

$$\left[\lambda^2\psi_m\left(\phi^O\psi_m+\psi_{CB,0}\right)+a_{CB}\left(\phi^O(1-\lambda\psi_m)-\lambda\psi_{CB,0}\right)(1-\lambda\psi_m)\right](\phi^O+\hat{\gamma}_{CB,0})=0.$$

This equation has two solutions, namely

$$\begin{aligned}\phi^O_{fund}&=-\hat{\gamma}_{CB,0},\\\phi^O_{add}&=-\frac{\lambda\psi_m-a_{CB}(1-\lambda\psi_m)}{\lambda^2(\psi_m)^2+a_{CB}(1-\lambda\psi_m)^2}\lambda\psi_{CB,0}.\end{aligned}$$

□

# C Proof of Proposition 2

## C.1 The Expected Value of $\mathbf{y^2}$

First we compare the expected value of $y^2$ under the fundamental equilibrium and under the additional equilibrium. In both cases it is given by

$$\begin{aligned}
\mathbb{E}[y^2] &= \mathbb{E}[(m-p+\varepsilon)^2] \\
&= \mathbb{E}\left[\left(\phi^O s_{CB,0} - \lambda\left(\left(\psi_m\phi^O + \psi_{CB,0}\right)s_{CB,0} + \psi_{CB,1}s_{CB,1} + \psi_i\varepsilon\right) + \varepsilon\right)^2\right] \\
&= \mathbb{E}\left[\left(\left(\phi^O(1-\lambda\psi_m) - \lambda\psi_{CB,0}\right)s_{CB,0} - \lambda\psi_{CB,1}s_{CB,1} + (1-\lambda\psi_i)\varepsilon\right)^2\right] \\
&= \left(\left(\phi^O(1-\lambda\psi_m) - \lambda\psi_{CB,0}\right)s_{CB,0} - \lambda\psi_{CB,1}s_{CB,1} + (1-\lambda\psi_i)\varepsilon\right)^2\sigma_\varepsilon^2 \\
&\qquad + \left(\phi^O(1-\lambda\psi_m) - \lambda\psi_{CB,0}\right)^2\sigma_{CB,0}^2 + \lambda^2(\psi_{CB,1})^2\sigma_{CB,1}^2,
\end{aligned}$$

where the first line uses (2); the second uses (22); the third can be obtained be rearranging terms; and the fourth utilizes $\mathbb{E}[\varepsilon^2] = \mathbb{E}[\varepsilon \cdot s_{CB,0}] = \mathbb{E}[\varepsilon \cdot s_{CB,1}] = \sigma_\varepsilon^2$, $\mathbb{E}[s_{CB,0}^2] = \sigma_\varepsilon^2 + \sigma_{CB,0}^2$ and $\mathbb{E}[s_{CB,0}^2] = \sigma_\varepsilon^2 + \sigma_{CB,1}^2$. With the help of (12)-(15), it is tedious but straightforward to calculate the difference between this expression for $\phi^O = \phi^O_{add}$ (see (24)) and $\phi^O = \phi^O_{fund}$ (see (23)) as

$$\begin{aligned}
&\frac{\sigma_\varepsilon^2\,\gamma_{CB,0}\,(1-\lambda)^2}{(\lambda^2\alpha^2 + a(1-\lambda)^2)^2\,(1-\gamma_i-\gamma_{CB,1})\,(1-\lambda(1-\alpha))^2\,(1-\lambda\,\gamma_i\,(1-\alpha))^2} \\
&\qquad\cdot\Big[(1-(1-\alpha)\,\lambda)\,\lambda\,\left(\alpha^2\lambda - a\,(1-\lambda)\right)\gamma_i \\
&\qquad\qquad + \lambda\,\alpha\,(\lambda\,\alpha - a\,(1-\lambda))\,\gamma_{CB,1} + a\,(1-\lambda)\,(1-(1-\alpha)\,\lambda)\Big]^2.
\end{aligned}$$

Because this expression is always weakly positive, $\mathbb{E}[y^2]$ is always higher under an additional equilibrium over and against a fundamental equilibrium.

## C.2 The Expected Value of $\pi_t^2 + \frac{\lambda^2}{1-\lambda}\,\mathrm{Var}_{i\in[0,\lambda]}\,p_{ti}$

It is again straightforward but extremely tedious to compute the difference between $\pi_t^2 + \frac{\lambda^2}{1-\lambda}\,\mathrm{Var}_{i\in[0,\lambda]}\,p_{ti}$ for an additional equilibrium and the respective equilibrium under a fundamental equilibrium. For this reason, we simply give the respective expression:

$$\frac{\left[\lambda\alpha\,(\lambda\alpha - a\,(1-\lambda))\,\gamma_{CB,1} + (1-(1-\alpha)\,\lambda)\,(\lambda^2\gamma_i\alpha^2 + a(1-\lambda)(1-\lambda\gamma_i))\right]^2}{\left(a\,(1-\lambda)^2 + \lambda^2\alpha^2\right)^2(1-\gamma_i-\gamma_{CB,1})\,(1-(1-\alpha)\,\lambda)^2\,(1-\lambda\gamma_i\,(1-\alpha))^2}\lambda^2\alpha^2\gamma_{CB,0}\sigma_\varepsilon^2$$

This expression is always weakly positive. Hence expected social losses are higher under the additional equilibrium over and against the fundamental equilibrium.

□

# D Proof of Proposition 3

In line with the law of large numbers, $\text{Var}_{i\in[0,\lambda]}\, p_i$ can be written as

$$\underset{i\in[0,\lambda]}{\text{Var}}\, p_i = \lambda(\psi_i)^2\sigma_i^2. \tag{32}$$

Inserting (15) yields

$$\underset{i\in[0,\lambda]}{\text{Var}}\, p_i = \lambda\frac{\alpha^2\gamma_i^2}{(1-\gamma_i\lambda(1-\alpha))^2}\sigma_i^2. \tag{33}$$

As this is a monotonically increasing function of $\gamma_i$, and $\gamma_i$ is a monotonically increasing function of $\sigma_{CB,1}^2$, Proposition 3 holds.

□

# E Proof of Proposition 4

In order to evaluate the impact of a marginal change in $\sigma_{CB,1}^2$ on $\mathbb{E}[\pi^2] = \mathbb{E}[(p-p_{-1})^2]$, we derive an expression for $\mathbb{E}[\pi^2]$ in equilibrium. This is straightforward and can be achieved by combining (12)-(15) and (16). However, as the respective calculations are rather tedious, we simply give the solution here:

$$\mathbb{E}[\pi^2] = \frac{\left[(1-\lambda-\lambda\,(1-\lambda+\alpha^2\lambda)\,\gamma_i)\,\gamma_{CB,1} + \gamma_i\,(1-\lambda(1-\alpha))^2\,(1-\lambda\gamma_i)\right]}{(1-\lambda\gamma_i(1-\alpha))^2\,(1-\lambda(1-\alpha))^2} \cdot \frac{(1-\hat{\gamma}_{CB,0})\,\lambda^2\alpha^2\sigma_\varepsilon^2}{1-\lambda} \tag{34}$$

Using (7)-(9) and (18) we can form the derivative of (34) with respect to $\sigma_{CB,1}^2$

$$\frac{d\,\mathbb{E}[\pi^2]}{d\,\sigma_{CB,1}^2} = -\frac{\lambda^2\alpha^2\gamma_{CB,1}^2\,(3\lambda\gamma_i\alpha+1-3\lambda\gamma_i+2\gamma_i)}{(1-\lambda\gamma_i(1-\alpha))^3\,(1-\lambda(1-\alpha))^2}. \tag{35}$$

We note that the enumerator is strictly positive for all admissible parameter values. Consequently, (35) is negative, which is equivalent to the statement of the proposition.

□

# F Proof of Proposition 5

Using (2) and (12)-(16) it is possible to compute $\mathbb{E}[y^2]$:

$$\mathbb{E}[y^2] = \frac{(1-\hat{\gamma}_{CB,0})\left(\frac{\lambda\alpha\gamma_{CB,1}(\lambda(-2\lambda+2\lambda\alpha+2-\alpha)\gamma_i+2\lambda-\lambda\alpha-2)}{(1-\lambda(1-\alpha))^2}+(1-\lambda\gamma_i)^2\right)}{(1-\lambda\gamma_i(1-\alpha))^2}\sigma_\varepsilon^2 \tag{36}$$

With the help of (7)-(9) and (18), the derivative of (34) with respect to $\sigma_{CB,1}^2$ can be stated as

$$\frac{d\,\mathbb{E}[y^2]}{d\,\sigma_{CB,1}^2} = \frac{\lambda\gamma_{CB,1}^2\alpha\left\{2(1-\lambda)+\lambda\alpha-\lambda\gamma_i\left[2(1-\lambda)+\lambda\alpha(1+\alpha)\right]\right\}}{(1-\lambda\gamma_i(1-\alpha))^3\,(1-\lambda(1-\alpha))^2}. \tag{37}$$

This expression is strictly positive if and only if

$$2(1-\lambda)+\lambda\alpha-\lambda\gamma_i\left[2(1-\lambda)+\lambda\alpha(1+\alpha)\right] > 0 \tag{38}$$

or, equivalently,

$$\gamma_i < \frac{1}{\lambda}\cdot\frac{2(1-\lambda)+\lambda\alpha}{2(1-\lambda)+\lambda\alpha(1+\alpha)}. \tag{39}$$

The claim of the proposition can be established by showing that the right-hand side of this inequality is larger than $1/(1+\alpha)$:

$$\frac{1}{\lambda}\cdot\frac{2(1-\lambda)+\lambda\alpha}{2(1-\lambda)+\lambda\alpha(1+\alpha)} > \frac{1}{1+\alpha}, \tag{40}$$

which can be reformulated as

$$(1+\alpha)\,(2(1-\lambda)+\lambda\alpha) \;>\; \lambda[2(1-\lambda)+\lambda\alpha(1+\alpha)] \tag{41}$$

$$2(1+\alpha-\lambda)(1-\lambda)+\lambda\alpha(1+\alpha)(1-\lambda) \;>\; 0. \tag{42}$$

Condition (42), which holds for all admissible parameter values, thus implies $\frac{d\,\mathbb{E}[y^2]}{d\,\sigma_{CB,1}^2} > 0$ for $\gamma_i < \frac{1}{1+\alpha}$. Hence we have proved the proposition.

□

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