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Output Gaps and Robust Monetary Policy Rules*

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Abstract

Policy makers often use the output gap to guide monetary policy, even though nominal gross domestic product (GDP) and prices are measured in real time more accurately than the output gap. Employing a small New Keynesian model with a lower bound on nominal interest rates, this article compares the performance of monetary-policy rules that are robust to errors in measuring the output gap, nominal GDP level, or price level. It shows that a robust policy rule that focuses on stabilizing the price level improves the tradeoffs faced by the central bank, especially when the analysis accounts for persistent measurement errors as faced in practice.

Keywords: nominal level targets, inertial Taylor rule, measurement errors

JEL: E31, E52, E58

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1 Introduction

In monetary policy analysis, a commonly used measure of economic activity is the output gap, which is a gauge of how far the economy is from its productive potential. The output gap is conceptually appealing as an indicator to help guide policy, because it is an important determinant of inflation developments. A positive output gap implies an overheating economy and upward pressure on inflation. By contrast, a negative output gap implies a slack economy and downward pressure on inflation. Thus, if available, accurate and timely estimates of the output gap could play a central role in the conduct of effective monetary policy. A positive output gap would prompt policy makers to cool an overheating economy by raising policy rates, whereas a negative output gap would prompt monetary stimulus.

In practice, however, the output gap is a noisy signal of economic activity.[1] Estimates of the output gap are often subject to large revisions, as more information becomes available, even long after the time policy is actually made. Given that the output gap can give an inaccurate signal in real time, there is broad interest in finding policies that are robust to errors in measuring the output gap. As Taylor and Williams (2010) explain, one view is that in monetary-policy rules the optimal coefficient on the output gap declines in the presence of errors in measuring the gap. The logic for this result is straightforward. The reaction to the mismeasured output gap adds unwanted noise to the setting of monetary policy, which causes unnecessary fluctuations in output and inflation. Such adverse effects of noise can, however, be reduced by lowering the coefficient on the output gap in the policy rule.

At the same time, many argue for greater policy activism when the zero lower bound (ZLB) on nominal interest rates constrains policy.[2] The concern is that the inability to reduce the policy interest rate below its effective lower bound can limit, or even impair, the ability of

[1] Measuring the output gap involves two complications. First, potential output cannot be measured directly and therefore must be estimated. Second, GDP data are regularly revised as government statistical agencies incorporate more complete source information and new methodologies into the published data. Orphanides and van Norden (2002) have shown that estimating potential output is the main source of errors in measuring the output gap.

[2] This article adopts the standard practice of referring to a zero lower bound for nominal interest rates, but the recent experience with negative nominal interest rates in Denmark, Japan, Sweden, Switzerland, and the eurozone suggests the effective lower bound is somewhat below zero. See Svensson (2010) for a discussion.

monetary policy to stabilize output and inflation. However, as Reifschneider and Williams (2000) showed, increasing the coefficient on the output gap in monetary-policy rules can help reduce the adverse effects of the ZLB constraint on the economy. The reason is that, such an active response to the output gap prescribes greater monetary stimulus before and after episodes when the ZLB constrains policy, which helps lessen the effects when the ZLB constrains policy. However, there are clear limits to such an approach, as it generally increases the volatility of inflation and interest rates, which is undesirable for monetary policy. Thus, a large response coefficient on the output gap can be counterproductive for monetary policy, especially when the output gap is mismeasured.

In light of such concerns, another perspective is that monetary-policy rules should ignore the output gap altogether and seek instead to stabilize the level of prices or level of nominal gross domestic product (GDP). Such an approach would have two advantages. First, monetary policy is then expected to be more robust to measurement errors, because revisions to prices and GDP are typically smaller than revisions to the output gap. In fact, estimates of prices and GDP are subject to revision as more information becomes available, but are not prone to errors from estimating potential output. Second, the approach is also conceptually appealing because the central bank then wants to make up for any past shortfalls from its nominal anchor, which ensures greater policy stimulus during ZLB episodes.

This article, thus, compares the performance of monetary-policy rules in a small New Keynesian model, with the central bank facing data uncertainty and a ZLB constraint. In the model, several types of shock buffet the economy. On the supply side of the economy, technology shocks push output gaps and prices in the same direction, whereas cost-push shocks instead cause an inflation-output tradeoff. On the demand side, adverse demand shocks and the ZLB create a tradeoff between stabilizing current and future output, because it is desirable for the central bank in a ZLB episode to promise to induce an expansion after the ZLB episode. In addition to such structural shocks, the central bank also faces noise shocks in the setting of monetary policy in real time. There is, thus, a tradeoff between fluctuations in the economy from structural shocks and those from noise shocks.

The stylized model offers a clear illustration of the tradeoffs facing the central bank. To evaluate the policy rules, the model is calibrated to recent U.S. data, with the conduct of monetary policy described by an inertial Taylor rule that features prominently in Federal Reserve discussions. This analysis considers three distinct economic environments, as regards the data uncertainty facing the central bank.[3] First, as the starting point, the analysis assumes the central bank does not face any noise shocks and thus observes economic conditions correctly in real time. Second, as an intermediate step toward realism, the central bank faces purely-temporary noise shocks that last only one period, after which it observes the economy correctly. In the third environment, the central bank faces persistent noise shocks, reflecting the actual persistence in revisions of the data. In each environment, the coefficients in the policy rules are chosen optimally, based on the model's social welfare function. Thus, in this analysis, the policy rules are robust to measurement errors.

In the absence of any data uncertainty, the analysis produces the following results, related to the types of shock buffeting the economy. First, if the economy is only subject to technology shocks, a nominal-GDP-level (NGDPL) rule is clearly inferior because it fails to insulate the economy from technology shocks. In contrast, a strict-price-level (SPL) rule and the inertial Taylor rule fully insulate the economy from technology shocks. Second, if the economy is only hit by cost-push shocks, the SPL rule is superior because the other rules result in costly price fluctuations.[4] Third, if the economy is only hit by demand shocks, the NGDPL rule is inferior because it involves less policy inertia and, ironically, leads to large falls in nominal GDP during ZLB episodes. The inertial Taylor rule is even less effective and causes large fluctuations in output and inflation. Fourth, accounting for all three types of structural shock, the SPL rule is superior because it involves greater policy inertia and improves the tradeoffs faced by the central bank. Finally, such results are robust to a wide range of alternate calibrations.

[3] At the same time, the analysis assumes that the private sector possesses full information about the state of the economy in real time, which implies that the model can be treated as structurally invariant under different policies, as argued by Aoki (2003, 2006) and Svensson and Woodford (2004).

[4] In the analysis, the structural shocks are persistent, to generate propagation in the model as in the data. However, if the model is only hit by purely-temporary cost-push shocks, the NGDPL rule and inertial Taylor rule may be preferable because they require the burden of shocks to be shared by prices and output, whereas the SPL rule still causes costly fluctuations in output (not shown). A similar result was shown by Billi (2016) comparing optimal policies under discretion instead of robust policy rules.

In the presence of measurement errors, the analysis shows that the inertial Taylor rule and SPL rule are no longer able to fully stabilize the economy from technology shocks, because the measurement errors cause mistakes in the setting of policy. As a consequence, under each policy rule, there is now a welfare loss due to fluctuations in output and inflation after technology shocks. Accounting for all types of shock, output and inflation volatility rise in the presence of measurement errors because of policy mistakes, but the total welfare loss increases by more under the SPL rule than under the NGDPL rule. The reason is that, under the SPL rule the central bank generally reacts to a greater extent to shocks in order to stabilize prices, whereas the NGDPL rule and inertial Taylor rule require the burden of shocks to be shared by prices and output. As a result, even though prices are measured in real time much more accurately than nominal GDP and the output gap, the policy mistakes from measurement errors are substantially larger under the SPL rule. Regardless of the central bank facing measurement errors, the SPL rule is still the most effective of the policy rules for social welfare, followed by the NGDPL rule and then by the inertial Taylor rule.

The effectiveness of monetary policy, moreover, depends on the actual persistence of the measurement errors as faced by the central bank when setting policy. As the analysis shows, under the inertial Taylor rule, the persistence of the measurement errors results in a higher volatility of the economy, in contrast to the outcome of the NGDPL and SPL rules. Under nominal-level rules, the current policy decision depends on the past level of prices, and any policy mistakes from measurement errors are then carried into the future. As shown, accounting for persistence in the measurement errors, output and inflation volatility fall under both the NGDPL rule and SPL rule, but the fall is substantially larger under the SPL rule. The reason for this outcome is that, because of persistence in the measurement errors, the central bank maintains for some time its incorrect perception and, therefore, the SPL rule avoids sharp policy reversals after any measurement errors that led to past policy mistakes.

In the New Keynesian literature, adverse demand shocks and the ZLB create a tradeoff between stabilizing current and future output, because it is desirable in a ZLB episode to promise to induce an economic expansion after the ZLB episode. As this article shows, the presence of data uncertainty worsens such a tradeoff, facing the central bank in the setting of monetary policy. As a consequence, monetary policy is not nearly as effective in stabilizing the economy as implied by the assumption that the central bank observes economic conditions correctly in real time. Because data uncertainty hampers the effectiveness of monetary policy, it is desirable for the central bank to be more cautious in reacting to its observation of the economy, to reduce the incidence of policy mistakes. At the same time, when monetary policy focuses on stabilizing the price level, the extent to which data uncertainty affects economic performance depends crucially on the persistence in revisions of the data.

As the literature has shown, facing the ZLB and data uncertainty, monetary policies that involve inertia (that is, history-dependent policies) improve economic performance. Accounting for the ZLB constraint, Eggertsson and Woodford (2003), Adam and Billi (2006, 2007), and Nakov (2008) studied history-dependent policies but in the absence of data uncertainty.[5] Accounting for data uncertainty, Orphanides et al. (2000), Orphanides (2001, 2003), Rudebusch (2002), Smets (2002), Aoki (2003, 2006), Svensson and Woodford (2003, 2004), Boehm and House (2014), and Garín, Lester and Sims (2016) studied monetary policy in the absence of the ZLB constraint. Gust, Johannsen and Lopez-Salido (2015) studied the interaction between the ZLB and data uncertainty, under the assumption that the central bank faces purely-temporary noise only. Relative to the existing literature, this article is the first to directly compare the performance of monetary policies that seek to stabilize the level of prices or level of nominal GDP, in the presence of both the ZLB and data uncertainty.

Sections 2 describes the model and Section 3 introduces the monetary-policy rules. Section 4 describes the notion of an equilibrium with monetary policy reacting to noisy observations of economic conditions. Section 5 presents the model outcomes and policy evaluation. Section 6 concludes. The Appendix contains technical details of the model solution.

[5] Svensson (1999), Vestin (2006), and Giannoni (2014) argued for price-level targeting versus inflation targeting, in the absence of both the ZLB and data uncertainty. Related to this, the desirability of a price-level target when the ZLB is a constraint was stressed by Eggertsson and Woodford (2003), Svensson (2003), Wolman (2005), and Evans (2012), among others. A shortlist of recent proponents of nominal-GDP-level targeting includes Hatzius and Stehn (2011, 2013), Sumner (2011, 2014), Woodford (2012, 2013), Frankel (2013), and others. There is also an extensive literature on the notion of nominal income *growth* targeting, at first suggested by Meade (1978) and Tobin (1980) and then studied by Bean (1983), Taylor (1985), West (1986), McCallum (1988), Clark (1994), Hall and Mankiw (1994), Jensen (2002), Walsh (2003), and Billi (2011b), among others.

2 The model

I use a small New Keynesian model as described in Woodford (2010), but I take into account that the nominal policy rate occasionally hits the ZLB. The behavior of the private sector is summarized by two structural equations, log-linearized around zero inflation, which describes the demand and supply sides of the economy.

On the demand side of the model economy, the Euler equation describes the representative household's expenditure decisions,

$$y_t = E_t y_{t+1} - \varphi \left(i_t - r - E_t \pi_{t+1} - v_t \right), \tag{1}$$

where E_t denotes the expectations operator conditional on information available at time t. y_t is output measured as the log-deviation from trend. π_t is the inflation rate, the log-change of prices from last period, $p_t - p_{t-1}$. Moreover, $i_t \geq 0$ is the short-term nominal interest rate constrained by a ZLB, whereas $r > 0$ is the steady-state real interest rate.[6] $\varphi > 0$ is the interest elasticity of real aggregate demand, capturing intertemporal substitution in household spending. The *demand shock*, v_t, represents other spending, such as government spending, which has asymmetric effects on the economy due to the ZLB. A positive demand shock can be countered entirely by raising the nominal interest rate, whereas a large adverse shock that leads to hitting the ZLB causes an economic downturn.

On the supply side of the economy, the Phillips curve describes the optimal price-setting behavior of firms, under staggered price changes à la Calvo,

$$\pi_t = \beta E_t \pi_{t+1} + \kappa x_t + u_t, \tag{2}$$

where $\beta \in (0, 1)$ is the discount factor of the representative household, determined as $1/(1+r)$. The slope parameter $\kappa > 0$ is a function of the structure of the economy.[7] $x_t = y_t - y_t^n$ is

[6] Thus, $i_t - r - E_t \pi_{t+1}$ is the real interest rate in deviation from steady state.

[7] In this model $\kappa = (1-\alpha)(1-\alpha\beta)\alpha^{-1}\left(\varphi^{-1} + \omega\right)(1+\omega\theta)^{-1}$, where $\omega > 0$ denotes the elasticity of a firm's real marginal cost. $\theta > 1$ is the price elasticity of demand substitution with firms in monopolistic competition, and thus the seller's desired markup is $\theta/(\theta - 1)$. Moreover, $\alpha \in (0, 1)$ is the share of firms keeping prices fixed each period, so the implied duration between price changes is $1/(1-\alpha)$.

the output gap in the economy. y_t^n is the natural rate of output, or potential output, the output deviation from the trend that would prevail in the absence of any price rigidities, which represents a *technology shock*. A positive technology shock implies slack in economic activity and downward pressure on prices, whereas a negative shock causes an economic upturn. Moreover, u_t is a cost-push shock, or *mark-up shock* resulting from variation over time in the degree of monopolistic competition between firms, which creates an inflation-output tradeoff for monetary policy.

In the model economy, the three types of exogenous structural shocks (y_t^n, u_t, v_t) are assumed to follow AR(1) stochastic processes, with first-order autocorrelation parameters $\rho_j \in (-1, 1)$ for $j = y^n, u, v$. Moreover, $\sigma_{\varepsilon j}\varepsilon_{jt}$ are the innovations that buffet the economy, which are independent across time and cross-sectionally, and normally distributed with mean zero and standard deviations $\sigma_{\varepsilon j} > 0$.

Finally, the policy rules to be considered are evaluated based on the model's social welfare function, a second-order approximation around zero inflation of the lifetime utility function of the representative household,

$$E_0 \sum_{t=0}^{\infty} \beta^t \left[\pi_t^2 + \lambda \left(x_t - x^*\right)^2\right], \tag{3}$$

where $\lambda = \kappa/\theta$ is the weight assigned to stabilizing the output gap relative to inflation. x^* is the target level of the output gap, which stems from monopolistic competition and distortion in the steady state. Output subsidies are assumed to offset the monopolistic distortion so that the steady state is efficient, $x^* = 0$. As a result, in the analysis there is no inflation bias but a stabilization bias facing the central bank.

3 The monetary policy rules

The conduct of monetary policy is described by simple rules, subject to the ZLB constraint. It is first described by a Taylor-type rule with smoothing, to be used in the model calibration. It is then described by rules that seek instead to stabilize the level of prices or level of nominal

GDP. In the different rules, the central bank faces errors in the measurement of prices and output when setting policy, which leads to policy mistakes.

First, in the model calibration the policy rule employed is an **inertial Taylor rule** along the lines of Taylor and Williams (2010):

$$i_t = \max\left[0, \phi_i i_{t-1}^u + (1-\phi_i)\left(r + \phi_\pi \pi_t^o + \phi_x x_t^o\right)\right], \tag{4}$$

where ϕ_π and ϕ_x are positive response coefficients on observed inflation, $\pi_t^o = \pi_t + e_t^\pi$, and the observed output gap, $x_t^o = x_t + e_t^x$, respectively. In the central bank's observation of economic conditions, e_t^π and e_t^x represent noise shocks or measurement errors, which cause mistakes in the setting of policy with this rule.[8] At the same time, the rule incorporates smoothing in the behavior of the interest rate, through a positive value of the coefficient ϕ_i. Moreover, i_{t-1}^u denotes an unconstrained or notional interest rate, the preferred setting of the policy rate in the previous period that would occur absent the ZLB constraint.

Such an approach to monetary policy implies that the central bank compensates to some extent for the lost monetary stimulus due to the existence of the ZLB, even though the central bank does not commit to making up for past shortfalls from a nominal-level target as in the other rules considered below. It also implies that, by increasing the extent of smoothing of the policy rate, the central bank reacts less to the measurement errors and reduces the incidence of its policy mistakes. As a result, the central bank may prefer a larger value of ϕ_i than would otherwise be the case in the absence of measurement errors.

The second monetary policy rule considered is a **strict-price-level (SPL) rule**, which takes the following form:

$$i_t = \max\left(0, r + \phi_p p_t^o\right), \tag{5}$$

where ϕ_p is a positive response coefficient on the observed log of the price level, $p_t^o = p_t + e_t^p$.

[8] In the data, both inflation and output gaps are subject to persistent revisions (Section 5.4). Thus, in the model, instead of using only one noise shock to reduce the number of state variables, both e_t^π and e_t^x are present for the policy rule to be consistent with the real-time data.

Whereas p_t is the actual log-price level, which is equal to $p_{t-1} + \pi_t$. In the central bank's observation of prices, e_t^p represents a noise shock or measurement error, which leads to policy mistakes. To reduce the incidence of policy mistakes, the central bank may prefer a lower value of ϕ_p than would be the case in the absence of measurement errors. At the same time, the central bank seeks to stabilize prices without concern for output stability and, therefore, transfers the entire burden of shocks onto output. Such a rule involves inertia in the behavior of monetary policy, because the current policy decision depends on the past price level.

As a third description of monetary policy, I employ a **nominal-GDP-level (NGDPL) rule** that takes the form:

$$i_t = \max\left(0, r + \phi_n n_t^o\right), \tag{6}$$

where ϕ_n is a positive response coefficient on the observed level of nominal GDP, $n_t^o = n_t + e_t^n$. Whereas n_t is actual nominal GDP measured as the log-deviation from trend, which is equal to $p_t + y_t$. In the central bank's observation of economic activity, e_t^n represents a noise shock or measurement error, which causes policy mistakes. To reduce the incidence of policy mistakes, the central bank may prefer a lower value of ϕ_n than would be the case in the absence of measurement errors. Using this level rule, the central bank seeks to stabilize both prices and output, as opposed to focusing entirely on price stability, which now requires the burden of shocks to be shared by prices and output. As a consequence, the current policy decision involves relatively less dependence on the past price level, and the policy maker acts less in accordance with a precommitment to price stability, relative to the SPL rule.

In the different policy rules, the four types of exogenous noise shocks $(e_t^\pi, e_t^x, e_t^p, e_t^n)$ are assumed to follow AR(1) stochastic processes, with first-order autocorrelation parameters $\rho_j \in (-1, 1)$ for $j = e^\pi, e^x, e^p, e^n$. Moreover, $\sigma_{\varepsilon j}\varepsilon_{jt}$ are the innovations that buffet the economy, which are independent across time and cross-sectionally, and normally distributed with mean zero and standard deviations $\sigma_{\varepsilon j} > 0$.

4 The noisy equilibrium

At equilibrium, the policy maker chooses a policy based on a response function $\mathbf{y}(\mathbf{s}_t)$ and state vector $\mathbf{s}_t$. The $\mathbf{s}_t$ includes the structural shocks buffeting the economy. It also includes the endogenous variables, as well as the noise shocks affecting the central bank's observation of economic conditions, which depends on the conduct of monetary policy. The corresponding expectations function is given by

$$\mathbf{E}_t \mathbf{y}_{t+1}(\mathbf{s}_{t+1}) = \int \mathbf{y}(\mathbf{s}_{t+1}) f(\boldsymbol{\varepsilon}_{t+1}) d(\boldsymbol{\varepsilon}_{t+1}),$$

where $f(\cdot)$ is a probability density function of all the future innovations, in the structural shocks and relevant noise shocks, which buffet the economy.

In such a setting, a noisy rational-expectations equilibrium (NREE) is then given by the response function and expectations function, $\mathbf{y}(\mathbf{s}_t)$ and $\mathbf{E}_t \mathbf{y}_{t+1}(\mathbf{s}_{t+1})$, which for $\mathbf{s}_t$ satisfy the equilibrium conditions of the model. Under the policy rules considered, the equilibrium conditions are

Policy rule	Equilibrium conditions	State vector $\mathbf{s}_t$
Inertial Taylor rule	(1), (2) and (4)	$\left(y_t^n, u_t, v_t, e_t^\pi, e_t^x, i_{t-1}^u\right)$
Strict-price-level rule	(1), (2) and (5)	$(y_t^n, u_t, v_t, e_t^p, p_{t-1})$
Nominal-GDP-level rule	(1), (2) and (6)	$(y_t^n, u_t, v_t, e_t^n, p_{t-1})$

The economic environment is inherently uncertain. Because there is uncertainty about the future state of the economy, the ZLB is an occasionally-binding constraint among the endogenous variables in the model. When the ZLB threatens, the mere possibility of hitting the ZLB causes expectations of a future economic downturn, as shown by Adam and Billi (2006, 2007), and Nakov (2008), among others. Ignoring the existence of unforeseen shocks buffeting the economy, the model could be solved with a standard numerical method, as for example in Williams (2009), Coibion, Gorodnichenko, and Wieland (2012), and Guerrieri and

Iacoviello (2015). By contrast, as in Billi (2011a, 2016), I use a numerical procedure that accounts for the ZLB and unforeseen shocks.[9]

5 The policy evaluation

Employing the small New Keynesian model with a calibration to recent U.S. data, I compare the performance of monetary-policy rules in three distinct economic environments, as regards the measurement errors facing the central bank. I first consider an environment without measurement errors and illustrate basic outcomes of the different rules. I also study a range of alternate calibrations to test the robustness of the outcomes. I then introduce purely-temporary measurement errors in the analysis, which represents an intermediate step toward realism. I finally consider an environment in which the measurement errors are persistent, reflecting the actual persistence in revisions of the data. In each environment, the coefficients in the policy rules are chosen optimally, based on the model's social welfare function, so the rules are robust to measurement errors.

5.1 Baseline calibration

The model economy is calibrated to revised U.S. data for recent decades, as in Billi (2016). Thus, monetary policy in the model is described by the inertial Taylor rule (4) that features prominently in Federal Reserve discussions. The values of the rule coefficients are taken from English, Lopez-Salido and Tetlow (2015), with ϕ_π set to 1.5, ϕ_x set to 1/4 (quarterly rates) and ϕ_i set to 0.85. The rule thus accounts for smoothing in the setting of the policy interest rate. At the same time, the noise shocks e_t^π and e_t^x are set to zero, to reflect revised data in the baseline calibration.

The values of the structural parameters of the model are standard in the related literature. Specifically, β is set to 0.99, to imply a steady-state interest rate of 4% annual. φ is set to 6.25.[10] The implied parameters κ and λ are then equal to 0.024 and 0.003 (quarterly),

[9] See Appendix A.1 for a description of the algorithm.

[10] α is set to 0.66, so the duration between price changes $1/(1-\alpha)$ is 3 quarters. θ is set to 7.66, so the

respectively. Finally, regarding the calibration of the structural shocks, $\rho_{y^n,u,v}$ are set to 0.8, to generate persistent effects on the economy. Moreover, $\sigma_{y^n,v}$ are set to 0.8% (quarterly) and σ_u is set to 0.05% (quarterly), to try to match the volatility of the economy as measured in the data. Overall, as Billi (2016) showed, with the inertial Taylor rule and baseline calibration, the model does a fairly good job in replicating the relevant features of recent U.S. data.[11]

5.2 Outcome without noise

Using the baseline calibration, I start the policy evaluation without the measurement errors, setting the noise shocks $(e_t^\pi, e_t^x, e_t^p, e_t^n)$ to zero in the policy rules. The response coefficients (ϕ_i, ϕ_p, ϕ_n) in the rules are chosen optimally based on the model's social welfare function.[12] Figure 1 shows the expected evolution of the economy after each of the three types of structural shocks considered in the model.[13] Shown are the responses of the real interest rate, price level, and nominal GDP level.

[Figure 1 about here]

The top panel of the figure shows the response to a positive technology shock, whereas the middle panel shows the response to a negative mark-up shock. Both types of supply shock put downward pressure on prices in the model, but the outcome depends on the policy rule considered. With the NGDPL rule (dashed green lines), the real interest rate edges up, prices fall, and nominal GDP is nearly stabilized. With the SPL rule (solid blue lines), the real interest rate edges down, nominal GDP rises, and prices are nearly stabilized. However, with the inertial Taylor rule (dash-dotted red lines), both prices and nominal GDP fluctuate after the mark-up shock. Thus, faced with supply shocks, each nominal-level rule almost-fully achieves its respective goal. However, to achieve the goal, the NGDPL rule requires the

markup over marginal cost $\theta/(\theta-1)$ is 15%. Moreover, ω is set to 0.47.

[11] The sample period used to calibrate the structural shocks is the same as in Billi (2016), 1984Q1-2014Q4, which ensures the results are directly comparable. Moreover, extending the sample to the latest available data does not affect the good fit of the model to the data.

[12] The other response coefficients in the inertial Taylor rule, ϕ_π and ϕ_x, are kept at their baseline values in the results shown, to simplify the analysis and exposition. Choosing also these coefficients optimally makes such a rule more effective at stabilizing the economy, but still not as effective as the nominal-level rules.

[13] Shown are expected paths after three-standard-deviation shocks. The expected paths are obtained by averaging across 10,000 stochastic simulations.

burden of the shocks to be shared by prices and output, whereas the SPL rule requires the entire burden of the shocks to be transferred onto output (not shown).

The bottom panel of the figure shows instead the response to a negative demand shock, which exerts downward pressure on output and prices in the model. Given the size of the shock, under each policy rule, the central bank cuts the nominal policy rate (not shown) all the way to the ZLB. During the ZLB episode, the real interest rate falls, prices fall, and nominal GDP falls. However, under the SPL rule, the real interest rate stays for a longer time below its equilibrium value, which implies a greater extent of monetary policy stimulus and therefore a smaller downturn in the economy. The reason for this better performance is that, as noted earlier, the SPL rule implies a greater dependence of current policy decisions on past policy actions, and thus a surge in economic activity and inflation after the ZLB episode. In contrast, the NGDPL rule provides less policy stimulus and, ironically, leads to a larger fall in nominal GDP. The fall in nominal GDP is large also under the inertial Taylor rule.

To rank the policy rules, Table 1 summarizes their performance in the absence of measurement errors. The table reports the optimal rule coefficients, the expected frequency and duration of ZLB episodes, as well as the welfare loss due to business cycles.[14] Each line shows the outcome for one type of shock only. The top panel shows the results for the inertial Taylor rule, the middle panel shows the outcome for the SPL rule, and the bottom panel reports results for the NGDPL rule.

[Table 1 about here]

As the table shows, the supply shocks do not lead to ZLB episodes in this analysis. Regarding the outcome for technology shocks, the inertial Taylor rule and SPL rule are more effective for social welfare, because they fully stabilize the economy with respect to technology shocks. In contrast, the NGDPL rule fails to insulate the economy from technology shocks and, therefore, results in a welfare loss due to fluctuations in prices and output. Regarding

[14]Under each policy rule, the optimal response coefficient minimizes objective function (3). To calculate the welfare loss, first the value of objective function (3) is obtained by averaging across 10,000 stochastic simulations each 1,000 periods long after a burn-in period. This value is then converted into a permanent consumption loss, as explained in Appendix A.2.

the results for mark-up shocks, the SPL rule is the most effective of the rules for social welfare, even though to offset inflationary pressures it causes costly fluctuations in output. At the same time, the other rules worsen the inflation-output tradeoff faced by the central bank, which results in costly fluctuations in prices.

The table also shows that demand shocks lead to hitting the ZLB, under each policy rule considered. Faced with demand shocks, the SPL rule is still the most effective of the rules for social welfare, because the other rules are less effective in dealing with the ZLB and therefore result in larger fluctuations in both prices and output. In sum, for all types of structural shocks considered, the SPL rule is the most effective for social welfare, in the baseline calibration. Moreover, beside from the welfare cost of technology shocks, both nominal-level rules perform better, in terms of social welfare in the model, compared to the inertial Taylor rule.

5.3 Alternate calibrations

Still without measurement errors, I consider a number of deviations from the baseline calibration. For each change in the calibration, the model-implied parameters (β, κ, and λ) are adjusted accordingly. Tables 2 and 3 summarize the resulting performance of the inertial Taylor rule and nominal-level rules, respectively, with the parameters changes. The tables report the expected frequency and duration of ZLB episodes, as well as the welfare loss due to business cycles.[15]

[Tables 2 and 3 about here]

I start with changes on the demand side of the economy. First, the equilibrium rate of interest is lowered substantially ($\beta = 0.993$), which implies that monetary policy is now more severely constrained by the ZLB.[16] As a consequence, as Table 3 shows, inflation and output

[15] In each alternate calibration shown, the response coefficients (ϕ_i, ϕ_p, ϕ_n) in the policy rules are set to their optimal baseline values, to simplify the analysis and comparison to the baseline results. Moreover, this simplification does not affect the ranking of the policy rules. Changes to ω are not reported, because varying ω as much as ± 50 percent makes no noticeable difference for the implied parameters and results.

[16] The equilibrium interest rate was lowered from 4 to 3 percent annual. At the same time, because the numerical procedure then failed to converge under the inertial Taylor rule, the smoothing coefficient ϕ_i in the rule was raised a little from 0.87 to 0.9 to ensure greater policy stimulus and obtain a numerical solution.

volatility rise under both nominal-level rules relative to the baseline, but the welfare loss increases by more under the NGDPL rule. This result occurs because, as noted earlier, such a rule is less effective in dealing with demand shocks that push the economy into a ZLB episode. Second, the interest elasticity of real aggregate demand is lowered substantially ($\varphi = 1$), which entails that changes in the nominal interest rate have smaller effects on output. At the same time, the supply side of the economy is also affected. As the Phillips curve becomes steeper (κ rises), changes in output have larger effects on prices. On net, monetary policy is now more effective, as inflation and output volatility fall under both nominal-level rules relative to the baseline, but the SPL rule is still more effective in terms of social welfare.

I now consider a range of parameter values on the supply side of the model economy.[17] In the model, if firms change prices less frequently or face more competition ($\alpha = 0.75$ and $\theta = 10$, respectively), the Phillips curve becomes flatter (κ falls), and changes in output have smaller effects on prices. As a result, monetary policy becomes less effective. As Table 3 shows, inflation and output volatility generally rise under both nominal-level rules relative to the baseline, but the total welfare loss is higher under the NGDPL rule. Conversely, if firms change prices more frequently or face less competition ($\alpha = 0.5$ and $\theta = 5$, respectively), inflation and output volatility generally fall under both nominal-level rules relative to the baseline, but the SPL rule is still more effective for social welfare.

Next, I consider the types of structural shocks that buffet the economy. First, as Table 3 shows, if supply shocks are assumed to have no persistence ($\rho_{y^n,u} = 0$), inflation volatility falls under the NGDPL rule, but not enough to change the policy ranking. Second, if the economy is only buffeted by supply shocks ($\sigma_v = 0$), which in this analysis implies that monetary policy is not constrained by the ZLB, inflation and output volatility fall substantially under both nominal-level rules, but the SPL rule is still more effective in terms of social welfare.[18]

[17] In the baseline calibration, the duration between price changes is 3 quarters ($\alpha = 0.66$) and the desired markup is 15 percent ($\theta = 7.66$). In the alternate calibrations reported in Tables 2 and 3, the price duration ranges from 2 to 4 quarters ($\alpha = 0.5$ and 0.75, respectively) and the markup ranges from 11 to 25 percent ($\theta = 10$ and 5, respectively).

[18] Conversely, if demand shocks or technology shocks are larger (not shown), the increase in the welfare loss is greater for the NGDPL rule, compared to the SPL rule.

Overall, as the results in Table 3 show, in the face of persistent supply and demand shocks buffeting the economy, the ranking of the two nominal-level rules is robust to a wide range of alternate calibrations of the model. Finally, a comparison of the results in Tables 2 and 3 shows, for all the calibrations considered, both nominal-level rules perform better, in terms of social welfare in the model, compared to the inertial Taylor rule.

5.4 Calibration of the noise

I now introduce the measurement errors in the analysis. To do this, the calibration of the noise shocks in the model is obtained fitting historical revisions of U.S. data, as done in Billi (2011b). The sample period used here to fit the data revisions is 1991Q1-2015Q4. In the data, real-time estimates reflect information actually available to policy makers in each quarter when deciding policy, whereas revised estimates reflect the information as available at the end of the sample period. Thus, the difference between the revised and real-time estimates represents the historical revisions, which are used to calibrate the noise shocks.[19]

Based on the historical revisions in the data, the standard deviations of the noise shocks $(\sigma_{\varepsilon e^{\pi}}, \sigma_{\varepsilon e^{x}}, \sigma_{\varepsilon e^{p}}, \sigma_{\varepsilon e^{n}})$ are set to match the volatility in the data revisions, $(0.3, 1.7, 0.3, 1.1)$ in percent annual. Whereas the autocorrelation parameters of the noise shocks $(\rho_{e^{\pi}}, \rho_{e^{x}}, \rho_{e^{p}}, \rho_{e^{n}})$ are set to match the persistence in the data revisions $(0.7, 0.85, 0.8, 0.8)$.[20] Thus, the data imply that, on average, the size of the revisions is almost four-times larger in nominal GDP than in prices, but nearly six-times larger in the output gap than in prices. The data also imply that, on average, the persistence of the revisions is the same for prices and nominal GDP, but is somewhat higher for the output gap.

In summary, in the U.S. data for recent decades, although prices are measured in real

[19] To fit the historical revisions, the price level is measured as the log-deviation from trend in the seasonally-adjusted personal consumption expenditures chain-type price index less food and energy, whereas the inflation rate is measured as the continuously compounded rate of change of the same index. The nominal GDP level is measured as the log-deviation from trend in seasonally-adjusted gross domestic product. And the output gap is calculated as the deviation of real gross domestic product from potential, as a fraction of potential using seasonally-adjusted data. Sources are the Congressional Budget Office for potential output and the Bureau of Economic Analysis for the other variables. The real-time and revised data were obtained from archival economic data available at the St. Louis Fed, https://alfred.stlouisfed.org.

[20] The half-lives of the noise shocks $log\,(0.5)\,/log\,(\rho_{e^{\pi}}, \rho_{e^{x}}, \rho_{e^{p}}, \rho_{e^{n}})$ are equal to $(1.9, 4.3, 3.1, 3.1)$ quarters.

time much more accurately than nominal GDP, both prices and nominal GDP are subject to persistent revisions over time. At the same time, compared to prices and nominal GDP, the output gap is subject to even larger and more persistent revisions.

5.5 White noise

As the next step in the analysis, I first assume the central bank faces measurement errors that have no persistence. Specifically, I continue to use the baseline calibration. At the same time, the volatility of the noise shocks in the model is calibrated to the data revisions (as explained in the previous section), but the autocorrelation parameters of the noise shocks ($\rho_{e^\pi}, \rho_{e^x}, \rho_{e^p}, \rho_{e^n}$) are set to zero. Accounting for the measurement errors, the response coefficients in the policy rules are chosen optimally based on the model's social welfare function.

With purely-temporary measurement errors, Figure 2 shows the expected evolution of the economy after a negative mismeasurement of the output gap, price level, or nominal GDP level.[21] Shown are the responses of the nominal and real interest rate, the actual inflation rate, and the actual output gap. Given the incorrect perception of deflationary pressures, under each policy rule, the central bank initially cuts the nominal and real interest rate, to provide stimulus to the economy. Under the SPL rule the nominal interest rate is cut all the way to the ZLB, whereas under the NGDPL rule and inertial Taylor rule the central bank generally reacts less because the burden of shocks is shared by prices and output. As a consequence of the policy rate cuts, the economy overheats under each of the policy rules, with output rising above potential and inflation rising above target.

[Figure 2 about here]

Already one period after the mismeasurement, however, the central bank observes the economy correctly and becomes fully aware of its earlier policy mistake. The central bank,

[21] Shown are expected paths after three-standard-deviation noise shocks. Regarding the path under the inertial Taylor rule, a noise shock to the inflation rate (not shown), instead of to the output gap, would result in a path with a similar shape but much smaller size than the one displayed in the figure. In fact, policy rate mistakes under rule (4) are proportional to $\phi_\pi \sigma_{\varepsilon e^\pi} = 0.45$ and $\phi_x \sigma_{\varepsilon e^x} = 1.7$ percent annual, and the latter mistake is nearly four-times larger than the former.

thus, withdraws its policy stimulus, to bring output and inflation down. However, as the figure shows, the extent of the policy mistake depends on the rule considered, with the initial cut and following reversal steepest under the SPL rule. As a result, even though prices are measured in real time much more accurately than nominal GDP and the output gap, the policy mistake due to mismeasurement is substantially larger under the SPL rule.

To rank the policy rules, Table 4 summarizes their performance in the presence of purely-temporary measurement errors. The table reports the optimal rule coefficients, the expected frequency and duration of ZLB episodes, as well as the welfare loss due to business cycles. Each line shows the results for one type of structural shock buffeting the economy, in the presence of the measurement errors. As the table shows, demand shocks still lead to ZLB episodes, under each policy rule considered.

[Table 4 about here]

Regarding the outcome for technology shocks, as the table shows, the inertial Taylor rule and SPL rule are no longer able to fully stabilize the economy, because the measurement errors cause mistakes in the setting of policy. As a consequence, under each policy rule, there is now a welfare loss due to fluctuations in prices and output after technology shocks. Nevertheless, for all types of structural shocks considered, the SPL rule is still the most effective of the rules for social welfare, generally followed by the NGDPL rule and then by the inertial Taylor rule, in the presence of measurement errors that have no persistence.

5.6 Persistent noise

I now consider the case of the central bank facing persistent measurement errors, with both the volatility and persistence of the noise shocks calibrated to the data revisions. The response coefficients in the policy rules are once again chosen optimally based on the model's social welfare function, but now in the presence of persistent measurement errors.

In such a setting, Figure 3 shows the expected evolution of the economy after a negative mismeasurement of the output gap, price level, or nominal GDP level.[22] The central bank still has an incorrect perception of deflationary pressures in the economy, but now such misperception is persistent. Under each policy rule, the central bank initially implements a cut in the real interest rate causing the economy to overheat, similarly to the previous case of purely-temporary measurement errors. The nominal interest rate is still cut all the way to the ZLB under the SPL rule. However, in contrast to the previous case, the central bank maintains for some time its incorrect perception and, therefore, does not fully withdraw its policy stimulus. As a result, compared to Figure 2, the sharp policy reversal under the SPL rule is now avoided.

[Figure 3 about here]

With persistence in the measurement errors, Table 5 summarizes the performance of the policy rules, similarly to the previous case. Demand shocks still lead to ZLB episodes, under each policy rule. Moreover, faced with technology shocks and measurement errors buffeting the economy, there is still a welfare loss due to fluctuations in prices and output. At the same time, similarly to the case of purely-temporary measurement errors, the inertial Taylor rule and SPL rule are unable to fully stabilize the economy after technology shocks, because of the mistakes in the setting of policy. Overall, for all types of structural shocks considered, the SPL rule is still the most effective of the rules for social welfare, followed by the NGDPL rule and then by the inertial Taylor rule, even in the presence of persistent measurement errors.

[Table 5 about here]

5.7 Effects of noise

As the last step in the analysis, Table 6 illustrates the impact of the measurement errors on the performance of the policy rules. The table reports the optimal rule coefficients, the expected frequency and duration of ZLB episodes, as well as the welfare loss due to business

[22] In the figure, under the inertial Taylor rule, despite the perceived fall in the output gap, the nominal interest rate now rises. Still, the real interest rate falls, and thus monetary policy is expansionary.

cycles. The top panel shows the performance without measurement errors, the middle panel shows the outcome with purely-temporary measurement errors, and the bottom panel reports results with persistent measurement errors.

[Table 6 about here]

As the table shows, the presence of measurement errors makes monetary policy less effective at stabilizing the economy, regardless of whether the measurement errors are purely-temporary or persistent. In both cases, under each policy rule, the central bank reacts less strongly to its observation of the economy than it would in the absence of measurement errors affecting its policy decision.[23] At the same time, the incidence of ZLB episodes generally falls, because the presence of measurement errors raises the welfare cost of ZLB episodes. Moreover, inflation and output volatility generally rise in the presence of measurement errors, but the total welfare loss increases by more under the SPL rule than the NGDPL rule. This outcome occurs because, as noted earlier, even though prices are measured in real time much more accurately than nominal GDP, the policy mistakes are substantially larger under the SPL rule.

The table also shows that the effectiveness of monetary policy depends on the persistence of the measurement errors faced by the central bank. Under the inertial Taylor rule, the persistence of the measurement errors results in a higher volatility of the economy, in contrast to the outcome of the nominal-level rules. Under the nominal-level rules, the current policy decision depends on the past level of prices and, as a result, any policy mistakes from measurement errors are carried into the future, especially under the SPL rule. However, as the table shows, by adding persistence to the measurement errors, inflation and output volatility fall under both nominal-level rules, but the fall is substantially larger under the SPL rule. The reason is that, as noted earlier, because of persistence in the measurement errors, the SPL rule avoids sharp policy reversals after any measurement errors that led to past policy mistakes. At the same time, regardless of the central bank facing measurement errors in the setting of policy, the SPL rule is the most effective of the policy rules, in terms of social welfare in the model economy, followed by the NGDPL rule and then by the inertial Taylor rule.

[23] As the table shows, if measurement errors are present, then ϕ_i rises, whereas ϕ_p and ϕ_n fall.

6 Concluding remarks

Policy makers often use the output gap to guide monetary policy, albeit estimates of the output gap are often revised substantially long after the time policy decisions are made. At the same time, the inability of central banks to reduce the policy interest rate below its effective lower bound can limit, or even impair, the ability of monetary policy to stabilize the economy. In light of such challenges, some argue that monetary-policy rules should ignore the output gap and seek instead to stabilize the level of nominal GDP. One advantage of such an approach would be that monetary policy is expected to be more robust to measurement errors, because GDP is measured in real time more accurately than the output gap. Another advantage would be that monetary policy is expected to make up for any past shortfalls from its nominal anchor, which implies greater policy stimulus during ZLB episodes.

This article, thus, compares the performance of monetary-policy rules that are robust to errors in measuring the output gap, nominal GDP level, or price level. To do this, the analysis uses a small New Keynesian model, with the central bank facing data uncertainty and a ZLB constraint. In the model, persistent supply and demand shocks buffet the economy. The central bank also faces persistent noise shocks, calibrated to the revisions of recent U.S. data, which cause mistakes in the setting of monetary policy in real time. The stylized model offers a clear illustration of the tradeoffs facing the central bank. The analysis shows that a robust policy rule that focuses on stabilizing the price level improves the tradeoffs faced by the central bank, especially when the analysis accounts for persistent measurement errors as faced in practice. Still, as the analysis is conducted in a stylized model, further study is needed to extend the results to a broader class of models.

A Appendix

A.1 Numerical procedure

I find a numerical solution, as in Billi (2011a, 2016), as a fixed-point in the equilibrium conditions. To do this, the state vector is discretized into a grid of interpolation nodes, with a support of ± 4 standard deviations for each state variable which is large enough to avoid erroneous extrapolation. If the state is not on this grid, the response function is evaluated with multilinear interpolation. The approximation residuals are evaluated at a finer grid, to ensure the accuracy of the results. The expectations function is evaluated with Gaussian-Hermite quadrature. The initial guess is the linearized solution that ignores the ZLB constraint.

A.2 Permanent consumption loss

I obtain the permanent consumption loss as in Billi (2011a, 2016). The expected lifetime utility of the representative household is validly approximated by

$$E_0 \sum_{t=0}^{\infty} \beta^t U_t = \frac{U_c \overline{C}}{2} \frac{\alpha\theta (1 + \omega\theta)}{(1 - \alpha)(1 - \alpha\beta)} L, \tag{7}$$

where $\overline{C}$ is steady-state consumption; $U_c > 0$ is steady-state marginal utility of consumption; and $L \geq 0$ is the value of objective function (3).

At the same time, a steady-state consumption loss of $\mu \geq 0$ causes a utility loss of

$$E_0 \sum_{t=0}^{\infty} \beta^t U_c \overline{C} \mu = \frac{1}{1 - \beta} U_c \overline{C} \mu. \tag{8}$$

Equating the right sides of (7) and (8) gives

$$\mu = \frac{1 - \beta}{2} \frac{\alpha\theta (1 + \omega\theta)}{(1 - \alpha)(1 - \alpha\beta)} L.$$

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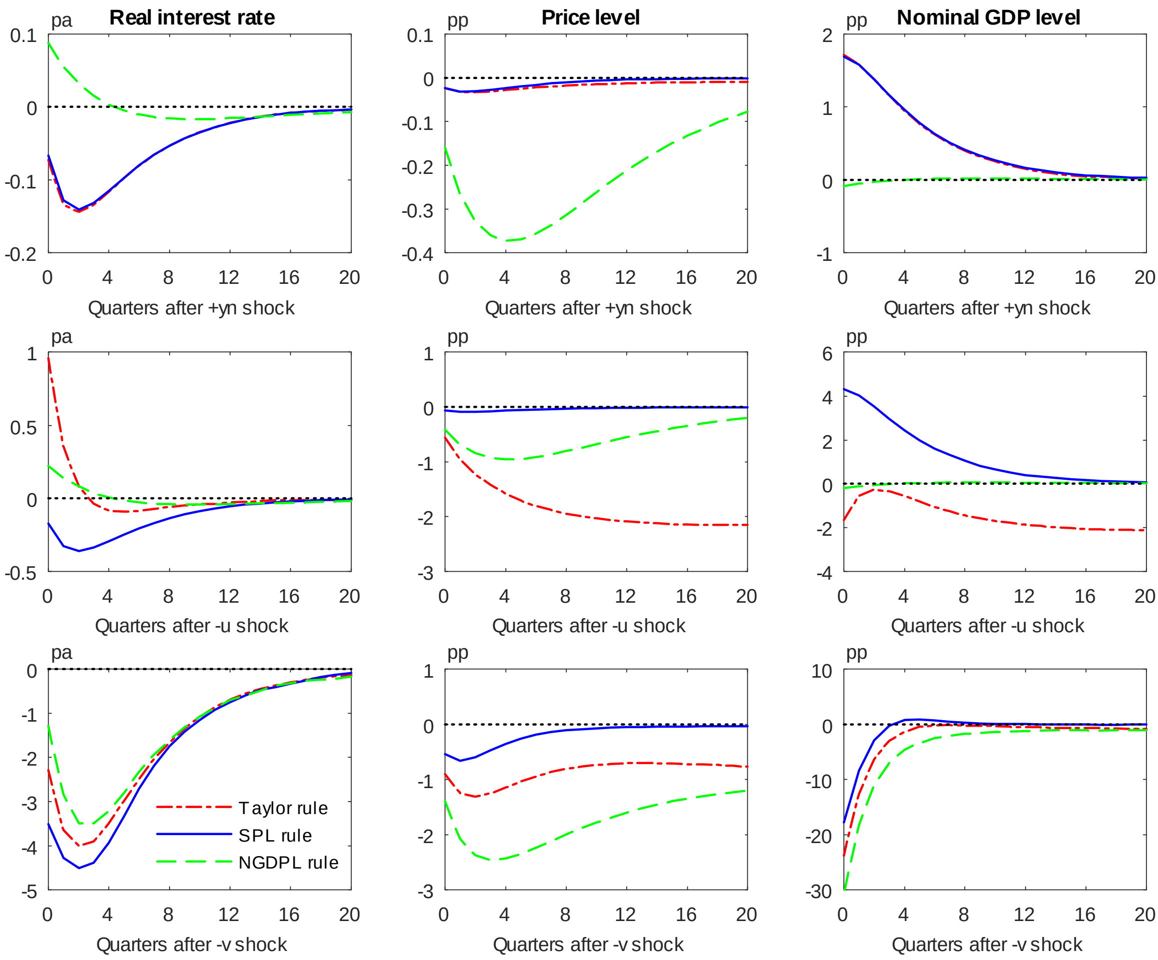
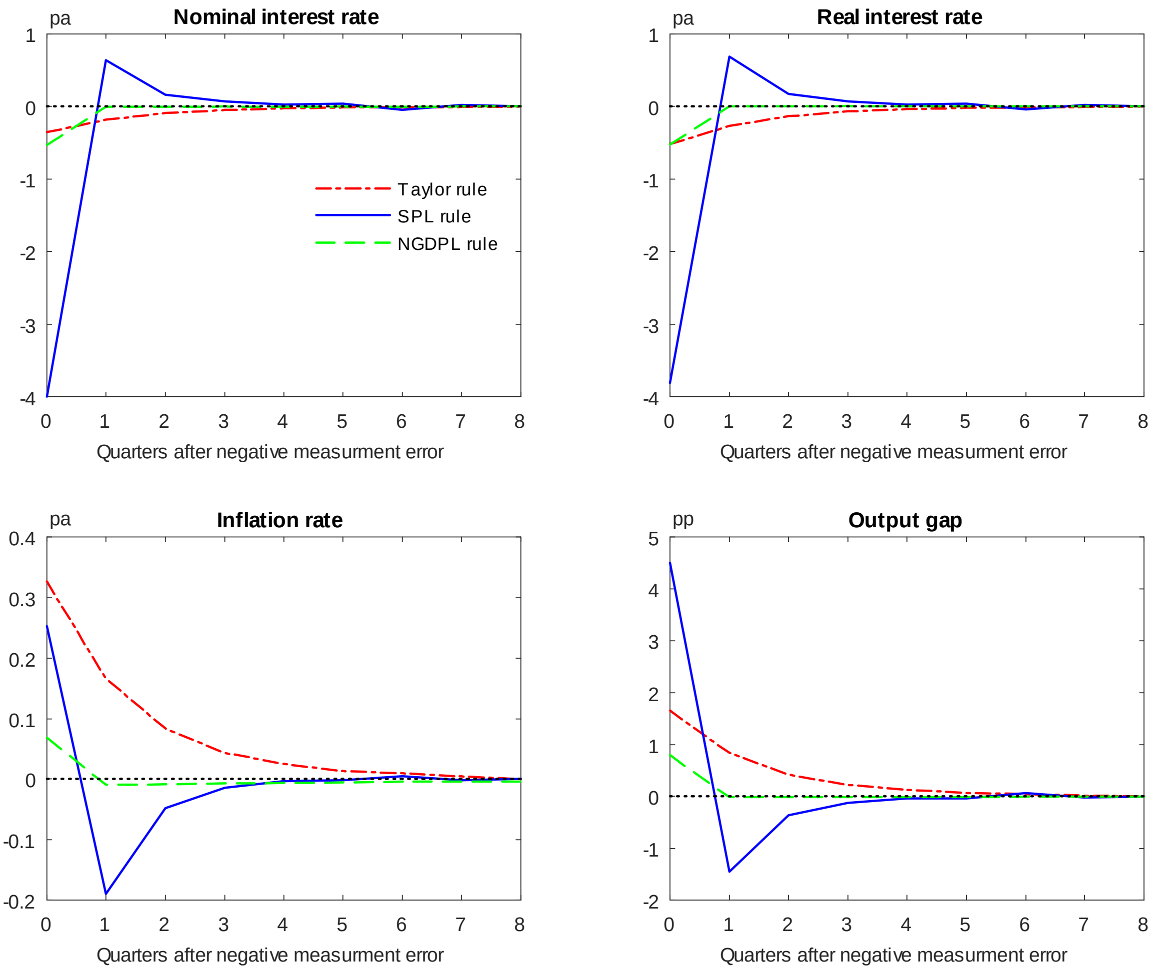
Figure 1: Evolution of the economy, without measurement errors



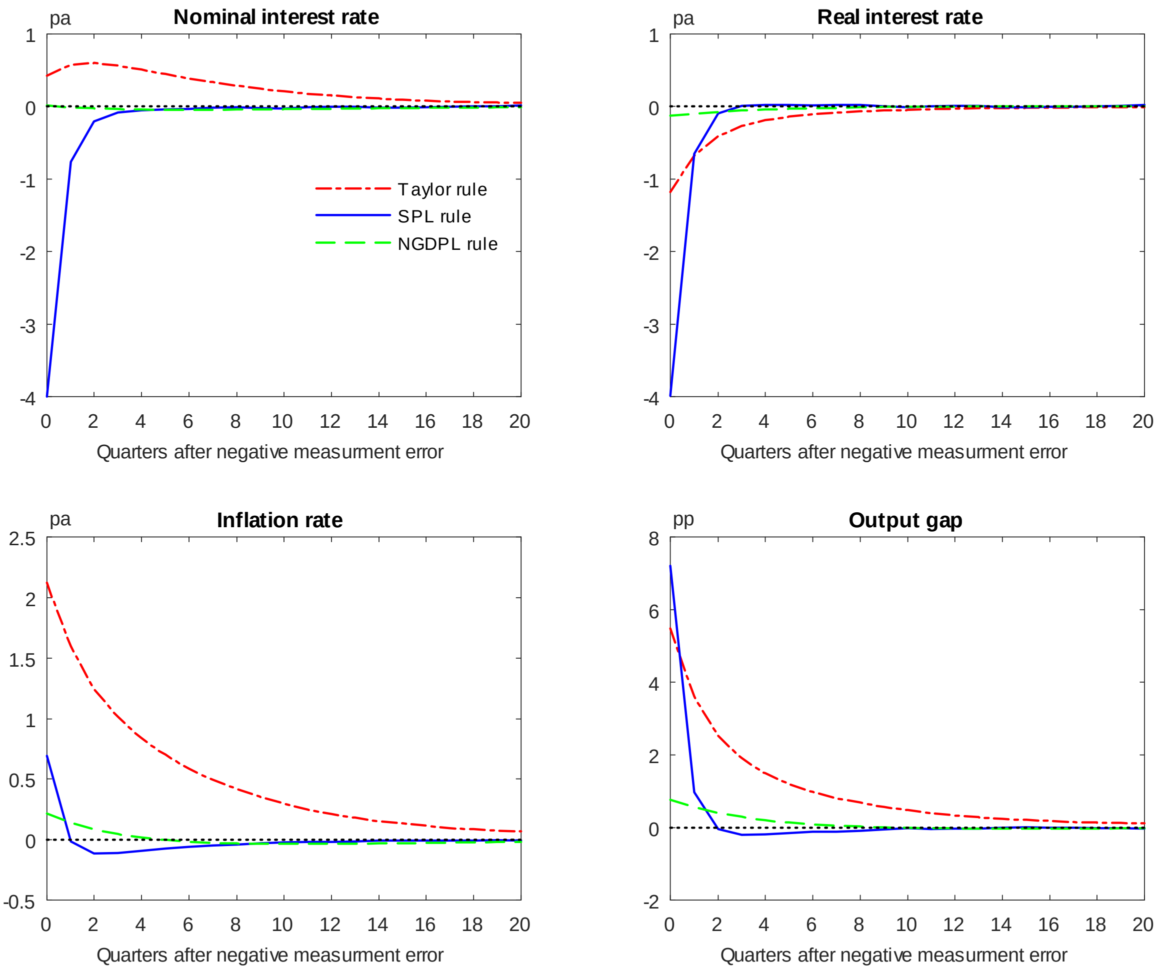
Notes: Shown are expected paths after three-standard-deviation shocks, for each type of shock as in Table 1, using the baseline calibration and optimal rule coefficients. Values are expressed as percent annual (pa) or in percentage points (pp), in deviation from trend.

Figure 2: Evolution of the economy after a purely-temporary measurement error



Notes: Shown are expected paths after a three-standard-deviation measurement error in the output gap, price level, or nominal GDP level, for the policy rules as in Table 6, using the baseline calibration and optimal rule coefficients. Values are expressed as percent annual (pa) or in percentage points (pp), in deviation from steady state.

Figure 3: Evolution of the economy after a persistent measurement error



Notes: Shown are expected paths after a three-standard-deviation measurement error in the output gap, price level, or nominal GDP level, for the policy rules as in Table 6, using the baseline calibration and optimal rule coefficients. Values are expressed as percent annual (pa) or in percentage points (pp), in deviation from steady state.

Table 1: Economic performance, without measurement errors[a]

	Rule coeff.	ZLB episodes		Welfare loss[b]		
	$\phi_{i,p,n}$	Freq.[c]	Duration[d]	π	x	Tot.
			Inertial Taylor rule			
Technology shock only	0.87	0.0	0.0	0.0	0.0	0.0
Mark-up shock only	0.87	0.0	0.0	10.1	0.4	10.5
Demand shock only	0.87	1.9	3.1	12.0	28.7	40.7
			Strict-price-level rule			
Technology shock only	1	0.0	0.0	0.0	0.0	0.0
Mark-up shock only	1	0.0	0.0	0.1	3.9	4.0
Demand shock only	100	12.5	2.6	1.1	4.0	5.1
			Nominal-GDP-level rule			
Technology shock only	1	0.0	0.0	0.8	0.6	1.4
Mark-up shock only	1	0.0	0.0	5.0	0.5	5.5
Demand shock only	100	15.0	2.4	6.3	9.5	15.8

a. Baseline calibration of Section 5.1 but with optimal rule coefficients.

b. Permanent consumption loss (basis points).

c. Expected percent of time at the ZLB.

d. Expected number of consecutive quarters at the ZLB.

Table 2: Economic performance, alternate calibrations

	ZLB episodes		Welfare loss[a]		
	Freq.[b]	Duration[c]	π	x	Tot.
Inertial Taylor rule[d]					
Baseline	1.5	2.9	23.1	29.7	52.8
Lower steady-state real rate ($\beta = 0.993$)[e]	4.2	3.4	28.4	38.5	66.9
Smaller demand elasticity ($\varphi = 1$)	0.0	2.1	25.2	8.8	34.0
Prices less sticky ($\alpha = 0.5$)	1.8	2.6	24.5	23.1	47.6
Prices more sticky ($\alpha = 0.75$)	1.6	3.1	38.9	32.9	71.8
Less competition ($\theta = 5$)	1.6	2.8	14.1	28.0	42.1
More competition ($\theta = 10$)	1.5	2.9	33.4	30.8	64.2
Purely-temporary supply shocks ($\rho_{y^n,u} = 0$)	1.7	3.0	12.9	29.1	42.0
Supply shocks only ($\sigma_v = 0$)	0.0	0.0	10.1	0.4	10.5

a. Permanent consumption loss (basis points).

b. Expected percent of time at the ZLB.

c. Expected number of consecutive quarters at the ZLB.

d. Smoothing coefficient ϕ_i set to 0.87, unless as otherwise noted.

e. The coefficient ϕ_i was raised to 0.9.

Table 3: Economic performance, alternate calibrations

	ZLB episodes		Welfare loss[a]		
	Freq.[b]	Duration[c]	π	x	Tot.
Strict-price-level rule[d]					
Baseline	10.7	2.6	1.1	9.1	10.2
Lower steady-state real rate ($\beta = 0.993$)	21.2	3.7	3.6	16.0	19.6
Smaller demand elasticity ($\varphi = 1$)	7.7	2.7	0.4	2.5	2.9
Prices less sticky ($\alpha = 0.5$)	12.7	2.8	1.7	3.3	5.0
Prices more sticky ($\alpha = 0.75$)	8.8	2.4	0.9	26.9	27.8
Less competition ($\theta = 5$)	11.4	2.6	0.8	6.3	7.1
More competition ($\theta = 10$)	10.0	2.5	1.3	12.1	13.4
Purely-temporary supply shocks ($\rho_{y^n,u} = 0$)	13.0	2.5	1.2	7.5	8.7
Supply shocks only ($\sigma_v = 0$)	0.0	0.0	0.0	5.2	5.2
Nominal-GDP-level rule[d]					
Baseline	11.0	2.1	11.8	10.8	22.6
Lower steady-state real rate ($\beta = 0.993$)	23.7	3.0	18.9	23.2	42.1
Smaller demand elasticity ($\varphi = 1$)	15.8	2.6	5.6	1.8	7.4
Prices less sticky ($\alpha = 0.5$)	11.0	2.0	7.7	5.9	13.6
Prices more sticky ($\alpha = 0.75$)	11.0	2.1	20.5	13.7	34.2
Less competition ($\theta = 5$)	10.8	2.0	6.6	9.3	15.9
More competition ($\theta = 10$)	11.1	2.1	17.4	11.6	29.0
Purely-temporary supply shocks ($\rho_{y^n,u} = 0$)	14.5	2.4	7.2	10.3	17.5
Supply shocks only ($\sigma_v = 0$)	0.0	0.0	5.7	1.0	6.7

a. Permanent consumption loss (basis points).

b. Expected percent of time at the ZLB.

c. Expected number of consecutive quarters at the ZLB.

d. Rule coefficients ϕ_p and ϕ_n set to 100.

Table 4: Economic performance, with purely-temporary measurement errors[a]

	Rule coeff.	ZLB episodes		Welfare loss[b]		
	$\phi_{i,p,n}$	Freq.[c]	Duration[d]	π	x	Tot.
Inertial Taylor rule						
Technology shock only	0.88	0.0	0.0	0.4	0.6	1.0
Mark-up shock only	0.88	0.0	0.0	10.4	0.9	11.3
Demand shock only	0.88	1.2	2.7	12.5	30.4	42.9
Strict-price-level rule						
Technology shock only	1	0.0	0.0	0.0	0.2	0.2
Mark-up shock only	1	0.0	0.0	0.1	4.1	4.2
Demand shock only	10	11.0	2.2	2.2	10.9	13.1
Nominal-GDP-level rule						
Technology shock only	1	0.0	0.0	0.8	0.6	1.4
Mark-up shock only	1	0.0	0.0	5.0	0.5	5.5
Demand shock only	20	14.0	2.4	6.4	9.7	16.1

a. Calibration from Sections 5.1 and 5.4, but with noise persistence set to zero and optimal rule coefficients.

b. Permanent consumption loss (basis points).

c. Expected percent of time at the ZLB.

d. Expected number of consecutive quarters at the ZLB.

Table 5: Economic performance, with persistent measurement errors[a]

	Rule coeff.	ZLB episodes		Welfare loss[b]		
	$\phi_{i,p,n}$	Freq.[c]	Duration[d]	π	x	Tot.
		Inertial Taylor rule				
Technology shock only	0.88	0.0	0.0	9.5	2.5	12.0
Mark-up shock only	0.88	0.0	0.0	19.4	2.8	22.2
Demand shock only	0.88	1.2	2.7	22.0	32.7	54.7
		Strict-price-level rule				
Technology shock only	1	0.0	0.0	0.1	0.3	0.4
Mark-up shock only	1	0.0	0.0	0.2	4.1	4.3
Demand shock only	20	7.7	2.5	1.8	7.1	8.9
		Nominal-GDP-level rule				
Technology shock only	1	0.0	0.0	0.8	0.6	1.4
Mark-up shock only	1	0.0	0.0	5.1	0.5	5.6
Demand shock only	20	14.3	2.3	6.5	9.7	16.2

a. Calibration from Sections 5.1 and 5.4, but with optimal rule coefficients.

b. Permanent consumption loss (basis points).

c. Expected percent of time at the ZLB.

d. Expected number of consecutive quarters at the ZLB.

Table 6: Effects of measurement errors on economic performance[a]

	Rule coeff.	ZLB episodes		Welfare loss[b]		
	$\phi_{i,p,n}$	Freq.[c]	Duration[d]	π	x	Tot.
		Without measurement errors				
Inertial Taylor rule	0.87	1.5	2.9	23.1	29.7	52.8
Strict-price-level rule	100	10.7	2.6	1.1	9.1	10.2
Nominal-GDP-level rule	100	11.0	2.1	11.8	10.8	22.6
		Purely-temporary measurement errors				
Inertial Taylor rule	0.88	0.7	2.1	23.1	31.0	54.1
Strict-price-level rule	10	8.6	2.2	2.3	15.8	18.1
Nominal-GDP-level rule	20	10.6	2.0	12.0	11.0	23.0
		Persistent measurement errors				
Inertial Taylor rule	0.88	0.9	2.3	33.4	33.5	66.9
Strict-price-level rule	20	6.4	2.6	1.9	12.1	14.0
Nominal-GDP-level rule	20	11.0	2.1	11.9	10.8	22.7

a. Calibration from Sections 5.1 and 5.4, but with optimal rule coefficients.

b. Permanent consumption loss (basis points).

c. Expected percent of time at the ZLB.

d. Expected number of consecutive quarters at the ZLB.

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