ISSN 1936-5330

THE FEDERAL RESERVE BANK of KANSAS CITY
RESEARCH WORKING PAPERS

Price Dispersion and Inflation Persistence

Takushi Kurozumi and Willem Van Zandweghe

October 2016
RWP 16-09
https://dx.doi.org/10.18651/RWP2016-09

Price Dispersion and Inflation Persistence*

Takushi Kurozumi† Willem Van Zandweghe‡

October 2016

Abstract

Persistent responses of inflation to monetary policy shocks have been difficult to explain by existing models of the monetary transmission mechanism without embedding controversial intrinsic inertia of inflation. Our paper addresses this issue using a staggered price model with trend inflation, a smoothed-off kink in demand curves, and a fixed cost of production. In this model, inflation exhibits a persistent response to a policy shock even in the absence of its intrinsic inertia, because the kink causes a measure of price dispersion, which is intrinsically inertial, to become a key source of inflation persistence under the positive trend inflation rate. In addition, output and labor productivity both rise after an expansionary policy shock as in an estimated structural vector autoregression model. Moreover, credible disinflation induces a gradual decline in inflation and a fall in output as observed during the Volcker disinflation era.

JEL Classification: E31, E52

Keywords: Staggered price setting; Trend inflation; Smoothed-off kink in demand curve; Fixed production cost; Monetary policy shock; Credible disinflation

*The authors are grateful to Susanto Basu, Brent Bundick, Andrew Foerster, Ferre De Graeve, Juan Rubio-Ramírez, Argia Sbordone, Lee Smith, Raf Wouters, and participants at the Federal Reserve System Committee Meeting on Macroeconomics and seminars at the University of Kansas, the National Bank of Belgium, and the Federal Reserve Bank of Kansas City for their comments and discussions. The views expressed herein are those of the authors and should not be interpreted as those of the Bank of Japan, the Federal Reserve Bank of Kansas City or the Federal Reserve System.

†Bank of Japan, 2-1-1 Nihonbashi Hongokucho, Chuo-ku, Tokyo 103-8660, Japan. *E-mail address:* takushi.kurozumi@boj.or.jp

‡Corresponding author. Research Department, Federal Reserve Bank of Kansas City, 1 Memorial Drive, Kansas City, MO 64198, USA. *E-mail address:* willem.vanzandweghe@kc.frb.org

1 Introduction

An extensive empirical literature has documented the persistent responses of inflation to monetary policy shocks (e.g., Christiano, Eichenbaum, and Evans, 1999, 2005; Boivin, Kiley, and Mishkin, 2011). Figure 1 displays impulse responses of the federal funds rate, inflation, output, and labor productivity (output per hour) to an expansionary policy shock in an estimated structural vector autoregression (VAR) model. This figure illustrates that inflation rises to a peak level in some quarters following the shock and thereafter returns gradually to the pre-shock level. In addition, both output and labor productivity rise after the shock.

To account for the empirical evidence, theoretical literature has introduced intrinsic inertia of inflation in models of the monetary transmission mechanism. Two popular sources of the inertia are price indexation to past inflation (e.g., Christiano, Eichenbaum, and Evans, 2005) and rule-of-thumb price setting (e.g., Galí and Gertler, 1999).[1] The literature notwithstanding, incorporating the intrinsic inertia remains controversial. Benati (2008) shows that the degree of inflation persistence varies with monetary policy regimes, thus concluding that inflation inertia may not be intrinsic.[2] Moreover, Woodford (2007) indicates that price indexation to past inflation by all firms other than those which reoptimize prices is at odds with the micro evidence that many individual prices remain unchanged for several months.

This paper addresses the question of what model can explain the empirical evidence without embedding controversial intrinsic inertia of inflation.[3] Specifically, the paper examines a staggered price model of Calvo (1983) with trend inflation (and homogeneous labor input). This model potentially generates a persistent response of inflation to a monetary policy shock even in the absence of the intrinsic inertia, because the model-implied inflation dynamics can

[1] Woodford (2007) and Fuhrer (2011) review different theories of intrinsic inertia in inflation.

[2] Fuhrer (2011) discusses the distinction between "intrinsic" versus "inherited" persistence in inflation.

[3] Galí and Gertler (1999) suggest that "it is worth searching for explanations of inflation inertia beyond the traditional ones that rely heavily on arbitrary lags" (p. 219). Moreover, Mankiw and Reis (2002) indicate that "[t]he key empirical fact that is hard to match, however, is not the high autocorrelations of inflation, but the delayed response of inflation to monetary policy shocks" (p. 1311).

be affected by relative price distortion, which is intrinsically inertial.[4] Yet this paper shows that in a plausibly calibrated version of the model, the inertia of relative price distortion induces little persistence in the response of inflation to a policy shock. In addition, labor productivity (output per hour) exhibits a counterfactual decline after an expansionary policy shock, since hours worked increase more than output due to a rise in relative price distortion following the shock. To obtain a persistent inflation response, Damjanovic and Nolan (2010) employ a decreasing-returns-to-scale production technology and a relatively long average duration of price change of two years. Such a technology amplifies relative price distortion—which is consistent with labor demand dispersion in their paper—and increases intrinsic inertia of the distortion along with the long average duration of price change, thereby generating a persistent response of inflation to a policy shock. However, this induces a counterfactual decline in output after an expansionary policy shock.[5] Thus, these models, by relying on relative price distortion, exhibit a tension between generating a persistent response of inflation and a response of labor productivity that goes in the right direction after a monetary policy shock.

To break this tension, our model introduces a smoothed-off kink in demand curves of goods.[6] In the presence of the kink, the model-implied inflation dynamics can be influenced by a measure of price dispersion in addition to relative price distortion, and such a measure is intrinsically inertial. Our model also incorporates a fixed cost of production so that production technology could exhibit increasing returns to scale.

In our model, inflation shows a persistent response to a monetary policy shock, with a hump shape and a gradual decline as documented by the empirical literature. In addition, output and labor productivity both rise after an expansionary policy shock. The persistent

[4]In a staggered price model with trend inflation, Kurozumi and Van Zandweghe (2016b) show that the model-implied inflation dynamics can be influenced by relative price distortion in the case of homogeneous labor input, whereas there is no such influence in the case of firm-specific one.

[5]In their model, labor productivity (output per hour) also exhibits a counterfactual decline following an expansionary policy shock, which is not presented in their paper. Regarding the counterfactual output decline, they suggest that "further work is required to understand this and reconcile it with how one typically thinks the economy responds to such a shock" (p. 1096).

[6]This kink in demand curves has been analyzed by Kimball (1995), Dotsey and King (2005), Levin et al. (2008), Shirota (2015), and Kurozumi and Van Zandweghe (2016a).

inflation response is mostly inherited from the measure of price dispersion, which exhibits a persistent response to a policy shock. Relative price distortion—which coincides with demand dispersion in the model—shows a muted response to an expansionary policy shock in the presence of the kink in demand curves. This is because the kink reduces the price elasticity of demand for goods with low relative prices and thereby subdues the increase in demand dispersion associated with a rise in price dispersion following the expansionary policy shock. Therefore, the kink (under the positive trend inflation rate) makes the price dispersion a key source of inflation persistence, and causes both output and labor productivity to rise after an expansionary policy shock, along with the increasing-returns-to-scale production technology.

This paper contributes to the literature concerning credible disinflation as well.[7] As Fuhrer (2011) points out, intrinsic inertia of inflation plays a key role in a canonical New Keynesian model, where a credible permanent reduction in trend inflation generates a gradual adjustment of inflation to its new trend rate and a decline in output. These responses align closely with historical experiences; for instance, they are reminiscent of the U.S. economy's evolution during the Volcker disinflation era. Without the inertia, inflation jumps to its new trend rate, while output never deviates from its trend level. However, in our model (with the kink in demand curves and the fixed cost of production), the credible disinflation induces a gradual decline in inflation and a fall in output even in the absence of intrinsic inertia in inflation.

The present paper is also related to a recent strand of literature that has examined the role of trend inflation for inflation persistence.[8] Cogley and Sbordone (2008) emphasize the role of nonstationary time-variation in trend inflation for understanding inflation persistence, and argue that intrinsic inertia of inflation is not needed once drift in trend inflation is taken into account.[9] Our paper offers a complementary explanation of inflation persistence based

[7]For studies on credible disinflation, see Ball (1994), Fuhrer and Moore (1995), and Mankiw and Reis (2002) among others.

[8]For a review of this literature, see, e.g., Ascari and Sbordone (2014).

[9]Note that their argument holds under an assumption of subjective expectations based on the anticipated utility model of Kreps (1998) but not under that of rational expectations. Our paper maintains the rational expectations assumption.

on the joint effect of the positive trend inflation rate and the kink in demand curves.

The remainder of the paper proceeds as follows. Section 2 presents a staggered price model with trend inflation, a smoothed-off kink in demand curves, and a fixed cost of production. In this model, Section 3 investigates impulse responses to a monetary policy shock. Section 4 applies the model to an analysis on credible disinflation. Section 5 concludes.

2 Model

The model economy is the same as that of Kurozumi and Van Zandweghe (2016a), except for the presence of a fixed cost of production. It is populated by a representative household, a representative final-good firm, a continuum of intermediate-good firms, and a monetary authority. Key features of the model are that in each period, a fraction of intermediate-good firms keeps prices of differentiated products unchanged, while the remaining fraction reoptimizes prices in the face of the final-good firm's demand curves with a smoothed-off kink. The behavior of each economic agent is described in turn.

2.1 Household

The representative household consumes final goods C_t, supplies homogeneous labor N_t, and purchases one-period riskless bonds B_t so as to maximize the utility function $E_0 \sum_{t=0}^{\infty} \beta^t [\log C_t - N_t^{1+\sigma_n}/(1+\sigma_n)]$ subject to the budget constraint $P_t C_t + B_t = P_t W_t N_t + i_{t-1} B_{t-1} + T_t$, where E_t denotes the expectation operator conditional on information available in period t, $\beta \in (0,1)$ is the subjective discount factor, $\sigma_n \geq 0$ is the inverse of the elasticity of labor supply, P_t is the price of final goods, W_t is the real wage, i_t is the gross interest rate on the bonds and equals the monetary policy rate, and T_t consists of lump-sum public transfers and firm profits.

Combining the first-order conditions for utility maximization with respect to consumption,

labor supply, and bond holdings yields

$$W_t = C_t N_t^{\sigma_n}, \tag{1}$$

$$1 = E_t\left(\frac{\beta C_t}{C_{t+1}}\frac{i_t}{\pi_{t+1}}\right), \tag{2}$$

where $\pi_t = P_t/P_{t-1}$ is the gross inflation rate.

2.2 Final-good firm

As in Kimball (1995), the representative final-good firm produces homogeneous goods Y_t under perfect competition by choosing a combination of intermediate inputs $\{Y_t(f)\}$ so as to maximize profit $P_tY_t - \int_0^1 P_t(f)Y_t(f)df$ subject to the production technology

$$\int_0^1 F\left(\frac{Y_t(f)}{Y_t}\right) df = 1, \tag{3}$$

where $P_t(f)$ is the price of intermediate good $f \in [0,1]$. Following Dotsey and King (2005) and Levin et al. (2008), the function $F(\cdot)$ is assumed to be of the form

$$F\left(\frac{Y_t(f)}{Y_t}\right) = \frac{\gamma}{(1+\epsilon)(\gamma-1)}\left[(1+\epsilon)\frac{Y_t(f)}{Y_t} - \epsilon\right]^{\frac{\gamma-1}{\gamma}} + 1 - \frac{\gamma}{(1+\epsilon)(\gamma-1)},$$

where $\gamma = \theta(1+\epsilon)$. The parameter $\epsilon \leq 0$ governs the curvature of the final-good firm's demand curve for each intermediate good. In the special case of $\epsilon = 0$, the production technology (3) is reduced to the CES one $Y_t = [\int_0^1 (Y_t(f))^{(\theta-1)/\theta} df]^{\theta/(\theta-1)}$, where the parameter $\theta > 1$ represents the price elasticity of demand for each intermediate good.

The first-order conditions for profit maximization yield the final-good firm's relative demand curve for intermediate good f,

$$\frac{Y_t(f)}{Y_t} = \frac{1}{1+\epsilon}\left[\left(\frac{P_t(f)}{P_t d_t}\right)^{-\gamma} + \epsilon\right], \tag{4}$$

where d_t is the Lagrange multiplier on the production technology (3) in profit maximization and is a measure of *price dispersion* given by

$$d_t = \left[\int_0^1 \left(\frac{P_t(f)}{P_t}\right)^{1-\gamma} df\right]^{\frac{1}{1-\gamma}}. \tag{5}$$

Then, the price elasticity of demand for good f is given by $\eta_t = \theta[1 + \epsilon - \epsilon(Y_t(f)/Y_t)^{-1}]$. Figure 2 illustrates the demand curve (4) with the two values of the curvature parameter $\epsilon = -9, 0$. In the case of $\epsilon = 0$, the price elasticity of demand is constant, i.e., $\eta_t = \theta$. When $\epsilon = -9$, the elasticity η_t varies inversely with relative demand $Y_t(f)/Y_t$, as can be seen in the figure. Therefore, in the presence of the smoothed-off kink in demand curves (i.e., $\epsilon < 0$), relative demand for an intermediate good becomes more price-elastic for a rise in the relative price of the good, while it becomes less price-elastic for a decline in the relative price.

The final-good firm's zero-profit condition implies that its product's price P_t satisfies

$$1 = \frac{1}{1+\epsilon} d_t + \frac{\epsilon}{1+\epsilon} e_t, \tag{6}$$

where

$$e_t = \int_0^1 \frac{P_t(f)}{P_t} \, df. \tag{7}$$

Note that in the case of $\epsilon = 0$, where the production technology (3) becomes the CES one and there is no kink in demand curves, Eqs. (4)–(6) can be reduced to $Y_t(f) = Y_t(P_t(f)/P_t)^{-\theta}$ (constant elasticity demand curve), $P_t = [\int_0^1 (P_t(f))^{1-\theta} df]^{1/(1-\theta)}$, and $d_t = 1$, respectively.

The final-good market clearing condition is given by

$$Y_t = C_t. \tag{8}$$

2.3 Intermediate-good firms

Each intermediate-good firm f produces one kind of differentiated good $Y_t(f)$ under monopolistic competition. This firm uses the production technology

$$Y_t(f) = N_t(f) - \phi \tag{9}$$

if $N_t(f) > \phi$; otherwise, $Y_t(f) = 0$, where $\phi > 0$ denotes a fixed cost of production. In the presence of the fixed cost, the production technology exhibits increasing returns to scale. It is assumed throughout the paper that $N_t(f) > \phi$ for each firm f in every period t. Given the real wage W_t, the first-order condition for minimization of the production cost shows that

the real marginal cost of each intermediate-good firm is identical and equal to the real wage. Thus, from the labor supply equation (1), it follows that the real marginal cost mc_t meets

$$mc_t = C_t N_t^{\sigma_n}. \tag{10}$$

The labor market clearing condition is given by

$$N_t = \int_0^1 N_t(f) df.$$

Combining this condition with the final-good firm's demand curve (4) and the production technology (9) yields

$$\frac{s_t + \epsilon}{1 + \epsilon} Y_t = N_t - \phi, \tag{11}$$

where $(s_t + \epsilon)/(1 + \epsilon)$ represents relative price distortion and

$$s_t = \int_0^1 \left(\frac{P_t(f)}{P_t d_t} \right)^{-\gamma} df. \tag{12}$$

Substituting the demand curve (4) into Eq. (12) leads to

$$\frac{s_t + \epsilon}{1 + \epsilon} = \int_0^1 \frac{Y_t(f)}{Y_t} df,$$

so that the relative price distortion coincides with *demand dispersion* in the model.

In the face of the demand curve (4) and the real marginal cost, intermediate-good firms set prices of their products on a staggered basis as in Calvo (1983). In each period, a fraction $\alpha \in (0, 1)$ of firms keeps previous-period prices unchanged, while the remaining fraction $1 - \alpha$ of firms sets the price $P_t(f)$ so as to maximize the relevant profit

$$E_t \sum_{j=0}^{\infty} \alpha^j q_{t,t+j} \left(\frac{P_t(f)}{P_{t+j}} - mc_{t+j} \right) \frac{1}{1 + \epsilon} \left[\left(\frac{P_t(f)}{P_{t+j} d_{t+j}} \right)^{-\gamma} + \epsilon \right] Y_{t+j},$$

where $q_{t,t+j} = \beta^j C_t / C_{t+j}$ is the stochastic discount factor between period t and period $t + j$. For this profit function to be well-defined, the following assumption is imposed.

Assumption 1 *The three inequalities $\alpha\beta\pi^{\gamma-1} < 1$, $\alpha\beta\pi^{\gamma} < 1$, and $\alpha\beta\pi^{-1} < 1$ hold, where π denotes the gross rate of trend inflation (i.e., the steady-state value of π_t).*

Using the final-good market clearing condition (8), the first-order condition for profit maximization leads to

$$E_t \sum_{j=0}^{\infty} (\alpha\beta)^j \prod_{k=1}^{j} \pi_{t+k}^{\gamma} \left[\left(p_t^* \prod_{k=1}^{j} \frac{1}{\pi_{t+k}} - \frac{\gamma}{\gamma-1} mc_{t+j} \right) d_{t+j}^{-\gamma} - \frac{\epsilon}{\gamma-1} \left(p_t^* \prod_{k=1}^{j} \frac{1}{\pi_{t+k}} \right)^{1+\gamma} \right] = 0, \quad (13)$$

where p_t^* is the relative price set by firms that reoptimize prices in period t.

Moreover, under the staggered price setting, Eqs. (5), (7), and (12) can be reduced to, respectively,

$$(d_t)^{1-\gamma} = \alpha \left(\frac{d_{t-1}}{\pi_t} \right)^{1-\gamma} + (1-\alpha) \left(p_t^* \right)^{1-\gamma}, \quad (14)$$

$$e_t = \alpha \left(\frac{e_{t-1}}{\pi_t} \right) + (1-\alpha) p_t^*, \quad (15)$$

$$(d_t)^{-\gamma} s_t = \alpha \left(\frac{d_{t-1}}{\pi_t} \right)^{-\gamma} s_{t-1} + (1-\alpha) \left(p_t^* \right)^{-\gamma}. \quad (16)$$

These equations show that the staggered price setting gives rise to persistence in the measures of price dispersion and relative price distortion.

2.4 Monetary authority

The monetary authority conducts interest rate policy according to a policy rule of the sort proposed by Taylor (1993). This rule adjusts the interest rate in response to deviations of the inflation rate from the trend inflation rate and allows for policy inertia, that is,

$$\log i_t = \rho \log i_{t-1} + (1-\rho)[\log i + \phi_\pi (\log \pi_t - \log \pi)] + \varepsilon_{it}, \quad (17)$$

where i is the steady-state gross interest rate, $\rho \in [0, 1)$ and $\phi_\pi \geq 0$ represent the degrees of policy inertia and the policy response to inflation, and ε_{it} is an i.i.d. shock to monetary policy.

2.5 Log-linearized equilibrium conditions

The equilibrium conditions (2), (6), (8), (10), (11), and (13)–(17) are log-linearized around a steady state (with the trend inflation rate π) under Assumption 1, and rearranging the

resulting equations leads to

$$\hat{Y}_t = E_t\hat{Y}_{t+1} - (\hat{\imath}_t - E_t\hat{\pi}_{t+1}), \tag{18}$$

$$\hat{Y}_t = \left(1 + \frac{\phi}{Y}\frac{1+\epsilon}{s+\epsilon}\right)\hat{N}_t - \frac{s}{s+\epsilon}\hat{s}_t, \tag{19}$$

$$\hat{mc}_t = \hat{Y}_t + \sigma_n\hat{N}_t, \tag{20}$$

$$\begin{aligned}\hat{\pi}_t = {} & \beta E_t\hat{\pi}_{t+1} + \frac{(1-\alpha\pi^{\gamma-1})(1-\alpha\beta\pi^{\gamma})}{\alpha\pi^{\gamma-1}[1-\tilde{\epsilon}\gamma/(\gamma-1-\tilde{\epsilon})]}\hat{mc}_t - \frac{1}{\alpha\pi^{\gamma-1}}\left(\hat{d}_t - \alpha\beta\pi^{\gamma-1}E_t\hat{d}_{t+1}\right) + \hat{d}_{t-1} - \alpha\beta\pi^{\gamma-1}\hat{d}_t \\ & - \frac{\gamma(1-\alpha\pi^{\gamma-1})[\alpha\beta\pi^{\gamma-1}(\pi-1)(\gamma-1)+\tilde{\epsilon}(1-\alpha\beta\pi^{\gamma})]}{\alpha\pi^{\gamma-1}[\gamma-1-\tilde{\epsilon}(\gamma+1)]}\hat{d}_t + \varphi_t + \psi_t,\end{aligned} \tag{21}$$

$$\hat{s}_t = \alpha\pi^{\gamma}\hat{s}_{t-1} + \frac{\alpha\gamma\pi^{\gamma-1}(\pi-1)}{1-\alpha\pi^{\gamma-1}}\left(\hat{\pi}_t + \hat{d}_t - \hat{d}_{t-1}\right), \tag{22}$$

$$\hat{d}_t = \frac{\alpha\pi^{-1}[1-\alpha\beta\pi^{\gamma-1}+\tilde{\epsilon}\pi^{\gamma}(1-\alpha\beta\pi^{-1})]}{1-\alpha\beta\pi^{\gamma-1}+\tilde{\epsilon}(1-\alpha\beta\pi^{-1})}\hat{d}_{t-1} - \frac{\tilde{\epsilon}\alpha\pi^{-1}(\pi^{\gamma}-1)(1-\alpha\beta\pi^{-1})}{(1-\alpha\pi^{-1})[1-\alpha\beta\pi^{\gamma-1}+\tilde{\epsilon}(1-\alpha\beta\pi^{-1})]}\hat{\pi}_t, \tag{23}$$

$$\varphi_t = \alpha\beta\pi^{\gamma}E_t\varphi_{t+1} + \frac{\beta(\pi-1)(1-\alpha\pi^{\gamma-1})}{1-\tilde{\epsilon}\gamma/(\gamma-1-\tilde{\epsilon})}\left[\gamma E_t\hat{\pi}_{t+1} + (1-\alpha\beta\pi^{\gamma})\left(E_t\hat{mc}_{t+1} + \gamma E_t\hat{d}_{t+1}\right)\right], \tag{24}$$

$$\psi_t = \alpha\beta\pi^{-1}E_t\psi_{t+1} + \frac{\tilde{\epsilon}\beta(\pi^{\gamma}-1)(1-\alpha\pi^{\gamma-1})}{\pi^{\gamma}\left[\gamma-1-\tilde{\epsilon}(\gamma+1)\right]}E_t\hat{\pi}_{t+1}, \tag{25}$$

$$\hat{\imath}_t = \rho\hat{\imath}_{t-1} + (1-\rho)\phi_{\pi}\hat{\pi}_t + \varepsilon_{it}, \tag{26}$$

where hatted variables denote log-deviations from steady-state values, φ_t and ψ_t are forward-looking auxiliary variables reflecting price-adjusting firms' sensitivity to expected future conditions in the presence of the nonzero trend inflation rate and the kink in demand curves, $\tilde{\epsilon} = \epsilon(1-\alpha\beta\pi^{\gamma-1})/(1-\alpha\beta\pi^{-1})[(1-\alpha\pi^{\gamma-1})/(1-\alpha)]^{-\gamma/(\gamma-1)}$, and $s = (1-\alpha)/(1-\alpha\pi^{\gamma})[(1-\alpha)/(1-\alpha\pi^{\gamma-1})]^{-\gamma/(\gamma-1)}$.

At the zero trend inflation rate (i.e., $\pi = 1$), Eqs. (22)–(25) imply that $\hat{s}_t = 0$, $\hat{d}_t = 0$, $\varphi_t = 0$, and $\psi_t = 0$, so that Eq. (21) can be reduced to the familiar New Keynesian Phillips curve (NKPC)

$$\hat{\pi}_t = \beta E_t\hat{\pi}_{t+1} + \frac{(1-\alpha)(1-\alpha\beta)}{\alpha[1-\epsilon\theta/(\theta-1)]}\hat{mc}_t. \tag{27}$$

Thus, Eq. (21) is a generalized NKPC (GNKPC). In the NKPC (27), the kink in demand curves reduces the slope (i.e., the real marginal cost elasticity of inflation) by the factor

$1/[1-\epsilon\theta/(\theta-1)]$. Moreover, the curvature of the demand curve (4) is given by $-\epsilon\theta$, so that the slope of the NKPC (27) flattens with the curvature.

Alternatively, if there is no kink in demand curves (i.e., $\epsilon = 0$), Eqs. (23) and (25) imply that $\hat{d}_t = 0$ and $\psi_t = 0$, so that Eqs. (21), (22), and (24) can be reduced to, respectively,

$$\hat{\pi}_t = \beta E_t \hat{\pi}_{t+1} + \frac{(1-\alpha\pi^{\theta-1})(1-\alpha\beta\pi^{\theta})}{\alpha\pi^{\theta-1}} \hat{mc}_t + \varphi_t, \tag{28}$$

$$\hat{s}_t = \alpha\pi^{\theta}\hat{s}_{t-1} + \frac{\alpha\theta\pi^{\theta-1}(\pi-1)}{1-\alpha\pi^{\theta-1}}\hat{\pi}_t, \tag{29}$$

$$\varphi_t = \alpha\beta\pi^{\theta}E_t\varphi_{t+1} + \beta(\pi-1)(1-\alpha\pi^{\theta-1})\left[\theta E_t\hat{\pi}_{t+1} + (1-\alpha\beta\pi^{\theta})E_t\hat{mc}_{t+1}\right]. \tag{30}$$

Here two points are particularly worth noting. First, under the nonzero trend inflation rate, the relative price distortion $[s/(s+\epsilon)]\hat{s}_t$ has an influence on inflation dynamics through the aggregate production equation (19), the real marginal cost equation (20), and the GNKPC (21), and thus inflation possibly inherits the persistence of the distortion, which is intrincially inertial as shown by the law of motion for $\hat{s}_t$, (22). Second, and more importantly, the kink in demand curves under the nonzero trend inflation rate causes the price dispersion $\hat{d}_t$ to have an influence on inflation dynamics directly through the GNKPC (21) and indirectly through the law of motion for $\hat{s}_t$, (22), and the equation for φ_t, (24). Consequently, inflation possibly inherits the persistence of the price dispersion, which is intrinsically inertial as can be seen in its law of motion (23). The next section examines whether the two possible sources of inflation persistence generate a persistent response of inflation to a monetary policy shock.

3 Impulse response analysis

This section investigates the effects of the positive trend inflation rate and the kink in demand curves on impulse responses to a monetary policy shock, using a realistic calibration of the model.

3.1 Calibration

The calibration of the quarterly model is summarized in Table 1. As is common in the literature, our calibration sets the subjective discount factor at $\beta = 0.99$, the inverse of the elasticity of labor supply at $\sigma_n = 0.5$, the probability of no price change at $\alpha = 0.75$, which implies that the average frequency of price change is four quarters, and the parameter governing the price elasticity of demand at $\theta = 10$, which implies a price markup of 11 percent at the zero trend inflation rate. As for the parameter governing the curvature of demand curves, two cases are considered: $\epsilon = 0$, the case of constant elasticity demand curves, that is, no kink in demand curves; and $\epsilon = -9$, which implies that the curvature equals $-\epsilon\theta = 90$, on the high side but within a wide range found in the literature surveyed by Dossche et al. (2010). The value of the fixed production cost ϕ is chosen so that intermediate-good firms' profits would be zero in steady state. The annualized trend inflation rate is set at 2.5 percent, which is the average inflation rate of the personal consumption expenditure price index over the period 1985:Q1–2007:Q4.[10] The degrees of policy inertia and the policy response to inflation are set at $\rho = 0.9$ and $\phi_\pi = 1.5$.

3.2 Responses to a monetary policy shock

Using the calibration, this subsection examines impulse responses to a monetary policy shock in the model presented in the preceding section. Especially, the empirical literature has documented two facts, which are summarized by the impulse responses in the VAR model (Figure 1): (i) inflation exhibits a persistent response to a policy shock, and (ii) both output and labor productivity (output per hour) rise after an expansionary policy shock. Thus, the present subsection evaluates the model in terms of the two empirical facts.

To begin with, the case of constant elasticity demand curves (i.e., $\epsilon = 0$) is investigated. In this case, there is no kink in demand curves, and the model has difficulty replicating the

[10] To meet Assumption 1 under the calibration, the annualized trend inflation rate needs to be greater than -1.46 percent if $\epsilon = -9$ and between -69.61 and $+12.65$ percent if $\epsilon = 0$.

two empirical facts. The dashed lines in Figure 3 display the impulse responses to a negative 60 basis points policy shock under the calibration (with $\epsilon = 0$). Regarding the empirical fact (i), the annualized inflation rate jumps about one percentage point on impact and its response dies out within about two years, as shown in the top right panel of the figure. This gradual decline in the inflation response reflects two possible sources of inertia: the inertia of the monetary policy rule and that of the relative price distortion. As can be seen in the bottom left panel, the distortion exhibits a persistent response to the policy shock. Under the nonzero rate of trend inflation, the inertia of the distortion potentially generates inflation persistence. However, such an effect of the relative price distortion on the inflation response is minor under the calibration (with the annualized trend inflation rate of 2.5 percent). Indeed, the inflation response to the policy shock (at that rate) is similar to that at the zero trend inflation rate, which is illustrated by the dotted line in the figure, and at the zero rate there is no effect of the relative price distortion because of no influence of the distortion on inflation dynamics. Therefore, under the calibration, the positive trend inflation rate by itself (that is, the inertia of the relative price distortion) induces little persistence in the response of inflation to the policy shock.

As for the empirical fact (ii), the starkest implication of the positive trend inflation rate in the case of no kink in demand curves is that labor productivity (output per hour) falls after an expansionary monetary policy shock as shown in the middle right panel of Figure 3, although the middle left panel illustrates that output rises following the shock. Such a fall is at odds with the rise in output per hour observed in the VAR model (the bottom right panel of Figure 1). The fall in labor productivity stems from the effect of the relative price distortion on output per hour. In the case of $\epsilon = 0$, the aggregate production equation (19) is reduced to

$$\hat{Y}_t - \hat{N}_t = \frac{\phi}{Y}\frac{1}{s}\hat{N}_t - \hat{s}_t.$$

This equation shows that output per hour rises with hours worked in the presence of the increasing returns to scale introduced by the fixed cost of production, while it declines with

the relative price distortion under the nonzero trend inflation rate.[11] Under the calibration (with $\epsilon = 0$), the effect of the distortion dominates after the initial impact of the shock, as can be seen in the middle right panel of Figure 3. That is, the distortion lowers labor productivity as it reduces the efficiency of labor in producing aggregate output. Therefore, the response of output per hour (inversely) reflects that of the relative price distortion shown in the bottom left panel.

This subsection now evaluates the joint effect of the positive trend inflation rate and the kink in demand curves on impulse responses to a monetary policy shock. The solid lines in Figure 3 display the impulse responses to the expansionary policy shock in the case of the kink (i.e., $\epsilon = -9$). The top right panel of the figure shows a persistent response of inflation to the policy shock—exhibiting a hump shape and a gradual decline—in line with the empirical fact (i), while the middle two panels illustrate that both output and labor productivity rise after the expansionary policy shock, corresponding to the empirical fact (ii).[12] Therefore, the kink in demand curves under the positive trend inflation rate enables the model to replicate the two empirical facts.

The kink in demand curves reduces the price elasticity of demand for goods with low relative prices and thereby subdues the increase in demand dispersion associated with a rise in price dispersion. As shown in the preceding section, the relative price distortion coincides with demand dispersion, and therefore, in the presence of the kink, the distortion exhibits a muted response to the expansionary policy shock as illustrated in the bottom left panel, although the shock increases price dispersion under the staggered price setting and the positive trend inflation rate.[13] The muted response of the relative price distortion has two consequences.

[11] Basu and Fernald (2001) evaluate different explanations of the procyclicality of output per hour.

[12] The responses of output and labor productivity lack the hump shape observed in the impulse responses in the VAR model (Figure 1). Adding habit formation in the consumption preferences would generate hump-shaped responses of output and labor productivity in the model, and would provide an additional source of inflation persistence. As this is well understood, we abstract from habit formation to clarify our paper's contribution to related literature.

[13] In this panel, the relative price distortion $[s/(s+\epsilon)]\hat{s}_t$ varies inversely with $\hat{s}_t$ in the case of the kink in demand curves (i.e., $\epsilon = -9$), since the coefficient $s/(s+\epsilon)$ is negative under the calibration.

First, the effect of the increasing returns to scale dominates and thus both output and labor productivity (output per hour) rise after the expansionary policy shock. Second, the key source of the persistence in the inflation response to the policy shock is the inertia of the price dispersion $\hat{d}_t$, which exhibits a persistent response to the policy shock, as can be seen in the bottom right panel. The persistent response of inflation to the policy shock is mostly inherited from the intrinsically inertial price dispersion in addition to the policy inertia.

The kink in demand curves affects inflation dynamics via distinct channels when trend inflation is positive or zero. At the zero trend inflation rate, the kink's only effect is to flatten the slope of the NKPC (that is, the real marginal cost elasticity of inflation in Eq. (27)). Figure 4 displays the slope for a range of values of the curvature parameter, ϵ. As shown by the dashed line, at the zero trend inflation rate the slope reduces by an order of magnitude as the curvature parameter declines from 0 to -9 (from 0.086 to 0.008). The smaller slope dampens the impulse response of inflation, but it does not generate a hump shape (not shown). The solid line shows that at the trend inflation rate of 2.5 percent, the kink has a smaller effect on the slope of the GNKPC (that is, the real marginal cost elasticity of inflation in Eq. (21)); it increases slightly from 0.055 if $\epsilon = 0$ to 0.061 if $\epsilon = -9$. Instead, at the positive trend inflation rate the kink primarily affects inflation dynamics through the price dispersion.

4 Credible disinflation

This section applies our model to an analysis of credible disinflation.

During the Volcker disinflation in the early 1980s, the U.S. economy was characterized by a gradual decline in inflation and a recession. To account for this evolution, existing literature has stressed that intrinsic inertia of inflation plays a key role in a canonical New Keynesian model. As Fuhrer (2011) points out, a credible permanent reduction in trend inflation leads inflation to jump to its new trend rate and output to have no deviation from its trend level in the absence of intrinsic inertia in inflation. Once the intrinsic inflation is embedded, the credible disinflation generates a gradual adjustment of inflation to its new trend rate and a

temporary decline in output.[14]

This section examines whether our model can explain the U.S. economy's evolution during the Volcker disinflation era even without embedding controversial intrinsic inertia of inflation. Specifically, the following experiment is carried out. In period 0, the economy is in steady state with an annualized trend inflation rate of three percent. At the start of period 1, the annualized trend inflation rate is reduced suddenly and credibly to two percent.[15] For simplicity, it is assumed that there is no policy inertia, i.e., $\rho = 0$. Denote the vector of endogenous state variables in the log-linearized model by $\hat{k}_t = \log k_t - \log k(\pi)$; for instance, $k_t = [s_t, d_t]'$ in the case of the kink in demand curves and $k_t = s_t'$ in the case of no kink. Here $k(\pi)$ denotes the vector of steady-state values of k_t, which stresses that these values are functions of the trend inflation rate π. Because in period 0 all variables are in steady state, in period 1 the lagged endogenous state variables under the new trend inflation rate are given by $\log k(\pi^0) - \log k(\pi^1)$, where $\pi^0 = 1.03^{1/4}$ and $\pi^1 = 1.02^{1/4}$. Then, the solution of the log-linearized model at the trend inflation rate of π^1 is used to compute inflation and output in period $t = 1, 2, 3, \cdots$.

Figure 5 displays the responses of inflation and output to the sudden and credible reduction in the annualized trend inflation rate from three to two percent, using the calibration presented in Table 1 (except $\rho = 0$). In the figure the dotted lines show the responses in the model where intrinsic inertia of inflation is embedded but there is no kink in demand curves (i.e., $\epsilon = 0$), which is a canonical New Keynesian model. Specifically, in this model, firms that do not reoptimize prices are assumed to index their prices fully to previous-period inflation as in Christiano, Eichenbaum, and Evans (2005). Then, inflation declines gradually toward its new trend rate, and output falls temporarily and thereafter rebounds gradually to the initial steady-state level, in line with the responses reported by Fuhrer (2011). Similar responses

[14] Fuhrer (2011) demonstrates this result using a NKPC and an ad hoc, backward-looking equation for output.

[15] The disinflation is sudden in that agents did not anticipate the possibility of a change in trend inflation before period 1, and is credible in that agents believe that the new rate of trend inflation is permanent.

to these are obtained in our model even in the absence of intrinsic inertia in inflation, as illustrated by the solid lines in the figure. One difference between our model and the model with intrinsic inertia of inflation is that in our model, output rebounds to its new steady-state level associated with the new rate of trend inflation, which is lower than the initial level of steady-state output.[16]

5 Conclusion

This paper has examined what model without embedding controversial intrinsic inertia of inflation can explain the two empirical facts: (i) inflation exhibits a persistent response to a monetary policy shock, and (ii) both output and labor productivity rise after an expansionary policy shock. The paper has shown that a staggered price model with a positive trend inflation rate, a smoothed-off kink in demand curves, and a fixed cost of production can replicate the two empirical facts even in the absence of intrinsic inertia in inflation, because the kink causes a measure of price dispersion to become a key source of inflation persistence under the positive trend inflation rate. With this model the paper has also demonstrated that a credible permanent reduction in trend inflation induces a gradual decline in inflation and a fall in output.

[16] Kurozumi and Van Zandweghe (2016a) show that the kink in demand curves can cause steady-state output to become an increasing function of trend inflation, in contrast with the case of constant elasticity demand curves. This is because the kink alters the effects of trend inflation on the two components of steady-state output, the steady-state average markup and the steady-state relative price distortion. In the case of constant elasticity demand curves, the responses of inflation and output to the sudden and credible reduction in trend inflation are displayed by the dashed lines. In such a case, inflation drops rapidly to its new trend rate, while output rises immediately to its new steady-state level, which exceeds the initial one because of the decrease in the steady-state relative price distortion associated with the reduction in trend inflation.

References

[1] Ascari, Guido, and Argia M. Sbordone. 2014. "The Macroeconomics of Trend Inflation." *Journal of Economic Literature*, 52(3), 679–739.

[2] Ball, Laurence. 1994. "Credible Disinflation with Staggered Price-setting." *American Economic Review*, 84(1), 282–289.

[3] Basu, Susanto, and John Fernald. 2001. "Why is Productivity Procyclical? Why Do We Care?" In: C. R. Hulten, E. R. Dean, and M. J. Harper (Eds.), *New Developments in Productivity Analysis*, University of Chicago Press, Chicago, pp. 225–302.

[4] Benati, Luca. 2008. "Investigating Inflation Persistence across Monetary Regimes." *Quarterly Journal of Economics*, 123(3), 1005–1060.

[5] Boivin, Jean, Michael T. Kiley, and Frederic S. Mishkin. 2011. "How Has the Monetary Transmission Mechanism Evolved Over Time?" In: B. M. Friedman and M. Woodford (Eds.), *Handbook of Monetary Economics*, Vol. 3A, Elsevier, North Holland, pp. 369–421.

[6] Calvo, Guillermo A. 1983. "Staggered Prices in a Utility-Maximizing Framework." *Journal of Monetary Economics*, 12(3), 383–398.

[7] Christiano, Lawrence J., Martin Eichenbaum, and Charles L. Evans. 1999. "Monetary Policy Shocks: What Have We Learned and to What End?" In: J. B. Taylor and M. Woodford (Eds.), *Handbook of Macroeconomics*, Vol. 1A, Elsevier, North Holland, pp. 65–148.

[8] Christiano, Lawrence J., Martin Eichenbaum, and Charles L. Evans. 2005. "Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy." *Journal of Political Economy*, 113(1), 1–45.

[9] Cogley, Timothy, and Argia M. Sbordone. 2008. "Trend Inflation, Indexation, and Inflation Persistence in the New Keynesian Phillips Curve. *American Economic Review*, 98(5), 2101–2126.

[10] Damjanovic, Tatiana, and Charles Nolan. 2010. "Relative Price Distortions and Inflation Persistence." *Economic Journal*, 120(547), 1080–1099.

[11] Dossche, Maarten, Freddy Heylen, and Dirk Van den Poel. 2010. "The Kinked Demand Curve and Price Rigidity: Evidence from Scanner Data." *Scandinavian Journal of Economics*, 112(4), 723–752.

[12] Dotsey, Michael, and Robert G. King. 2005. "Implications of State-dependent Pricing for Dynamic Macroeconomic Models." *Journal of Monetary Economics*, 52(1), 213–242.

[13] Fuhrer, Jeffrey C. 2011. "Inflation Persistence." In: B. M. Friedman and M. Woodford (Eds.), *Handbook of Monetary Economics*, Vol. 3A, Elsevier, North Holland, pp. 423–486.

[14] Fuhrer, Jeffrey, and George Moore. 1995. "Inflation Persistence." *Quarterly Journal of Economics*, 110(1), 127–159.

[15] Galí, Jordi, and Mark Gertler. 1999. "Inflation Dynamics: A Structural Econometric Analysis." *Journal of Monetary Economics* 44(2), 195–222.

[16] Kilian, Lutz 1998. "Small-sample Confidence Intervals for Impulse Response Functions." *Review of Economics and Statistics*, 80(2), 218–230.

[17] Kimball, Miles S. 1995. "The Quantitative Analytics of the Basic Neomonetarist Model." *Journal of Money, Credit and Banking*, 27(4), 1241–1277.

[18] Kreps, David M. 1998. "Anticipated Utility and Dynamic Choice." In: D. P. Jacobs, E. Kalai, and M. I. Kamien (Eds.), *Frontiers of Research in Economic Theory: The Nancy L. Schwartz Memorial Lectures, 1983–1997*, Cambridge University Press, Cambridge, MA, pp. 242–274.

[19] Kurozumi, Takushi, and Willem Van Zandweghe. 2016a. "Kinked Demand Curves, the Natural Rate Hypothesis, and Macroeconomic Stability." *Review of Economic Dynamics*, 20, 240–257.

[20] Kurozumi, Takushi, and Willem Van Zandweghe. 2016b. "Trend Inflation and Equilibrium Stability: Firm-Specific Versus Homogeneous Labor." *Macroeconomic Dynamics*, forthcoming.

[21] Levin, Andrew T., J. David López-Salido, Edward Nelson, and Tack Yun. 2008. "Macroeconomic Equivalence, Microeconomic Dissonance, and the Design of Monetary Policy." *Journal of Monetary Economics*, 55(Supplement), S48–S62.

[22] Mankiw, N. Gregory, and Ricard Reis. 2002. "Sticky Information Versus Sticky Prices: A Proposal to Replace the New Keynesian Phillips Curve." *Quarterly Journal of Economics*, 117(4), 1295–1328.

[23] Shirota, Toyoichiro. 2015. "Flattening of the Phillips Curve under Low Trend Inflation." *Economics Letters*, 132, 87–90.

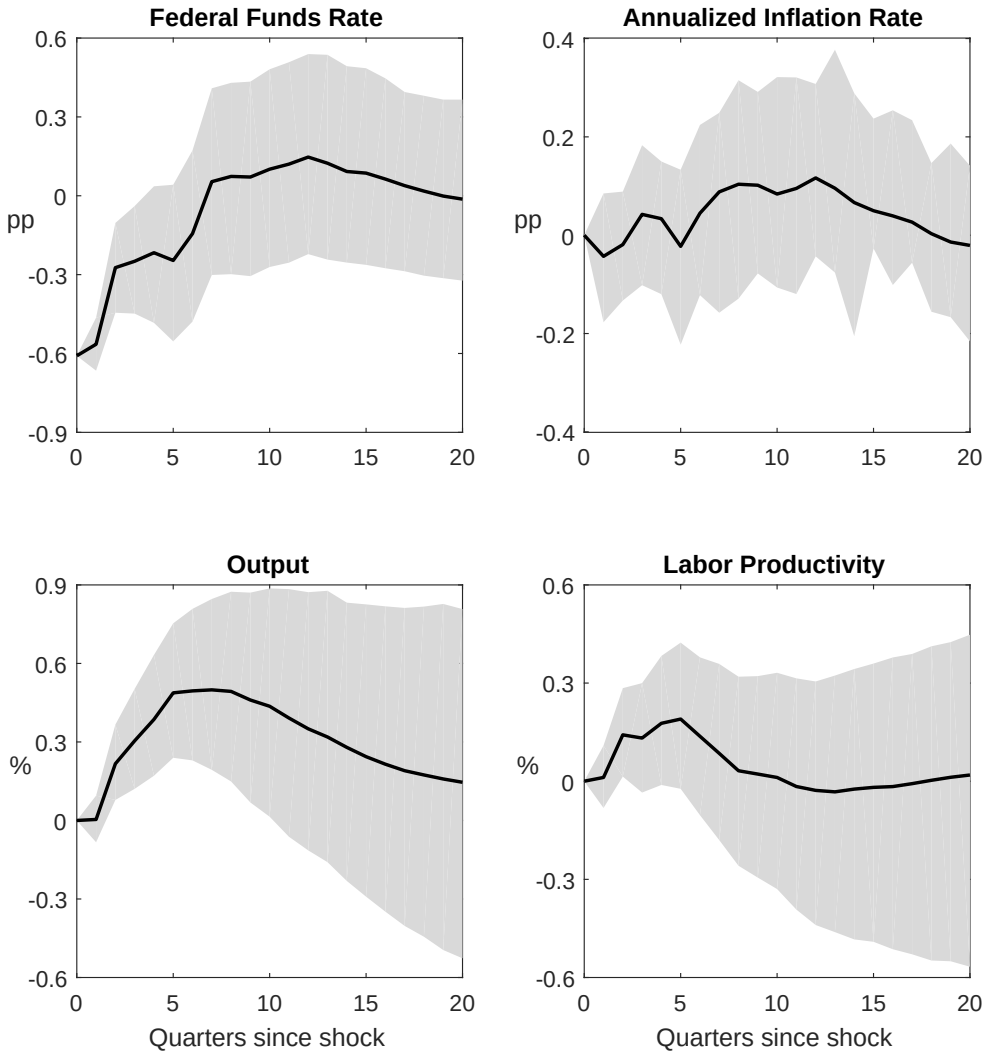
[24] Taylor, John B. 1993. "Discretion Versus Policy Rules in Practice." *Carnegie-Rochester Conference Series on Public Policy*, 39(1), 195–214.

[25] Woodford, Michael. 2007. "Interpreting Inflation Persistence: Comments on the Conference on 'Quantitative Evidence on Price Determination'." *Journal of Money, Credit and Banking*, 39(Supplement s1), 203–210.

Table 1: Calibration of the quarterly model

β	Subjective discount factor	0.99
σ_n	Inverse of the elasticity of labor supply	0.5
α	Probability of no price change	0.75
θ	Parameter governing the price elasticity of demand	10
ϵ	Parameter governing the curvature of demand curves	-9 or 0
π	Gross rate of trend inflation	$1.025^{1/4}$
ρ	Degree of policy inertia	0.9
ϕ_π	Degree of policy response to inflation	1.5

Figure 1: Empirical impulse responses to a monetary policy shock.



Note: Impulse responses are obtained from a structural VAR model estimated on the log of the GDP deflator, the log of real GDP, the log of output per hour in the business sector, the federal funds rate, and a commodity price index, for the sample period from 1959:Q1 to 2007:Q4. The lag length of the VAR is six quarters as determined by the Akaike information criterion. A history of monetary policy shocks is recovered from the error terms under the identifying assumption that no economic variable, except the federal funds rate and the commodity price index, responds contemporaneously to such a shock. Gray areas are 90 percent confidence intervals obtained using the bootstrap procedure of Kilian (1998).

Figure 2: Smoothed-off kink in demand curve.

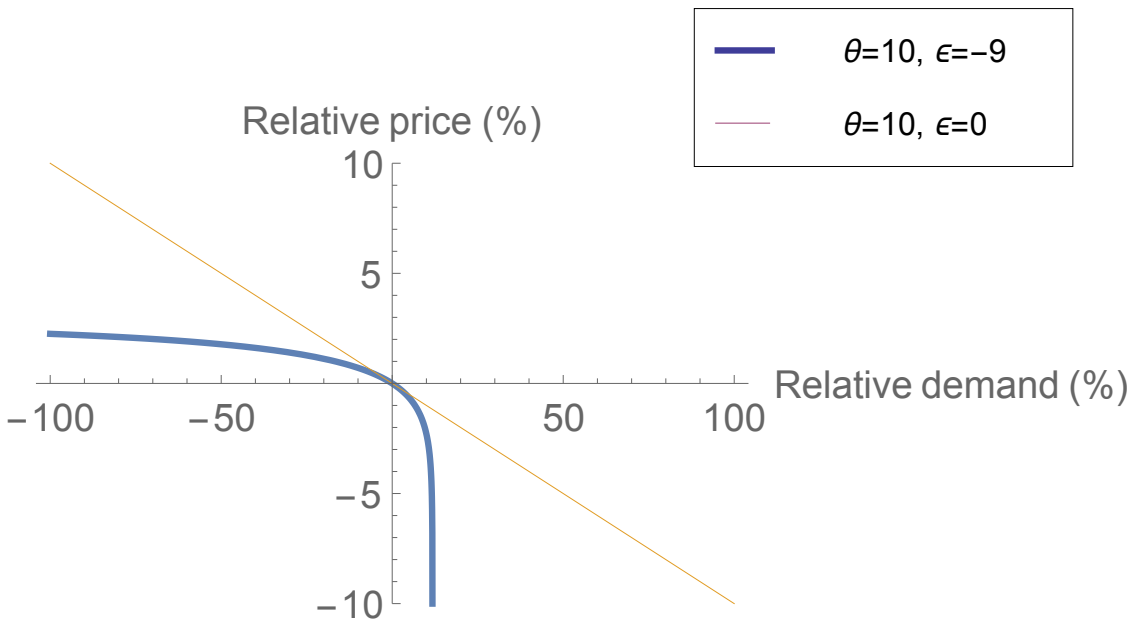
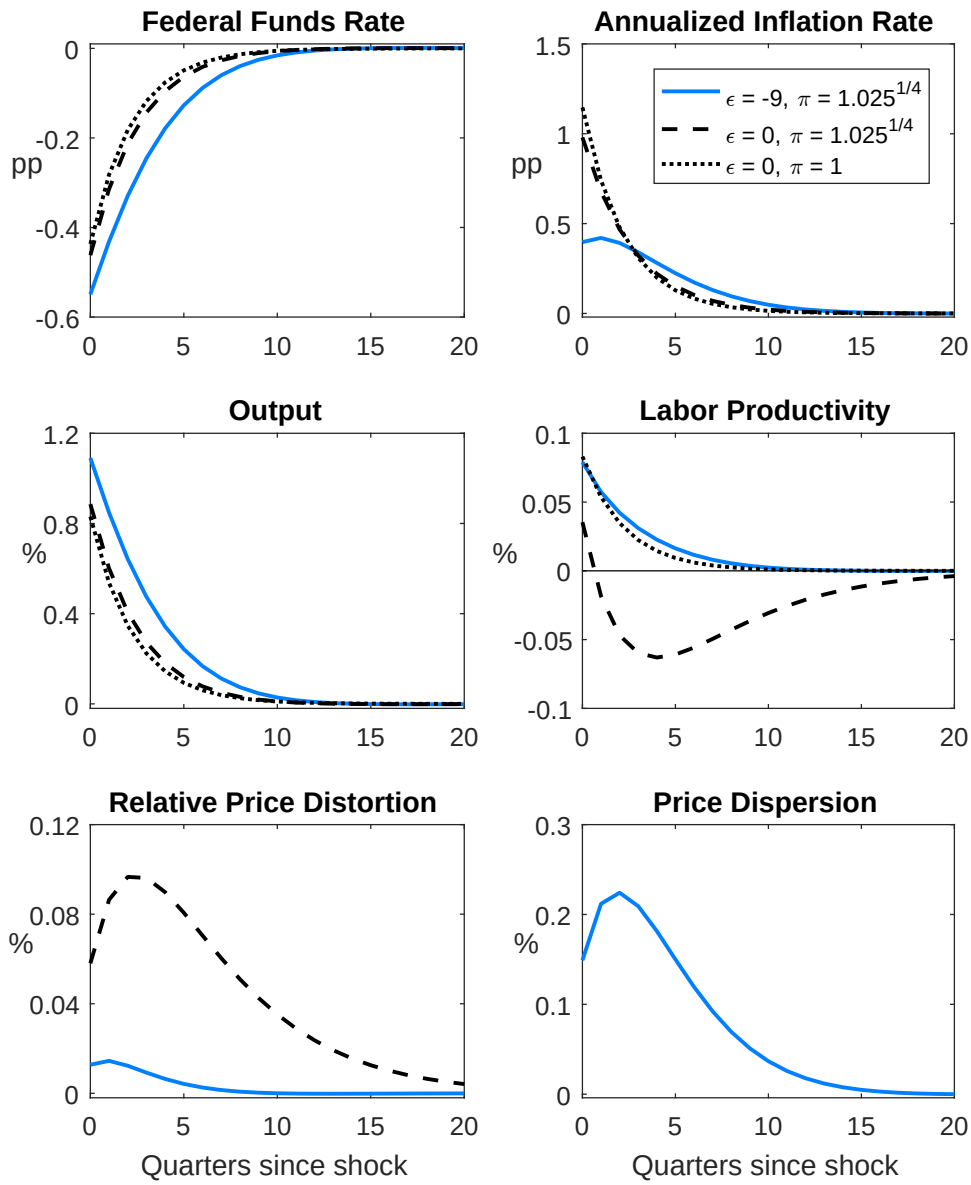
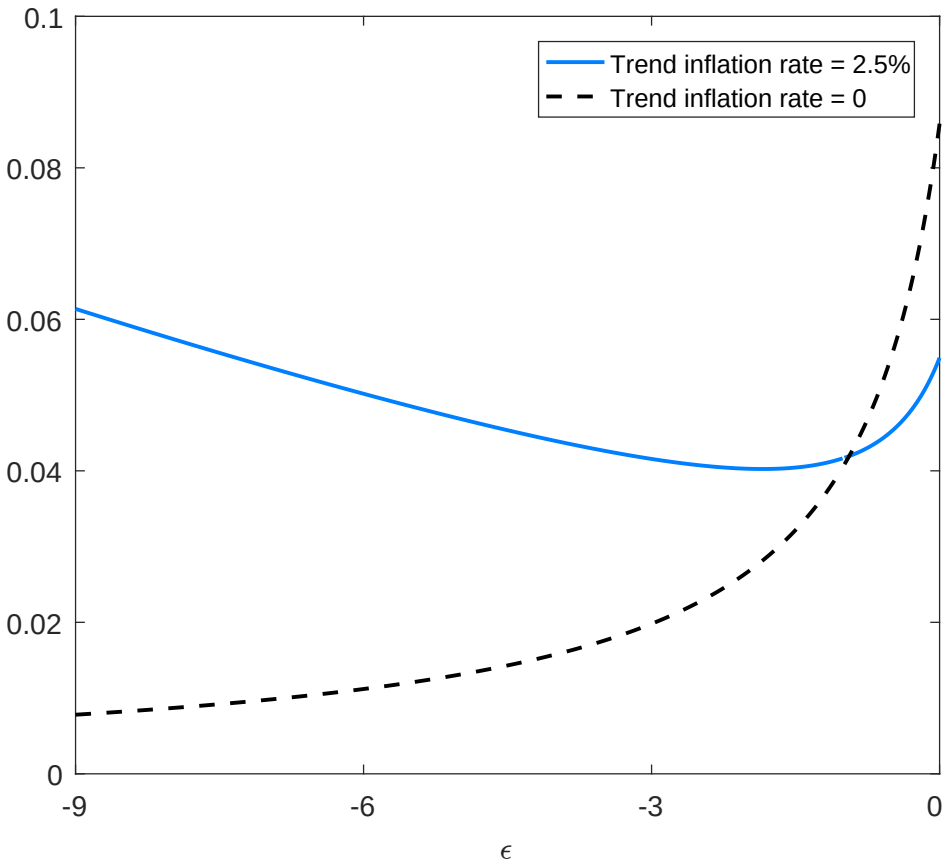


Figure 3: Effects of a positive trend inflation rate and a kink in demand curves on impulse responses to a monetary policy shock.



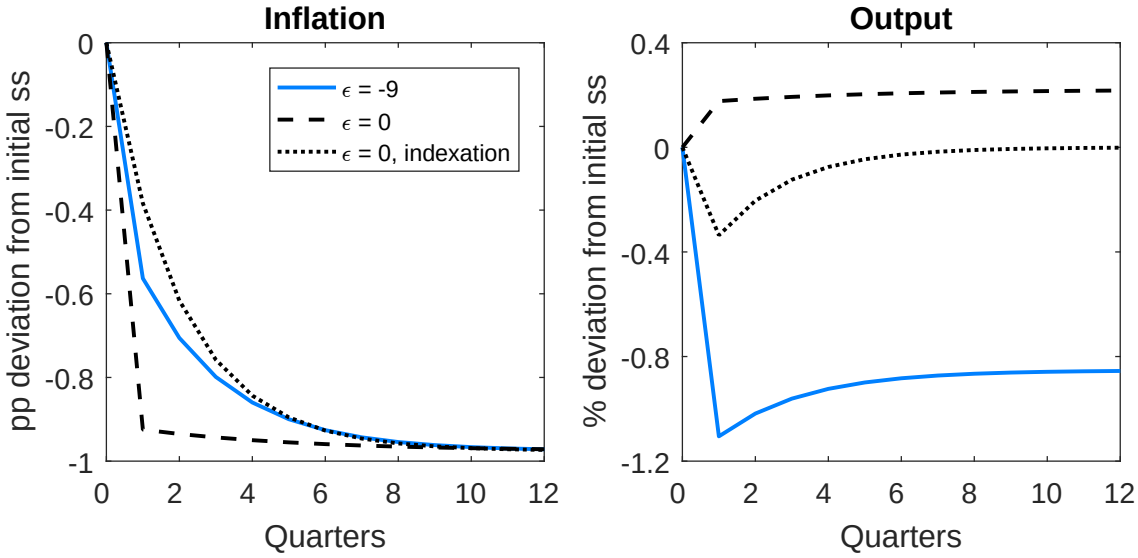
Note: Solid lines are impulse responses obtained under the calibration in the case of a kink in demand curves, i.e., $\epsilon = -9$. Dashed lines are impulse responses obtained under the calibration in the case of no kink in demand curves, i.e., $\epsilon = 0$. Dotted lines are impulse responses obtained under the calibration in the case of no kink, except for the zero rate of trend inflation, i.e., $\epsilon = 0$, $\pi = 1$.

Figure 4: Slope of the Generalized New Keynesian Phillips Curve.



Note: The vertical axis shows the elasticity of inflation with respect to real marginal cost.

Figure 5: Credible disinflation.



Note: Solid lines are responses obtained in the case of a kink in demand curves, i.e., $\epsilon = -9$. Dashed lines are responses obtained in the case of no kink in demand curves, i.e., $\epsilon = 0$. Dotted lines are responses obtained in the case of no kink and full price indexation to previous-period inflation.