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Slumps under Real Wage Rigidity**

by **Mewael F. Tesfaselassie**

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The paper studies the effects of credible disinflation in the presence of real wage rigidity, comparing the Calvo and Rotemberg price setting mechanisms (the two popular variants of the New-Keynesian model). In both types of models, a credible, gradual disinflation is shown to lead to a delayed slump in output along the transition path. The delayed-slump result is novel and owes to negative real wage growth along the transition path, whose effect is amplified by the degree of real wage rigidity.

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JEL classification: E31, E50

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The paper studies the effects of credible disinflation in the presence of real wage rigidity, comparing the Calvo and Rotemberg price setting mechanisms (the two popular variants of the New-Keynesian model). In both types of models, a credible, gradual disinflation is shown to lead to a delayed slump in output along the transition path. The delayed-slump result is novel and owes to negative real wage growth along the transition path, whose effect is amplified by the degree of real wage rigidity.

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I INTRODUCTION

In an influential paper Ball (1994) set out to clarify the real effects of a credible disinflation in the presence of nominal price rigidities, noting that “the literature contains a confusing array of answers to this question.” (p.282). According to Ball (1994) the source of confusion was related to whether the thought experiment involves a reduction in the level of money (deflation) or its growth rate (disinflation). He then shows that a cold-turkey (i.e., instant or immediate) disinflation causes a recession while a quick, though gradual, disinflation may lead to boom, where a boom is defined as “an output path that rises above the natural rate temporarily and never falls below the natural rate.” (p.286). Recent research has revisited the issue of credible disinflation in the context of two workhorse models of the New-Keynesian type—the Calvo price staggering and Rotemberg price adjustment costs.¹

One candidate source of real rigidities that has received particular attention is real wage rigidity.² Using a log-linearized version of the standard New Keynesian model with Calvo-type price staggering, Blanchard and Gali (2007) show that real wage rigidity helps generate a slump following a sudden, unexpected and permanent reduction in inflation, the so-called “cold-turkey” (i.e., immediate) disinflation.³ However, Ascari and Merkl (2009) argue that a log-linear model can give misleading results for a disinflation thought experiment that involves initial inflation rates that are significantly higher than zero, in which case nonlinear dynamics are crucial. They show that, in the nonlinear Calvo model, output and the real wage transition from low to high steady state values, while in the log-linear version used by Blanchard

¹The dynamic and welfare properties of these models have been a subject of recent studies (see, e.g., Ireland (2011), Keen and Wang (2007) and Lombardo and Vestin (2008)).

²This is in the spirit of Ball and Romer (1990), who point out the need to complement nominal rigidities with real rigidities so as to generate realistic output dynamics. Real wage rigidity has also received recent attention in the business cycle literature (see, e.g., Christoffel and Kuester (2008)).

³The distinction between cold-turkey and gradual disinflation in the disinflation literature is an old one. See, e.g., Buiter and Miller (1985) for an early discussion of the issue.

and Gali (2007) they transition from high to low steady state values. Second, in the nonlinear version, there is a boom along the transition path when real wage rigidity is strong enough. By contrast, the log-linear version implies a slump along the transition path. Similarly, Ascari and Rossi (2011) show that when nonlinearity is taken into account, the Rotemberg-type sticky price model does a better job than the Calvo-type counterpart in generating a realistic disinflationary dynamics. They show that in the presence of real wage rigidity the Rotemberg model implies not only a slump but also a long-lasting one.

A closer look into the issue shows that, besides allowing for nonlinear effects, Ascari and Merkl (2009), Ascari and Rossi (2011) are crucial departures from Blanchard and Gali (2007) and related literature (e.g., Goodfriend and King (2005)), in which the thought experiment involves deriving the output path that supports a sudden, unexpected permanent reduction in inflation to its desired level.⁴ In this approach, one could derive an instrument rule that implements the desired disinflation path, which in turn depends on the operating procedures of monetary policy (e.g., interest rates, money supply, borrowed/non-borrowed reserves, and even non-conventional tools). For instance, Hagedorn (2011) derives recursively the optimal interest rate rule that is consistent with the optimal path of a disinflation.

By contrast, the thought experiment in Ascari and Merkl (2009) and Ascari and Rossi (2011) involves a sudden reduction in the long-run rate of inflation and a simple, ad-hoc interest rate rule to implement monetary policy, with the implication that the disinflation policy does not pin the desired path.⁵ Importantly, under a simple instrument rule disinflation may not proceed smoothly. Instead, it may undershoot its long-run desired level along the transition path, a result that is at

⁴Goodfriend and King (2005) analyze the case of incredible, gradual disinflation in a New-Keynesian model with the Calvo-type price staggering. In their analysis “the central bank specifies a path for the inflation rate.” (p.988).

⁵This is also the case in Ascari and Rossi (2012), who follow the disinflation thought experiment of Ascari and Merkl (2009) and Ascari and Rossi (2011) but abstract from real wage rigidity.

odds with linear disinflation that is typically considered to be the case (see, e.g., Ball (1994) and Goodfriend and King (2005)). In the thought experiment of Ascari and Merkl (2009), as well as the Calvo-type model of Ascari and Rossi (2011), the economy goes through a deflationary path when real wage rigidity is strong enough (see, e.g., Figure 3 of Ascari and Merkl (2009)). Such deflationary paths are implausible considering that central banks dislike deflation as much as high inflation.⁶

In the present paper we reexamine the issue of credible disinflation and compare the nonlinear versions of the Calvo and Rotemberg-type models. We follow the disinflation thought experiments of Goodfriend and King (2005) and Blanchard and Gali (2007).⁷ We do this for at least four reasons. First, we are able to meaningfully differentiate between a cold-turkey disinflation (as in Blanchard and Gali (2007)) and a gradual disinflation (as in Goodfriend and King (2005)).⁸ Second, we avoid the drawbacks of postulating an ad-hoc instrument rule (such as the one in Ascari and Merkl (2009) and Ascari and Rossi (2011)). As was remarked above under an instrument rule the transition path may involve deflation in the presence of real wage rigidity. In addition, as is often pointed out (see, e.g., Svensson (2003)) there are infinitely many instrument rules that can implement monetary policy. Estimated Taylor-type rules tend to take varying forms. Some of these include forward expectations and interest rate inertia (see, e.g., Clarida and Gali and Gertler (2000)) and interest rate inertia have been shown to have appealing theoretical attributes (see, e.g., Woodford (1999)). Thus, it is not clear a priori what rules one should assume in a disinflation analysis. Third, the effects of the disinflation

⁶For example, in a 2002 speech “Deflation: Making Sure “It” Doesn’t Happen Here”, the then Fed Governor, and later Fed Chairman, Ben Bernanke argued that “sustained deflation can be highly destructive to a modern economy and should be strongly resisted.” (see Bernanke (2002)).

⁷Blanchard and Gali (2007) consider cold-turkey but not gradual disinflation while Goodfriend and King (2005) consider gradual disinflation but under imperfect credibility. Both papers analyze disinflation in the standard log-linearized New-Keynesian model with Calvo-type price staggering.

⁸The approach is analogous to Ball (1994), in which the central bank announces a credible path for the actual rate of money growth.

thought experiment we consider, in the presence of nonlinearity, are less known in the literature. Finally, despite the nonlinear framework, we are able to derive some novel results analytically by exploiting the recursive nature of the problem.

We characterize the output effects of disinflation as an outcome of the interaction of three variables: (i) the level of the real wage, (ii) the real wage growth and (iii) the consumption-output wedge in the Rotemberg model (analogously, the price dispersion in the Calvo model). Our results can be summarized as follows.

First, in a credible, gradual disinflation both the Calvo and Rotemberg-type models have similar transitional dynamics in the presence of real wage rigidity: along the transition path a boom is followed by a slump.⁹ This delayed-slump result is novel.¹⁰ In both models the boom is higher and the slump is deeper the stronger is real wage rigidity. The reason is that in both models real wage growth is initially positive, which helps raise output (and more strongly the stronger is the degree of real wage rigidity). As disinflation proceeds farther real wage growth turns negative contributing to a slump.

Second, in the Rotemberg model transitional dynamics of output ends soon after the disinflation ends, as the real wage and the consumption-output wedge reach their new steady states when disinflation ends while real wage growth reaches zero one period after. By contrast, in the Calvo model output continues its adjustment even after disinflation ends, for the same reason as in the cold-turkey disinflation—price dispersion reaches its new steady state only asymptotically and so does output.

Third, in the limiting case of a cold-turkey disinflation the Rotemberg model implies

⁹In line with the literature, a boom (slump) is where output rises (falls) below its initial value. As will be shown below, when output is below its initial value it is also below its terminal value.

¹⁰In the Calvo model, along the transition path, output first rises from its initial, low steady state level and then falls below it before resuming its convergence path towards its final, high steady state level. In the Rotemberg model output first rises from its old, high steady state level and then falls below it before resuming its convergence path towards its final, low steady state level.

an immediate slump. This is due to the presence of real wage rigidity in conjunction with negative real wage growth in the first period of the disinflation process. The slump is however short-lived, as real wage growth is zero in subsequent periods and the consumption-output wedge displays no persistence. By contrast, the Calvo model implies an immediate boom but no delayed slump. The reason behind the initial boom is similar to that under gradual disinflation while the lack of a delayed slump is due to real wage growth being zero in subsequent periods. Since price dispersion is persistent output converges to its new steady state level only asymptotically.

We remark that, while in both models real wage rigidity helps generate a delayed slump under gradual disinflation, the initial boom observed in both models represents a drawback in light of the conventional wisdom that disinflations are costly (Ball (1994)). The paper is organized as follows. In section II we present the key aggregate equations characterizing private sector behavior under Calvo and Rotemberg-type price rigidities and the respective steady state equilibrium. In section III we analyze transitional dynamics in the special case of cold-turkey disinflation. We show analytical results and give illustrations in calibrated versions of the two models. In section IV we analyze gradual disinflation, first considering a disinflation that lasts for two periods. Besides its amenability to analytical derivation and showing our main results regarding delayed slumps, the two-period case sets the stage for the general case of a more gradual disinflation. We give concluding remarks in section V .

II THE NONLINEAR MODELS

In this section we present the standard nonlinear Calvo and Rotemberg-type New-Keynesian models, which follows Ascari and Merkl (2009), Ascari and Rossi (2011)

and Ascari and Rossi (2012). In particular, except for the source of nominal price inertia the two models are identical. There is a representative household, which makes consumption and labor supply decisions, and faces a perfectly competitive labor market subject to real wage rigidity. Utility is logarithmic in consumption and quadratic in hours worked. There is a continuum of firms selling differentiated goods under monopolistic competition and technology is linear in labor. As the two models are quiet standard in what follows we only show the key nonlinear equations that characterize private sector behavior. Details on derivations are given in the appendix.

A Rotemberg-type Price Adjustment Costs

The Rotemberg-type price setting is the simpler of the two models. There are two key equations that characterize our analysis. The first is related to optimal price setting in the presence of quadratic price adjustment costs,

$$w_t = \mu^{-1} + \epsilon^{-1} \left(\kappa \Pi_t (\Pi_t - 1) - \kappa \beta E_t \left(\frac{\delta_t}{\delta_{t+1}} \Pi_{t+1} (\Pi_{t+1} - 1) \right) \right). \quad (1)$$

where w_t is the real wage, $\Pi_t \equiv P_t/P_{t-1}$ is gross inflation, C_t is consumption, Y_t is output, β is the subjective discount factor, κ controls the strength of price adjustment costs, $\mu = \epsilon/(\epsilon-1)$ is the price markup in the absence of price adjustment costs, ϵ is the elasticity of substitution between the differentiated goods. In deriving equation (1) we made use of the aggregate resource constraint relating consumption and output, $C_t = \delta_t Y_t$, where $\delta_t = 1 - \kappa (\Pi_t - 1)^2 / 2$ is a measure of the consumption-output wedge, to substitute out consumption.

Since all firms behave symmetrically aggregate employment is equal to aggregate output ($N_t = Y_t$). Using this equation and the aggregate resource constraint in the optimal labor supply condition of the representative household, in the presence of

real wage rigidity, leads to the third key equation

$$w_t = w_{t-1}^\gamma (\delta_t Y_t^{1+\eta})^{1-\gamma}, \quad (2)$$

where $1/\eta$ is the elasticity of intertemporal substitution in labor supply and γ ($0 \leq \gamma \leq 1$) controls the degree of real wage rigidity (see, e.g., Blanchard and Gali (2007)).

Rearranging equation (2) gives

$$Y_t = \left(\frac{w_t}{\delta_t} \left(\frac{w_t}{w_{t-1}} \right)^{\gamma'} \right)^{1/(1+\eta)}. \quad (3)$$

where $\gamma' = \gamma/(1 - \gamma)$. According to equation (3) along the transition path, output can deviate from its long-run steady state as a result of the deviation of either the level of the real wage, the real wage growth or the consumption-output wedge from the respective steady state. Moreover, the effect of real wage growth is stronger the higher the degree of real wage rigidity.

Steady state equilibrium. For any x_t , let x denote the steady state value. Then the steady state equilibrium of the model is given by $w = \mu^{-1} + (1 - \beta)\kappa\Pi(\Pi - 1)/\epsilon$, $\delta = 1 - \kappa(\Pi - 1)^2/2$, and $Y = (w/\delta)^{1/(1+\eta)}$. We see that w and Y increase while δ decreases monotonically with Π . At a zero steady state rate of inflation ($\Pi = 1$), $w = \mu^{-1}$, $\delta = 1$ and $Y = w^{1/(1+\eta)}$. Thus a disinflation from $\Pi > 1$ to $\Pi = 1$ leads to a permanent fall in w and a permanent rise in δ and therefore a permanent fall in Y .

B Calvo-type Price Staggering

In the Calvo-type price setting, in any given period a fraction θ of firms cannot reset their prices optimally. The first key equation is the optimal relative price

$$z_t = \mu \frac{F_{n,t}}{F_{d,t}} \quad (4)$$

where $z_t \equiv P_t^*/P_t$, μ is the price markup in the absence of price staggering, and $F_{n,t}$ and $F_{d,t}$ are auxiliary variables given by (taking into account the market clearing condition $C_t = Y_t$).

$$F_{n,t} = w_t + \beta\theta\Pi_{t+1}^\epsilon F_{n,t+1},$$

and

$$F_{d,t} = 1 + \beta\theta\Pi_{t+1}^{\epsilon-1} F_{d,t+1},$$

The second key equation is related to the price index, which under Calvo-type price staggering implies

$$z_t = \left(\frac{1 - \theta\Pi_t^{\epsilon-1}}{1 - \theta} \right)^{1/(1-\epsilon)}, \quad (5)$$

while the second key equation is related to the dynamics of price dispersion s_t ,

$$s_t = (1 - \theta)z_t^{-\epsilon} + \theta\Pi_t^\epsilon s_{t-1}. \quad (6)$$

In the presence of price dispersion aggregate employment is given by $N_t = s_t Y_t$. Using this equation and the market clearing condition in the optimal labor supply condition of the representative household leads to the third key equation

$$w_t = w_{t-1}^\gamma (s_t^\eta Y_t^{1+\eta})^{1-\gamma},$$

which can be rearranged so that

$$Y_t = \left(\frac{w_t}{s_t^\eta} \left(\frac{w_t}{w_{t-1}} \right)^{\gamma'} \right)^{1/(1+\eta)}. \quad (7)$$

Analogous to its counterpart in the Rotemberg model output can deviate from its long-run steady state as a result of either the deviation of the real wage, the real wage growth or price dispersion from their respective steady states.

Steady state equilibrium. In steady state $z = ((1 - \theta\Pi^{\epsilon-1})/(1 - \theta))^{1/(1-\epsilon)}$ and $s = (1-\theta)z^{-\epsilon}/(1-\theta\Pi^\epsilon)$. Then equations $z = \mu(1-\beta\theta\Pi^{\epsilon-1})w/(1-\beta\theta\Pi^\epsilon)$ and $w = s^\eta Y^{1+\eta}$ determine equilibrium w and Y , respectively. At a zero steady state rate of inflation $\Pi = 1$, $w = \mu^{-1}$, $s = 1$ and $Y = w^{1/(1+\eta)}$. A disinflation from $\Pi > 1$ to $\Pi = 1$ leads to a permanent fall in z and s , and a permanent rise in w and Y if $\Pi > 1$ is sufficiently larger than 1 but a permanent fall in w and Y if $\Pi > 1$ is sufficiently close to 1 (see, e.g., Ascari and Rossi (2012)).

In the remainder of the paper we compare the Calvo and Rotemberg models' transitional dynamics, first under a cold-turkey disinflation and then under a gradual disinflation. As in the related studies (i) the disinflation involves moving from an old steady state inflation $\Pi_0 > 1$ to a new steady state $\Pi_n = 1$ and (ii) since the long-run properties of the two models differ when Π_0 is sufficiently larger than one, we maintain this assumption so as to give a chance for the two models to potentially differ in terms of transitional dynamics.¹¹

Given Π_0 is sufficiently larger than one, in the Calvo model $w_0 < w_n = \mu^{-1}$ and $Y_0 < Y_n = w_n^{1/(1+\eta)}$, where the subscript “ n ” denotes the new long-run (i.e., steady state) value consistent with a zero steady state rate of inflation. By contrast, in the Rotemberg model as long as $\Pi_0 > 1$ a disinflation decreases the real wage and output permanently (see also section 3 of Ascari and Rossi (2012)). That is $w_0 > w_n$ and $Y_0 > Y_n$.

III COLD-TURKEY DISINFLATION

Consider, as in Blanchard and Gali (2007), a sudden, permanent, unexpected reduction in inflation from its old steady state $\Pi_0 > 1$ to $\Pi_t = 1$ (i.e., zero rate of inflation) for all $t \geq 1$ and private agents believe that it will succeed so that one-period ahead

¹¹If Π_0 is sufficiently close to one the two models have similar long run properties.

expected inflation $E_t \Pi_{t+1} = \Pi_{t+1} = 1$ for all $t \geq 1$. Given the disinflation path one determines the implied path for output. In what follows we derive the implied path for output analytically, which involves intermediate steps involving determination of the paths of the real wage as well as the consumption-output wedge in the Rotemberg model (analogously, the price dispersion in Calvo model).

A Rotemberg Model

Consistent with the cold-turkey disinflation under consideration we have $\delta_t = \delta_n = 1$ for all $t \geq 1$. That is the consumption-output wedge rises immediately to its new long-run level. Then from equation (1) $w_t = w_n$ for all $t \geq 1$. That is the real wage falls immediately to its new, lower long-run level (implying negative wage growth in period 1 and zero thereafter) so as to support the immediate fall in inflation.

Given $w_1 = w_n$ and $\delta_1 = 1$ output in period 1 can be inferred from equation (3)

$$Y_1 = \left(w_n \left(\frac{w_1}{w_0} \right)^{\gamma'} \right)^{1/(1+\eta)} = \left(\frac{w_1}{w_0} \right)^{\gamma'/(1+\eta)} Y_n.$$

where $\gamma' = \gamma/(1-\gamma)$ and the second equality results from the steady state relating Y_n to w_n . Thus only real wage rigidity matter for the transitional dynamics of output, as the consumption-output wedge adjusts immediately to its new steady state. Since $w_1 < w_0$ (real wage growth is negative) it follows that $0 < (w_1/w_0)^{\gamma'} \leq 1$ and $Y_1 < Y_n < Y_0$ provided $\gamma > 0$. In the absence of real wage rigidity ($\gamma = 0$) output adjusts immediately to the new steady state ($Y_1 = Y_n < Y_0$).

Since real wage growth is zero for all $t > 1$ the effect of real wage rigidity is short-lived. Then we have

$$Y_t = w_n^{1/(1+\eta)} = Y_n.$$

That is, output reaches its new steady state in period 2 and stays there forever, which shows that the effect of real wage rigidity is only temporary.

B Calvo Model

First, consistent with the cold-turkey disinflation the price index implies $z_t = 1$ for all $t \geq 1$, which can be substituted into the optimal pricing equation (4) to yield $F_{d,t} = 1/(1 - \beta\theta)$, $F_{n,t} = \mu^{-1}F_{d,t}$ and thus $w_t = w_n$ for all $t \geq 1$. Thus, the real wage adjusts immediately to its new, higher long-run level (implying positive wage growth in period 1 and zero thereafter) so as to support the immediate fall in inflation. Moreover, consistent with $\Pi_t = z_t = 1$ for all $t \geq 1$ the price dispersion dynamics is given by $s_t = 1 + \theta(s_{t-1} - 1)$, given the initial value $s_0 > 1$. Thus, price dispersion adjusts smoothly to its lower, long-run level of 1.

Next, given $w_1 = w_n$ and $s_0 > s_1 > 1$ period 1 output can be inferred from equation (7),¹²

$$Y_1 = \left(\frac{w_n}{s_1^\eta} \left(\frac{w_1}{w_0} \right)^{\gamma'} \right)^{1/(1+\eta)} = \left(\frac{1}{s_1^\eta} \left(\frac{w_1}{w_0} \right)^{\gamma'} \right)^{1/(1+\eta)} Y_n.$$

Both real wage rigidity and price dispersion matter for output in period 1. Note that the slow adjustment of price dispersion alone slows output adjustment to the new steady state, as price dispersion is too high relative to the new long-run value of 1 (given $\gamma = 0$, $s_1 > s_n = 1$ implies $Y_0 < Y_1 < Y_n$). By contrast, real wage rigidity alone implies overshooting of Y_1 because real wage growth is positive (given $\eta = 0$, $w_1 > w_0$ implies $Y_0 < Y_n < Y_1$). Thus output overshooting may occur if real wage rigidity is strong enough.¹³

¹²Note that there is price dispersion in period 1 because some prices are set prior to the disinflation and conditioned on the old steady state inflation.

¹³We show that this is the case in our numerical illustrations below.

Since real wage growth is zero for all $t > 1$ the effect of real wage rigidity is short-lived and equation (7) implies

$$Y_t = \left(\frac{w_n}{s_t^\eta} \left(\frac{w_t}{w_{t-1}} \right)^{\gamma'} \right)^{1/(1+\eta)} = \left(\frac{1}{s_t^\eta} \right)^{1/(1+\eta)} Y_n.$$

Importantly, beyond period 1 only the price dispersion effect matters for output dynamics. Since $s_t > 1$ for all $t > 1$, it follows that $Y_t < Y_n$. Thus if, due to strong real wage rigidity, output overshoots its new steady state in period 1, in period 2 output falls below its new steady state and thereafter, follows a smooth upward adjustment to its new steady state, as price dispersion adjusts smoothly towards its new steady state.

We now illustrate our analytical results graphically in calibrated versions of the two models. The parameters values are standard in the literature ($\beta = 0.99$, $\eta = 1$, $\theta = 0.75$ and $\epsilon = 10$). The value of κ is set such that in a zero steady state inflation the slope of the short-run Phillips curve is the same as in the Calvo model (see, e.g., Keen and Wang (2007)). We consider $\gamma \in \{0, 0.35, 0.7\}$ where the upper bound is consistent with recent estimates of real wage rigidity (see, e.g., Knell (2013)).¹⁴

Figure 1 plots the transitional dynamics of output, the real wage, and the consumption-output wedge in the Rotemberg model following a cold-turkey disinflation from 4 percent to zero percent (annualized). Similarly Figure 2 plots the transitional dynamics of output, the real wage, and price dispersion in the Calvo model. The horizontal axis shows time (in quarters). The vertical axis shows the percentage deviation of a variable from the new steady state value. The exception is inflation, for which the vertical axis shows the level of inflation.

Both figures illustrate our analytical results derived above. In the absence of real wage rigidity and in the Rotemberg model output adjusts immediately to the new

¹⁴In their nonlinear simulations Ascari and Merkl (2009) and Ascari and Rossi (2011) consider values of γ as large as 0.9 for illustration purposes. Nevertheless, the quantitative response of initial output in those papers is quite similar to ours.

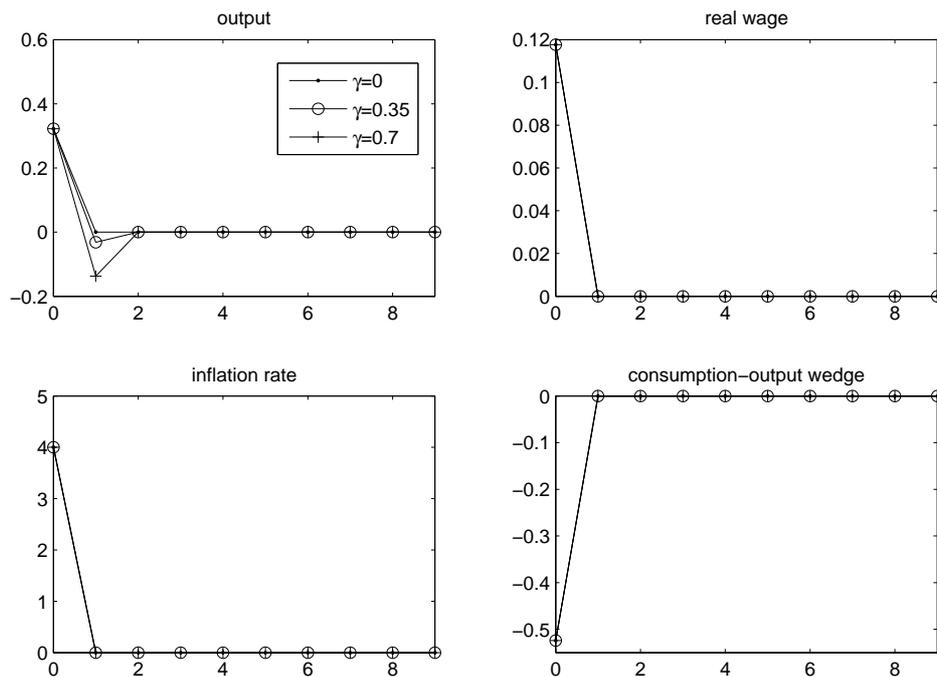


Figure 1: Transitional dynamics under a cold-turkey disinflation in the Rotemberg model

steady state, as the consumption-output wedge displays no persistence. In the Calvo model output adjusts smoothly to the new steady state owing to smooth adjustment of the price dispersion. These results are in line with previous research (see Ascari and Merkl (2009), Ascari and Rossi (2011) and Ascari and Rossi (2012)).

It is the presence of real wage rigidity that changes results dramatically. In the Rotemberg model there is output undershooting in period 1 followed by immediate adjustment to the new steady state. In the Calvo model and under $\gamma = 0.7$ (strong real wage rigidity) there is output overshooting in period 1 followed by a fall in output in period 2 but not a slump (output is never below its initial level).

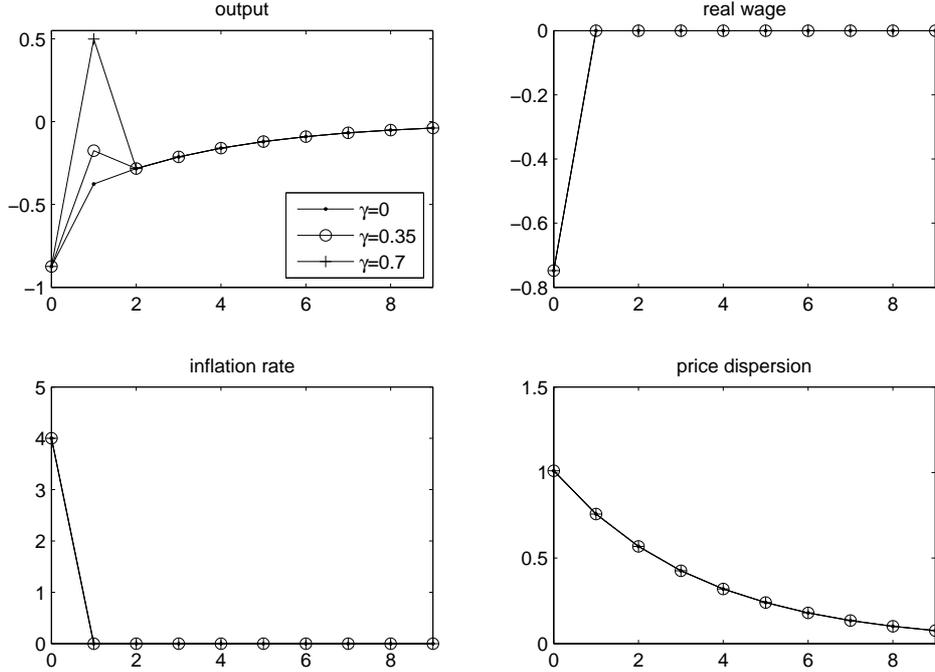


Figure 2: Transitional dynamics under a cold-turkey disinflation in the Calvo model

IV GRADUAL DISINFLATION

We now analyze the effects of real wage rigidity under a credible, gradual disinflation. We consider first the simplest case where a disinflation path achieves price stability within two periods ($\Pi_0 > \Pi_1 > \Pi_t = 1$ for $t = 2, 3, 4, \dots$). We then illustrate graphically the (algebraically) more tedious case of a more gradual disinflation.

A Rotemberg Model

First, consistent with the gradual disinflation under consideration, in period 1 equation (1) implies

$$w_1 = \mu^{-1} + \epsilon^{-1} \kappa \Pi_1 (\Pi_1 - 1) = w_n + \epsilon^{-1} \kappa \Pi_1 (\Pi_1 - 1) > w_n$$

while $w_t = w_n$ for all $t > 1$. Thus, in contrast to a cold-turkey disinflation the period 1 real wage is above its new steady state. Moreover, period 1 real wage growth is positive given that β is very close to one. To see this, first note that at the old steady state $w_0 = \mu^{-1} + (1 - \beta)\epsilon^{-1}\kappa\Pi_0(\Pi_0 - 1)$. Then

$$w_1 - w_0 = \epsilon^{-1}\kappa(\Pi_1(\Pi_1 - 1) - (1 - \beta)\Pi_0(\Pi_0 - 1)) > 0$$

if β is sufficiently close to one. As is shown below, the initial rise in the level and growth of the real wage imply that output rises above its initial level.

Next, consistent with the gradual disinflation we have $\delta_1 < \delta_n = 1$, while $\delta_t = \delta_n$ for all $t > 1$. Given δ_1 and w_1 , in period 1 equation (3) becomes

$$Y_1 = \left(\frac{w_1}{\delta_1} \left(\frac{w_1}{w_0} \right)^{\gamma'} \right)^{1/(1+\eta)} = \left(\frac{w_1}{w_0} \right)^{\gamma'/(1+\eta)} Y_1'.$$

where $Y_1' = (w_1/\delta_1)^{1/(1+\eta)} > Y_n$ is period 1 output in the absence of real wage rigidity. It is easy to see that period 1 output is higher than its new steady state because (i) the consumption-output wedge δ_1 is below its new steady state and (ii) the real wage w_1 is above its new steady state. These effects are reinforced by the presence of real wage rigidity, as real wage growth in period 1 is positive. Period 1 output may even rise above its initial level if real wage rigidity is strong enough.¹⁵

Since the disinflation process ends in period 2, $w_2 = w_n$ and $\delta_2 = 1$, and the equilibrium condition (3) implies

$$Y_2 = \left(w_n \left(\frac{w_2}{w_1} \right)^{\gamma'} \right)^{1/(1+\eta)} = \left(\frac{w_2}{w_1} \right)^{\gamma'/(1+\eta)} Y_n < Y_n.$$

Since $w_2 < w_1$ (real wage growth is negative in period 2) output undershoots its new steady state. Since output transitions from an initial, high steady state to a

¹⁵To see this, note that at the old steady state $Y_0 = (w_0/\delta_0)^{1/(1+\eta)}$. It follows that $Y_1 > Y_0$ if and only if $w_1/\delta_1(w_1/w_0)^{\gamma'} > w_0/\delta_0$. Given that $w_1 > w_0$ and $\delta_1 > \delta_0$, the inequality condition is more likely to be fulfilled the larger is γ' (i.e., the stronger is real wage rigidity).

final, low steady state, our result above implies that there is a slump in period 2. This is our delayed-slump result.

Repeating the same steps for $t > 2$ we get

$$Y_t = Y_n,$$

so that output reaches its new steady state in period 3 and stays there forever.

B Calvo Model

As in the case of a cold-turkey disinflation we consider the case where Π_0 is sufficiently higher than 1 so that in the Calvo model disinflation increases the real wage and output permanently ($w_0 < w_n$ and $Y_0 < Y_n$). Then consistent with the gradual disinflation under consideration $z_0 > z_1 > z_2 = 1$, while $F_{d,t} = F_d = 1/(1 - \beta\theta)$ for all $t \geq 1$ and $F_{n,t} = \mu^{-1}z_t F_d$ while $F_{d,t} = 1/(1 - \beta\theta)$ and $F_{n,t} = \mu^{-1}F_{d,t}$ for all $t > 1$. It follows from the auxiliary equation pertaining to $F_{n,t}$ that

$$w_1 = F_{n,1} - \beta\theta F_{n,2} = \mu^{-1}F_d(z_1 - \beta\theta z_2) > w_n$$

and $w_t = w_n$ for all $t > 1$. Thus, unlike in a cold-turkey disinflation, in period 1 the real wage is larger than its old as well as new steady state levels. From equation (7)

$$Y_1 = \left(\frac{w_1}{s_1^\eta} \left(\frac{w_1}{w_0} \right)^{\gamma'} \right)^{1/(1+\eta)} = \left(\frac{w_1}{w_0} \right)^{\gamma'/(1+\eta)} Y_1',$$

where $Y_1' = (w_1/s_1^\eta)^{1/(1+\eta)}$ is period 1 output in the absence of real wage rigidity, and shows that period 1 output is higher than its old steady state on account of real wage being higher than its old steady state and price dispersion being lower than its old steady state. The presence of real wage rigidity reinforces the initial rise in output, as period 1 real wage growth is positive ($w_1 > w_0$).

Next, since $w_2 = w_n$, period 2 output is given by

$$Y_2 = \left(\frac{w_n}{s_2^\eta} \left(\frac{w_2}{w_1} \right)^{\gamma'} \right)^{1/(1+\eta)} = \left(\frac{w_2}{w_1} \right)^{\gamma'/(1+\eta)} Y_2',$$

where $Y_2' = (w_n/s_2^\eta)^{1/(1+\eta)} < Y_n$ is period 2 output in the absence of real wage rigidity (Y_2' is smaller than Y_n because period 1 price dispersion is higher than its new steady state value of one). The presence of real wage rigidity reinforces the effect of price dispersion, lowering it below Y_2' , as period 1 real wage growth is negative ($w_2 < w_1$). More importantly, period 2 output may fall below its old steady state, implying a delayed-slump, if real wage rigidity is strong enough. Our numerical illustration below confirms this intuition (see Figure 4). The delayed-slump result is novel and in stark contrast to Ascari and Merkl (2009), who find, as a result of adopting a simple instrument rule, that output overshoots its new steady state along the transition path if real wage rigidity is strong enough (see their Figure 3).

For $t > 2$, the output path is given by

$$Y_t = \left(\frac{w_n}{s_t^\eta} \right)^{1/(1+\eta)}.$$

Note that $Y_t > Y_2$, as $s_t < s_2$ for all t and real wage growth is zero for all $t > 2$. Moreover, since price dispersion converges smoothly to its new steady state, output converges asymptotically to its new steady state from below ($Y_2 < Y_t < Y_n$).

C Generalization

Consider the more general case of a disinflation that takes an arbitrary T periods to complete. We have shown above that for $T = 2$ there is an immediate boom in the Calvo model and similarly in the Rotemberg model provided β is sufficiently close to one, a condition that holds also for any $T \geq 2$. To see this, first note that in the

Rotemberg model period 1 real wage is given by

$$w_1 = \mu^{-1} + \epsilon^{-1} \kappa \left(\Pi_1(\Pi_1 - 1) - \beta \frac{\delta_1}{\delta_2} \Pi_2(\Pi_2 - 1) \right)$$

so that in this more general case period 1 real wage is determined not only by period 1 inflation (as in the case where disinflation run for two periods) but also by period 2 inflation as well as by period 1 and period 2 consumption-output wedge. The previous equation and the equation determining w_0 imply that

$$w_1 - w_0 = \epsilon^{-1} \kappa (\Pi_1(\Pi_1 - 1) - \beta \frac{\delta_1}{\delta_2} \Pi_2(\Pi_2 - 1) - (1 - \beta) \Pi_0(\Pi_0 - 1)).$$

Since $\Pi_0 > \Pi_1 > \Pi_2$ and $\delta_1 < \delta_2$ it follows that $w_1 - w_0 > 0$ if β is sufficiently close to one.

Next, we show that in the presence of real wage rigidity period T output is below its new steady state. Consider first the Rotemberg model. In period T, $\Pi_T = 1$ implies $\delta_T = \delta_n = 1$, and from equation (1) $w_T = w_n$. In period $T - 1$, $\Pi_{T-1} > 1$ so that $w_{T-1} = w_n + \epsilon^{-1} \kappa \Pi_{T-1}(\Pi_{T-1} - 1) > w_n$. Thus $w_{T-1} > w_T$. Then from equation (3) period T output is given by

$$Y_T = \left(\frac{w_T}{w_{T-1}} \right)^{\gamma'/(1+\eta)} Y_n.$$

Thus, $Y_T < Y_n$ on account of negative wage growth ($w_{T-1} > w_T$) while $Y_t = Y_n$ for $t > T$ on account of zero wage growth. In the absence of real wage rigidity ($\gamma' = \gamma = 0$), $Y_T = Y_n$.

Analogously, equation (4) in the Calvo model implies $w_{T-1} > w_T = w_n$ and in turn equation (7) implies

$$Y_T = s_T^{-\eta/(1+\eta)} \left(\frac{w_T}{w_{T-1}} \right)^{\gamma'/(1+\eta)} Y_n.$$

Thus, $Y_T < Y_n$ on account of negative wage growth ($w_{T-1} > w_T$) as well as price dispersion being higher than its new steady state ($s_T > 1$). Output converges

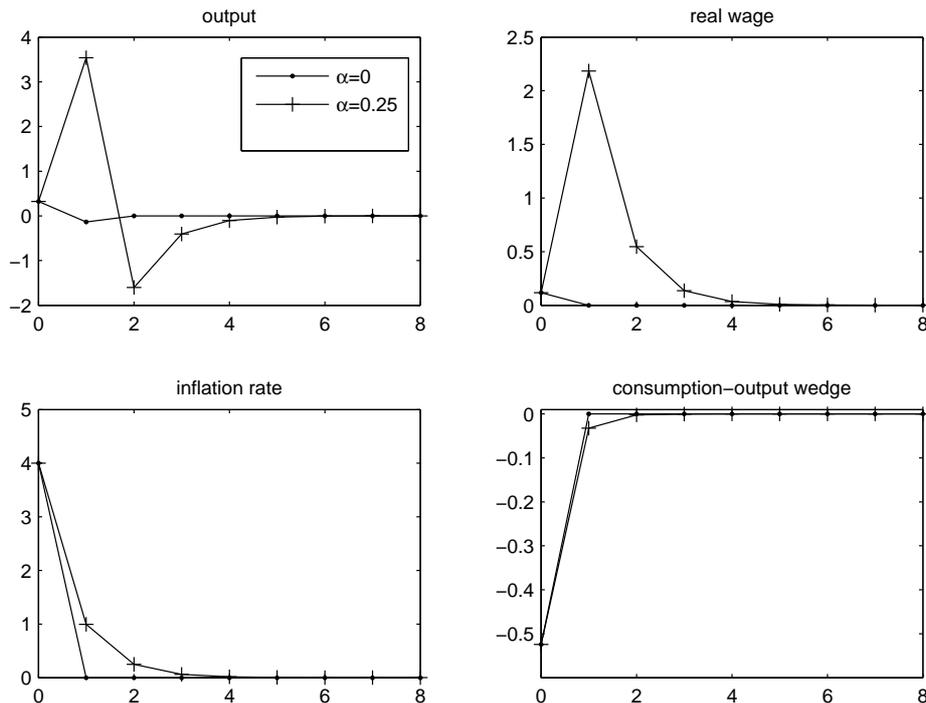


Figure 3: The speed of disinflation and transitional dynamics in the Rotemberg model.

asymptotically to its new steady state from below reflecting the slow convergence of price dispersion to its new steady state.

To summarize, in the Calvo model output transitions through a boom and a slump before converging towards its new steady state if real wage rigidity is strong enough. The same holds for the Rotemberg model provided β is sufficiently close to one. As the general case is algebraically more tedious, we illustrate our results numerically. We show that in the presence of real wage rigidity gradual disinflation amplifies the initial boom and the subsequent slump.

In our numerical illustrations, we let the disinflation path follow a smooth downward path by positing a first-order autoregressive process $\Pi_t = (1 - \alpha) + \alpha\Pi_{t-1}$ where α controls the speed of disinflation. We use two illustrative values— $\alpha \in \{0, 0.25\}$ so

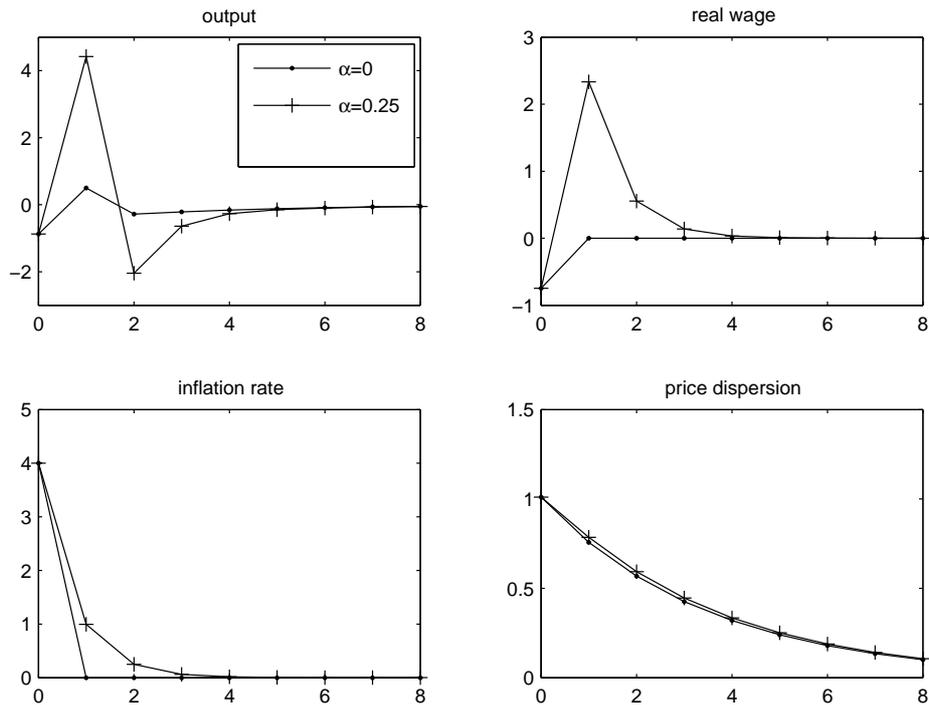


Figure 4: The speed of disinflation and transitional dynamics in the Calvo model.

that under $\alpha = 0$ inflation adjusts immediately to its new steady state (cold-turkey disinflation) while under $\alpha = 0.25$ the bulk of the disinflation process is over by the end of period 3. In Figures 3 and 4 we plot the transitional dynamics in the Rotemberg and Calvo models, respectively, setting $\gamma = 0.7$. The plots under $\alpha = 0$ replicate those in Figure 1 and 2 corresponding to $\gamma = 0.7$.

In the Rotemberg model and under gradual disinflation the real wage rises in period 1 and then declines smoothly towards its new steady state. Output jumps to a higher level in period 1, undershoots its new steady state in period 2 and then adjusts smoothly towards its new steady state. The decline in period 2 output after its initial rise is a result of three factors: a decline in the level of real wage, a rise in the consumption-output wedge and negative real wage growth in period 2. The initial boom followed by a slump contrasts with the initial slump under cold-turkey

disinflation.

In the calvo model and under gradual disinflation the real wage overshoots initially and then converges smoothly towards its new steady state. Output overshoots in period 1, declines in period 2 below its old steady state (a delayed-slump) and then adjusts smoothly towards its new steady state. The delayed-slump shown in Figure 4 confirms the intuition behind our analytical results above and is in contrast to the case of cold-turkey disinflation, in which case there is no slump at all (as output is never below its old steady state). As we argued above the slump in period 2 under gradual disinflation is due to negative real wage growth in the presence of real wage rigidity.

The assumption of an autoregressive process for inflation implies that disinflation proceeds nonlinearly—the central bank reduces inflation by a smaller amount as time goes by. In Figures 3 and 4, the inflation rate declines by three percent in the first period and by less than one percent in period 2. Alternatively, one may assume that disinflation proceeds linearly (see, e.g., Goodfriend and King (2005)). For instance if the disinflation process lasts for three periods then in each period the central bank closes one-third of the gap between the old steady state of 4% inflation and the new steady state of 0% inflation.

Figures 5 and 6 show the effects of a disinflation process that lasts for three periods. We make two observations. First, the plots corresponding to $\gamma = 0.7$ are comparable to the case with autoregressive process and $\alpha = 0.25$ shown in Figure 3 and 4. That is, we see similar effects in terms of the initial boom and the delayed slump, thus again confirming our analytical results. The difference is quantitative: in Figures 3 and 4 the slump happens in period 2 while in Figures 5 and 6 the slump happens in period 3. Second, Figures 5 and 6 show a delayed slump also under $\gamma = 0.35$, which represents a mild degree of real wage rigidity, although the slump is less pronounced than in the case where $\gamma = 0.7$.

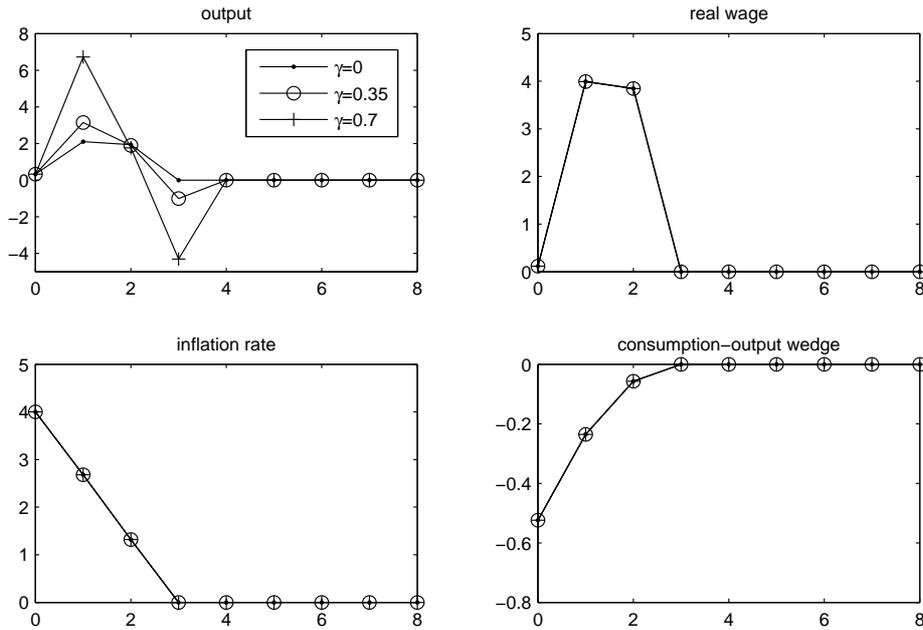


Figure 5: Linear disinflation and transitional dynamics in the Rotemberg model.

We end the section by pointing out that the similarity in transitional dynamics of the Calvo and Rotemberg models is despite allowing for different long-run properties. Features such as nominal indexation (e.g., as in Ireland (2011)) may be incorporated so as to make the two models more realistic. Indexation also makes them more similar in terms of long-run properties without changing the nature of the transitional dynamics.¹⁶

V CONCLUSION

The present paper revisits the old question regarding the output effects of credible disinflation by incorporating real wage rigidity into the workhorse nonlinear models of the New-Keynesian type—the Calvo price staggering and Rotemberg price adjustment costs. Unlike previous studies of these non-linear models our approach

¹⁶Results for the case of partial indexation are available upon request.

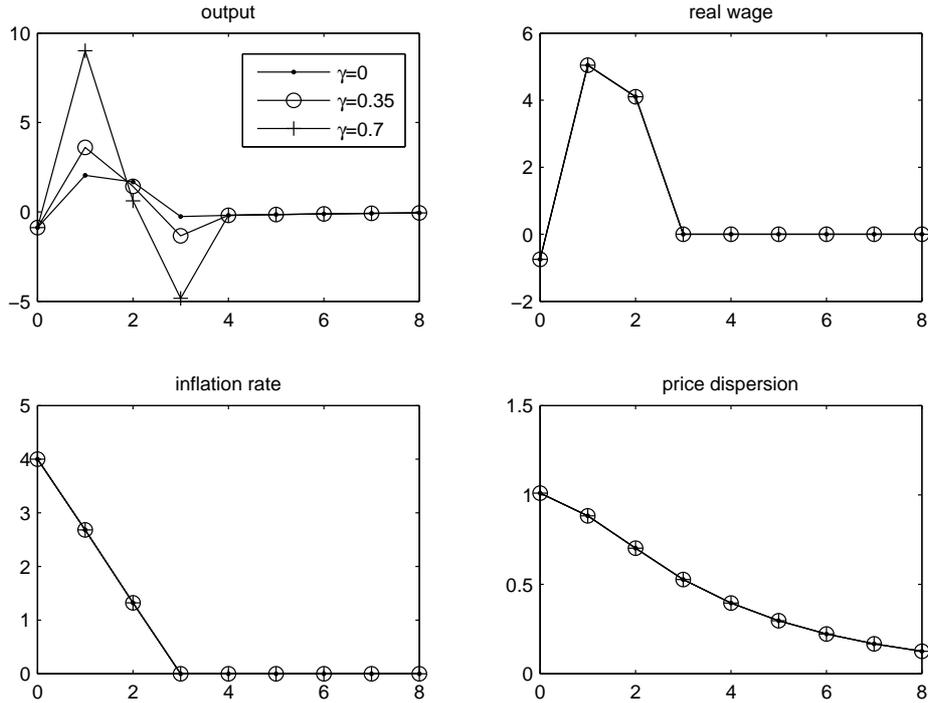


Figure 6: Linear disinflation and transitional dynamics in the Calvo model.

enables us to analyze the effects of a less or more gradual disinflation as well to avoid implausible deflationary paths.

We have demonstrated that, in a credible gradual disinflation and in the presence of real wage rigidity the Calvo and Rotemberg-type models have similar transitional dynamics—both models feature a delayed output slump. That is, after an initial boom, output falls below its old steady state level. The delayed-slump result is novel and is due to the interaction of real wage rigidity and nonlinearity (associated with a non-zero inflation rate) along the transition path. We find similar transitional dynamics in the two models despite allowing for differences in their long-run properties, as do previous studies. We also find that features such as nominal indexation to trend inflation tend to make the two models more similar in terms of their long-run properties without changing the nature of the transitional dynamics.

We remark that, the initial boom featured in these models is a drawback, in light of the conventional wisdom that disinflations are costly, as was pointed out, among others, by Ball (1994).

Appendix: Derivation of private sector behavior

Households

There is a representative household whose period utility is $U(C_t, N_t) = \log C_t - N_t^{1+\eta}/(1+\eta)$, $\eta > 0$. The household maximizes $E_t \sum \beta^i U(C_t, N_t)$ subject to the budget constraint $P_t C_t + B_t = W_t N_t + R_{t-1} B_{t-1} + D_t$, where β is the discount factor, P_t is the (final good) price level, R_t is the nominal interest rate on bond holdings B_t , W_t is the nominal wage, D_t is profit from ownership of firms. Intertemporal optimization leads to the familiar Euler equation $1 = E_t (Q_{t,t+1} R_t / \Pi_{t+1})$, where $\Pi_t \equiv P_t / P_{t-1}$ and $Q_{t,t+1} \equiv \beta (C_{t+1} / C_t)^{-1}$ is the household's stochastic discount factor. In the absence of real wage rigidity optimal labor supply decision leads to the equation $w_t = MRS_t$ where w_t is the real wage and $MRS_t = C_t N_t^\eta$ is the marginal rate of substitution between consumption and labor. In the presence of real wage rigidity (see, e.g., Blanchard and Gali (2007)), the modified labor supply equation is given by (2) of the main text.

As is standard C_t is a Dixit-Stiglitz composite of final goods $C_t = \left(\int_0^1 C_{k,t}^{1/\mu} dk \right)^\mu$, where ϵ is the elasticity of substitution between goods and $\mu \equiv \frac{\epsilon}{\epsilon-1}$. Optimal consumption allocation across gives the demand equation $C_{k,t} = \left(\frac{P_{k,t}}{P_t} \right)^{-\epsilon} C_t$ where $P_t = \left(\int_0^1 P_{k,t}^{1-\epsilon} dk \right)^{\frac{1}{1-\epsilon}}$ is the price index.

Firms

There is a continuum of monopolistically competitive firms over the unit interval. Firm k 's production function is given by $Y_{k,t} = N_{k,t}$. With perfectly competitive labor market, the real marginal cost is identical across firms and is equal to the real wage w_t . While firms choose prices optimally, output is demand determined, which in turn pins labor demand. We let $P_{k,t}$ denote firm k 's output price.

Rotemberg-type Price Adjustment Costs. Suppose price setting is subject to Rotemberg-type price adjustment costs, which takes a standard quadratic form,

$$PAC_{k,t} = \frac{\kappa}{2} \left(\frac{P_{k,t}}{P_{k,t-1}} - 1 \right)^2 Y_t$$

where $\kappa > 0$ and Y_t is aggregate output. Firm k maximizes the expected lifetime profit

$$E_t \sum_{i=0}^{\infty} Q_{t,t+i} ((z_{k,t+i} - w_{t+i}) Y_{k,t+i} - PAC_{k,t+i}) \quad (\text{A1})$$

where $z_t \equiv P_{k,t}/P_t$ is the relative price. Each good k is either consumed or used by firms to pay for costly price adjustments

$$Y_{k,t} = \left(\frac{P_{k,t}}{P_t} \right)^{-\epsilon} Y_t \quad (\text{A2})$$

where by market clearing $Y_t = C_t + PAC_t$ and

$$PAC_t = \frac{\kappa}{2} \left(\frac{P_t}{P_{t-1}} - 1 \right)^2 Y_t \quad (\text{A3})$$

is the aggregate price adjustment cost. The standard assumption is that firms' allocation of their demand across the differentiated goods, so as to meet the price adjustment costs, is analogous to that of households so that $PAC_{k,t} = (P_{k,t}/P_t)^{-\epsilon} PAC_t$.

Substituting the demand equation as well as the equation defining price adjustment costs for good k in the profit function, differentiating with respect to $P_{k,t}$ and imposing symmetry across firms leads to equation (1) of the main text.

Calvo-type Price Staggering. Suppose instead firms face Calvo-type price staggering. Firm k maximizes its expected lifetime profit

$$E_t \sum_{i=0}^{\infty} \theta^i Q_{t,t+i} \left(\left(\frac{P_{k,t}}{P_{t+i}} - w_{t+i} \right) Y_{k,t+i} \right) \quad (\text{A4})$$

Then using demand for good k in the profit function, differentiating with respect to $P_{k,t}$ and imposing symmetry across optimizing firms leads to the first-order condition

$$z_t = \mu \frac{E_t \sum_{i=0}^{\infty} (\beta\theta)^i C_{t+i}^{-1} Y_{t+i} m c_{t+i} \left(\frac{P_{t+i}}{P_t} \right)^\epsilon}{E_t \sum_{i=0}^{\infty} (\beta\theta)^i C_{t+i}^{-1} Y_{t+i} \left(\frac{P_{t+i}}{P_t} \right)^{\epsilon-1}} \quad (\text{A5})$$

By using the market clearing condition $Y_t = C_t$ the optimal relative price can be rewritten as equation (4) of the main text.

The aggregate price index can be rewritten as a weighted average of optimized and non-optimized prices

$$P_t = \left((1 - \theta) P_t^{*1-\epsilon} + \theta P_{t-1}^{1-\epsilon} \right)^{\frac{1}{1-\epsilon}} \quad (\text{A6})$$

and is given by equation (5) of the main text. Furthermore under price staggering $N_t = s_t Y_t$ where $s_t \equiv \int_0^1 (P_{k,t}/P_t)^{-\epsilon} dk$ is a measure of price dispersion given by equation (6) of the main text.

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