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OPTIMAL STATE-DEPENDENT RULES, CREDIBILITY AND THE COST OF DISINFLATION

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Abstract

We examine the costs of disinflation and the role of credibility in a model where pricing rules are optimal and individual prices are rigid. Individual nominal price rigidity is modelled as resulting from menu costs. The interaction between optimal pricing rules and credibility is essential in the determination of the costs of disinflation. When disinflation is not credible, inflationary inertia is engendered by the asymmetry of the price deviations distribution in the inflationary steady state. A perfectly credible disinflation causes an immediate change of pricing rules which, by rendering the price deviations distribution less asymmetric, pratically annihilates inflationary inertia. We also develop an analytical framework for analyzing intermediate imperfect credibility cases.

1. Introduction

The reluctance of inflation to respond to stabilization policies centered on aggregate demand control is an issue that has attracted attention from different branches of macroeconomics. If inflation does not respond immediately to reductions in aggregate demand growth, the economy is penalized with output losses that can render the disinflation process extremely costly.

Theoretical explanations for the costs of disinflation that became notorious are those of Sargent (1983), and Taylor (1983). According to Sargent, the costs of disinflation arise from imperfect credibility of the policy makers. More specifically, agents do not reduce price growth in response to decreases in money growth because they do not believe that the monetary authorities will maintain money growth at a low level. In contrast to that view, Taylor (1983) suggests that even if the stabilization policy is perfectly credible, the disinflation must be extremely slow, in order to avoid output losses. The main obstacle to disinflation would be the microeconomic rigidity of wages, coupled with the staggering of the decision making about the future path of this variable among different sectors. Although based on realistic features of the labor market, which include some predetermined adjustments of wages, the existence of such rules and their duration are exogenous such agents when responding to monetary policy shifts, as a method which yields invaluable insights on the mechanics of monetary based disinflations.

The optimal pricing policies in our model are state dependent[1] [2]. The literature on the costs of disinflation until now have used only time-dependent pricing policies (Taylor 1983, Ball 1994a, b, Bonomo and Garcia 1994, Simonsen 1983)[3]. In those models each individual price is fixed for a preset amount of time. In this setting, whatever happens during the period in which a price is fixed cannot affect individual behavior, even a drastic change in the policy environment. This ad-hoc unresponsiveness of individual prices is the mechanism through which disinflation can be made costly in this setting. Still, credibility matters because prices are set for a period of time with base on expectations about the environment in this period.[4] However, since the rules are not optimally derived, they are

[1] Barro (1972) and Sheshinski and Weiss (1977, 1983) are pioneer works on the derivation of optimal state-dependent rules under menu costs. The optimal rule in Barro is a two-sided Ss rule, while the optimal rule in Sheshinski and Weiss is a one-sided Ss rule. The latter is motivated by an inflationary environment. Although one-sided Ss rules are often consider as good characterizations of pricing rules in an inflationary economy, their optimality, even under high inflation, is implausible. This issue has been analyzed in Bonomo (1994).

[2] Excellent expositions of the problem of deriving optimal rules under kinked adjustment costs are Bertola and Caballero (1990) and Dixit (1993).

[3] Bonomo and Garcia (94) and Simonsen (83) use rules that include indexation. However, the moment of adjustment by the past inflation is predetermined. The price adjustments in the former alternates optimal adjustments and adjustments by past inflation, while prices are fixed in the meantime. When inflation is high, a rule similar to this should be optimal when there are both menu costs and infrequent information about the optimal price.

[4] Ball (1994a) shows in the context of a fixed price staggering model, as Taylor (1979), that under perfect credibility, disinflation can be obtained without costs, while imperfect credibility would add disinflation costs to the same model (Ball 1994b).

kept invariant to the changes in monetary policy, even the credible ones.

By contrast, rigidity of individual prices in state-dependent rules does not imply that a individual price is fixed at any moment notwithstanding what happens in the environment. A price is fixed only to the extent that the optimal price is not driven too far away from the current. Moreover, optimal state-dependent pricing rules are affected by the credibility of monetary policy. We believe that those features make optimal state-dependent rules a much better description of individual behavior in the context of a changing policy environment.

Non-credible disinflations can be actually costly in an model with state-dependent rules. However, the mechanism is entirely different from the one that renders disinflation costly in a time-dependent model. As it will be shown, an inflationary economy is characterized by an asymmetric distribution of deviations of individual prices from optimal ones. That is, there are always a much larger number of firms with prices substantially lower than the optimal than firms with prices higher than the optimal. As money growth is stalled, this asymmetry interacts with symmetric idiosyncratic shocks to produce inflation persistence: the symmetric idiosyncratic shocks trigger more upward than downward adjustments[5]. This

[5]The mechanism of inflationary inertia in our model justifies the concern of policymakers in high inflation countries with alignment of prices (with respect to the frictionless optimal levels) when the stabilization is launched. Sucessfull stabilization of high inflation economies often

effect was mentioned by Caballero and Engel (1992), but they did not pursue the issue further[6].

When the policy is credible, the change of policy rules results in a narrower inaction range, specially for positive price deviations. Therefore, a substantial number of units are caught with price deviations that exceed the upper bound of the new inaction range, triggering a substantial amount of instantaneous downward adjustments. As a consequence of that, the distribution of price deviations changes abruptly becoming nearly symmetric. Our results show that this effect practically annihilates inflationary inertia.

The money-based disinflations we examine are specified in the following way. We start from a situation where inflation has been positive and constant for some time, and suppose that policy makers reduce nominal aggregate demand growth instantaneously and unexpectedly to zero. They also announce that the new regime is going to last forever. Alternative hypotheses about the credibility of the policy change are considered. Full credibility means that the agents will choose

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occur after alignment of prices: if all prices become quoted in a referential which has stable real value (a foreign currency or a referential contructed with that purpose, as in the Real Plan in Brazil) before stabilization, when the new currency is created prices are close to the frictionless optimal price. That is the distribution of price deviations will not have a large proportion of firms close to the upward adjustment threshold.

[6]Their main concern was the influence of inflation on the asymmetric effects of positive and negative monetary shocks.

their optimal rules forecasting the monetary policy as announced. A case of extreme lack of credibility is examined, where agents do not change their pricing rules because they do not believe that there will be any change in the monetary policy. Imperfect credibility is also examined, through an analytically convenient setup. Agents believe that monetary policy has changed to the policy announced, but attribute a constant hazard that the old monetary policy will be resumed. Variation in the degree of credibility is examined through changes in the hazard parameter.

This work benefited from the substantial progress in the aggregation of state dependent rules made in the last decade (see Bertola and Caballero 1990 for a general exposition). Although this new approach was applied to a variety of macroeconomic issues including monetary effects (Caballero and Engel 1992,1993, Caplin and Spulber 1987, Caplin and Leahy 1991 and Tsiddon 1993), there was little concern about disinflation costs.

We proceed as follows: section 2 presents the model, the optimal pricing rule of individual agents and aggregate equilibrium that arises from a situation of stable nominal aggregate demand growth and inflation. Section 3 introduces the policy change and discusses how the effective path of the inflation may differ from the path that would be obtained in a frictionless economy. For simplicity, at first, all uncertain is assumed to be idiosyncratic. Numerical simulations for the path of inflation are then carried out for the case of no credibility in the monetary policy, because of its relative simplicity. Section 4 considers the more complex effects of a fully credible disinflation. In section 5, we study the effects of intermediate levels of credibility. In order to generate those results, conditions that determine optimal pricing rules when the frictionless optimal price process follows a diffusion process with a drift that follows a jump process are derived, and the rules numerically evaluated. Section 6 introduces aggregate uncertainty in the nominal aggregate demand, and compares disinflation paths for various configurations of uncertainty parameters. Conclusions are presented in section 7.

2. The Model and the Inflationary Steady State

In this section, we characterize the inflationary environment that precedes the disinflation policy. We rely on the substantial progress made in the last decade, both in derivation of optimal rules under adjustment costs, and aggregation of those state dependent rules[7]. State dependency of pricing rules allows us to summarize the relevant information about the economy in the distribution of the

[7]See Dixit (1993) for an excelent exposition of the optimization problem and Bertola and Caballero (1990) for both the individual and the aggregation parts.

price deviations (from the frictionless optimal level). We find the distribution of price deviations correspondent to a certain inflation rate by aggregating optimal individual pricing rules, derived under the assumption that this inflation rate will last forever. We will make several simplifying assumptions which renders the model tractable, while keeping the main insights.

2.1. Optimal pricing rule in a stable environment

All the variables in the following model are in log.

We assume that the optimal level of individual relative price, in the absence of adjustment costs, is given by:

$$p_i^* - p = vy + e_i \tag{2.1}$$

where p_i^* is the individual frictionless optimal price, p is the average level of prices, y is aggregate demand and e_i is an idiosyncratic shock to the optimal price level. Equation 2.1 states that the relative optimal price depends on aggregate demand and on shocks specific to the firm. It can be derived from utility maximization in an yeoman farmer economy, as in Ball and Romer (1989).

Nominal aggregate demand is given by the quantity of money:

$$y + p = m$$

Substituting the quantity money equation into equation 2.1 yields:

$$p_i^* = vm + (1 - v)p + e_i \tag{2.2}$$

This equation can also be derived directly from other specifications, such as Blanchard and Kiyotaki (1987), where real balances enter the utility function. According to equation 2.2 the aggregate component of individual optimal price is a convex combination between the money supply and the average price level. We assume that v is equal to one. This evades strategic complementarities in prices, simplifying aggregation substantially[8]. Thus, the aggregate component is reduced to the money supply:

$$p_i^* = m + e_i \tag{2.3}$$

[8]The inclusion of strategic complementarities should magnify departures from the natural output level, but should not change the qualitative insights of the simpler model. Caplin and Leahy (1992) is one of the few articles to include price interdependence among agents in the state dependent literature. Their results are not qualitatively different from Caplin and Leahy (1991), where each individual optimal price depends only on the money supply.

To keep an individual price aligned to its optimal level is costly due to the existence of a lump-sum adjustment cost k. On the other hand to let the price drift away from the optimal entails profit losses, that flow at a rate $l(p_i - p_i^*)^2$ [9]. Without loss of generality we assume l to be equal one[10]. Time is discounted at a constant rate ρ.

Given the stochastic process for the optimal price, each price setter solves for the optimal pricing rule. We assume that e_i follows a driftess Brownian motion and that the money supply has a deterministic constant rate of growth π[11]. Thus, the frictionless optimal price is a Brownian motion with a drift given by the rate of the money supply growth:

$$dp_i^* = \pi dt + \sigma_i dw_i \tag{2.4}$$

where w_i is a Wiener process. Thus, when the price is constant, the dynamics of the price deviation $z_i = p_i - p_i^*$ is given by:

$$dz_i = -\pi dt + \sigma_i dw_i'$$

[9] Observe that this form corresponds to a second order Taylor approximation to the profit loss whenever the second derivative of the profit function is constant.

[10] The optimal rule depends only on k/l.

[11] In later sections we deal with alternative assumptions about m.

where $w_i' = -w_i$ is also a Wiener process. To find the optimal rule, first we observe that the value function C, given by the minimized cost, should satisfy the following equation whenever the price deviation z is inside the region where it is optimal not to adjust[12]:

$$\rho C(z_i)dt = z_i^2 dt + E_t[dC] \tag{2.5}$$

where E_t denotes the conditional expectation given the price deviation at time t. The equation can be interpreted intuitively as stating that the required (by time-discounting) addition to the value C should be equal to the flow cost at this moment plus the increase in the stock of C. Applying Ito's Lemma to the second term in the right-hand side, we arrive at the following ordinary differential equation for C:

$$\frac{\sigma_i^2}{2}C''(x) - \pi C'(x) - \rho C(x) + x^2 = 0$$

which implies that C has the following general form[13]:

[12]See, for example, Dixit and Pindyck (1994).

[13]A particular solution is found as the expected present value of the flow cost under no control, as in Dixit (1993).

$$C(x) = Ae^{\alpha x} + Be^{\beta x} + \frac{x^2}{\rho} - \frac{2\pi x}{\rho^2} + \frac{\sigma_i^2}{\rho^2} + 2\frac{\pi^2}{\rho^3} \tag{2.6}$$

where

$$\begin{aligned}
\alpha &= \frac{\pi}{\sigma_i^2} - \sqrt{\frac{\pi^2}{\sigma_i^4} + 2\frac{\rho}{\sigma_i^2}} \\
\beta &= \frac{\pi}{\sigma_i^2} + \sqrt{\frac{\pi^2}{\sigma_i^4} + 2\frac{\rho}{\sigma_i^2}}
\end{aligned}$$

and the constants A and B are to be jointly determined with the optimal rule parameters by the Value Matching and Smooth Pasting Conditions (see Dixit, 1993, for the intuition and derivation of these conditions).The optimal rule is characterized by three parameters (L, c, U), where c is the target level for adjustments and, L and U are the levels of price deviation which trigger upward and downward adjustments, respectively. The Value Matching Conditions state that the value function at a trigger level of deviation level should be equal to the value function at the target level plus the adjustment cost, that is

$$\begin{aligned}
C(L) &= C(c) + k \\
C(U) &= C(c) + k
\end{aligned} \tag{2.7}$$

The Smooth Pasting Conditions are optimality conditions for L, c, and U. According to them the derivative of the value function at the optimal trigger and target levels should be zero, that is

$$C'(L) = C'(U) = C'(c) = 0 \tag{2.8}$$

Substituting the value function equation (2.6) into conditions 2.7 and 2.8 we get a system with five equations and five unknowns (A, B, L, c, U), which can be solved numerically.

Figure 1 plots the values of (L, c, U) for different values of the inflation parameter, π, while the other parameters are fixed. The price setters take into consideration that the price will be depreciated soon with high probability and because of that reset their prices at a level higher than the optimal one. Thus, the optimal target point, c, is always greater than zero, and increases with inflation. The size of the upward adjustments, $c - L$, also grows with inflation in order to prevent a too high frequency of adjustments, which will result in a large increase in adjustment costs.

In what follows our main objective is to characterize the behavior of the aggregate price level, p, during disinflation. It will be useful to relate it to the money supply and to the average price deviation or disequilibrium, z:

$$p = \int p_i di = \int (p_i^* + z_i) di = \int (m + e_i + z_i) di = m + z \tag{2.9}$$

Substituting equation 2.9 into the money quantity equation results that the level of output is the symmetric of the average price deviation:

$$y = -z \tag{2.10}$$

2.2. The Inflationary Steady State

The inflation rate, that is the rate of growth of the average price, depends not only on the rate of growth of the money supply, but also on the distribution of price deviations. Given the change in each individual frictionless optimal price, the distribution of price deviations will govern the proportion of units with positive and negative price adjustments, and will determine the new distribution of price deviations. When the distribution of price deviations is the ergodic one, the new distribution will be equal to the old one[14]. This does not mean that the price

[14]This is true only in the absence of aggregate uncertainty. Whenever aggregate shocks are present, the distribution of price deviations fluctuates through time and the ergodic distribution is only the time average of those distributions. See Bertola and Caballero (1990) for a derivation of the ergodic distribution and its properties.

deviations of individual firms are not changing, but that they are evolving in such a way that the density of firms that leave each point in the price deviation space is equal to the density of firms that arrive to it. The invariance of the distribution of price deviations implies a constant average disequilibrium. Thus, equation 2.10 implies that output is constant, and the inflation rate must be equal to the rate of growth of the money supply.

If a certain rate of money growth is kept constant indefinitely, the distribution of price deviations will converge to the ergodic one. Then, if a certain money inflation is unaltered for a long period of time, it is reasonable to assume that the distribution of the price deviations is ergodic and that the price inflation is equal to the money inflation. We can say that the economy is in an *inflationary steady state.*

Each inflationary steady state will have an ergodic distribution of price deviations associated to it through a pricing rule, in the following way: given a volatility parameter for the idiosyncratic shocks, σ_i, each inflation rate π is associated to a different optimal pricing rule, that together with the stochastic process parameters for p_i^* jointly determine the ergodic distribution (see Appendix A and Bertola and Caballero, 1990).

For an example, suppose that inflation has been equal to zero for some time.

In this case, the optimal pricing rule of firms entails $L = -U$ and $c = 0$. The ergodic density of price deviations for this case is shown in Figure 2. It is symmetric around zero and decreases linearly with the absolute size of price deviation. The existence of adjustment costs will cause inaction at the microeconomic level, and therefore some firms will have prices that are different from the frictionless optimal. The frictionless optimal price of each firm is changing with time due to the existence of idiosyncratic shocks. Since we are assuming that there is a very large number of firms, the ergodicity of the distribution assures that it will be invariant to the occurrence of those shocks.

Figure 3 shows the ergodic density for the same volatility of idiosyncratic shocks, but for a high inflation rate. The shape of the density is extremely sensitive to the inflation rate. With a positive, high inflation, the fraction of firms that are close to the lower barrier L is much larger than the fraction of firms close to the upper barrier U. This comes from the fact that with a large, positive inflation the optimal price tends to appreciate, resulting in much more frequent upwards than downwards price adjustments. The ergodicity of the distribution again implies that microeconomic frictions have no effect on output. However, this is a long run phenomenon. If there is a structural change in the economy, as a new monetary policy, the microeconomic frictions might, in principle, matter, and output can be affected. In the next sections we will examine the transition dynamics between a high inflation and a zero inflation steady states using different credibility assumptions. For expositional clarity, we start with the no credibility case.

3. Disinflation with No Credibility

Suppose that the economy is initially in a high inflation steady state, as the one depicted in Figure 3. The money has been growing at a constant rate, and agents believe that this state will last forever. Then, the monetary authorities decide suddenly to stop printing money and to keep the money supply constant indefinitely. Assume, for simplicity, that the agents never believe in this change, and because of that maintain the same pricing rules they were following before. Notice that this does not mean that they will automatically continue to increase their prices: since the rules are state-dependent, any price increase must be triggered by a simultaneous increase in the frictionless optimal price. However, our simulations show that inflation will continue to grow for several months. What is the reason for that?

The substantial asymmetry of the distribution of price deviations associated to the inflationary steady state indicate that there is a large proportion of firms with prices far below their optimal one. Since their price deviations are close to the trigger level, a small positive idiosyncratic shock to the optimal price of each one of those firms may be enough to trigger a large price increase from them. Thus, large price increases may be numerous although there is no macroeconomic fundamentals driving them. On the other hand there are few firms with prices far above their optimal one. Therefore, price decreases will be much less numerous. With the continued incidence of idiosyncratic shocks, the asymmetry of the price deviation distribution is corroded, hence reducing residual inflation.

Figure 4 shows the path of inflation after the non-credible policy change starting at different steady state levels of inflation (see Appendix B and Bertola and Caballero (1990) for the discretization of the continuous time model in which the simulations are based). Inflation is gradually reduced as the asymmetry of the initial price-deviation distributions diminishes. The role of idiosyncratic shocks and the timing of their effect are illustrated by the results depicted in Figure 5. A higher idiosyncratic uncertainty initially causes a higher inflationary inertia, because a larger proportion of price increases in triggered. However, the asymmetries in the price-deviation distributions are eroded faster in this case, ensuing a lower residual inflation after some time has elapsed.[15]

[15]The distribution of price deviations will converge in the long run to an ergodic distribution

It is important to notice that since money supply is constant after the monetary policy change, the rate of change in output is symmetrical to the inflation level. Thus a persistent inflation implies in output reductions, and therefore inflationary inertia and the costs of disinflation are two ways of referring to the same phenomenon.

4. Disinflation with Perfect Credibility

Consider now that there has been constant inflation for some time, and that the monetary authorities credibly announce that money printing will be halted. The distribution of price deviations is initially asymmetric as in Figure 3. However, because the change of monetary policy is perfect credible, the agents will change instantaneously their pricing rules, resulting in a sudden change in the price deviation distribution. The inflationary inertia will hinge on the asymmetry of the new distribution.

To understand the distribution change, first observe that a high inflation entails a very large upper barrier. The reason is that agents with prices substantially

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which is different from the one associated with a no inflation steady state. The distribution is linear, as in the steady state, but asymmetric, because the pricing rules are still associated with the old inflationary state. This result is mentioned as a curiosity, since a persistent state of no inflation, in which economic agents are certain that inflation will be high very soon, is not plausible.

superior to the frictionless optimal price will not decrease them, because they foresee a fast erosion of this gap. By contrast, when there is no trend in the frictionless optimal price, any difference between the actual price and the frictionless optimal level is expected to remain unaltered, and large price deviations are not tolerated. Therefore, the upper barrier reduces substantially with a credible fall in the money supply growth. This causes a downward adjustment of all prices who were at the interval between the old and the new upper barriers. An instantaneous deflation and a simultaneous boom, will then occur.

However, the instantaneous deflation generated at the moment the money supply is credibly halted does not guarantee a successful inflation stabilization. As mentioned before, for a given level of idiosyncratic uncertainty, the persistence of inflation hinges solely on the asymmetry of the new distribution of price deviations. The new distribution will have an atom at the new target level, because of the substantial number of downwards adjustments instantaneously triggered. It will also be substantially less asymmetric than the distribution inherited from the inflationary steady state, because the reduction of the upper barrier eliminates the portion with lower density at the right side of the old distribution. Thus, the abrupt change of rules induced by the credible change of rules destroy the mechanism of inflation reproduction. Despite substantial price stickiness at the microeconomic level, inflation is eliminated nearly instantaneously, with very little cost.

We simulate a credible disinflation when the economy is initially at an inflationary steady state with an instantaneous rate of 1.5 a year[16]. The initial optimal price rule, evaluated numerically from equations 2.6,2.7,2.8, is $(-0.25, 0.2, 0.45)$ and the initial distribution of price deviations is portrayed in Figure 3. When the money supply printing is credibly stopped, the price rule changes immediately to $(-0.27, 0, 0.27)$ and the distribution changes instantaneously to the one depicted in Figure 6. All the units with price deviation between $0, 27$ and 0.45 decreased their prices to the frictionless optimal level, generating an atom in the new distribution. This also caused an instantaneous deflation, as illustrated in Figure 7. The distribution in Figure 6 is much more symmetric than the one in Figure 3. However there is a small empty space in the left side, because of the decrease of the lower barrier. In the moments subsequent to the policy change, there will be a small deflation: while the space on the left side of the distribution is not filled there will be no upward price adjustments. According to Figure 7, after some time there will be a small inflation until convergence to zero inflation.[17] This inflation

[16]This is equivalent to an annual inflation of 348%.

[17]While inflation converges to zero, the distribution of price deviation converges to the triangular distribution of Figure 2, which is associated to the zero inflation steady state.

is negligible, specially if compared to the original level, which leads us to conclude that disinflation can be attained almost instantaneously without costs[18].

The cases of perfect credibility and of no credibility are extreme, and therefore not realistic. Nonetheless, they constitute useful benchmarks. In the next section we examine the more realistic case of imperfect credibility.

5. Disinflation with Imperfect Credibility

The assumption of imperfect credibility is more realistic. The economic agents in general do not fully believe that a change in the monetary policy will last forever. It is not true, either, that they are absolutely sure that the new policy will be abandoned immediately. Here we model imperfect credibility as a conjecture that in each finite time interval there is a positive probability that the monetary authorities will renege. For simplicity, we assume that the probability of reneging at the next time interval is always the same. Thus, we model the rate of growth of the money supply after stabilization as a Poisson process with constant arrival rate λ. Once the new policy is abandoned, the agents believe that the old policy

[18] Notice that the time unit in Figure 7 is one day, while in Figures 4 and 5 the time unit is one week.

will be kept forever[19].

Specifically, after the stabilization policy is launched, the process for the money supply is:

$$dm = (0 + \pi 1_{\{N_t \geq 1\}})dt$$

where N is a Poisson counting process with constant arrival rate λ, and $1_{\{.\}}$ is the indicator function. Then, the drift of the money supply will change from zero to π when an arrival occurs. We assume that stabilization is launched at time zero.

The parameter λ can be interpreted as a measure of credibility. The extreme cases of perfect and no credibility are associated with zero and infinity values for λ, respectively. Imperfect credibility is represented by positive finite values, and the higher is λ, the lower the degree of credibility.

In order to analyze disinflation effects under imperfect credibility, the first step is to derive the optimal pricing rule. Let us define T as the random time of the abandonment[20]. Then, after T, the monetary policy is the same as before,

[19]For simplicity, we specify a constant money supply growth rate after the stabilization flaw. To choose this inflation rate to be the same as the pre-stabilization level is appealing, if one believes that certain structural features of the economy determine the money supply growth.

[20]Formally:

$$T(\omega) = \inf\{t : N_t(\omega) \geq 1\}$$

and the optimal pricing rule is given by equations 2.6, 2.7, and 2.8 in section 2. Before T, the money supply is constant, but there is a constant hazard λ that the old inflationary policy is resumed. So, the price setters have to take that into consideration when choosing their inaction range. We now turn our attention to the characterization of the optimal pricing rule under those conditions.

5.1. Optimal pricing rule under imperfectly credible monetary policy

First, we observe that the probability that the old monetary policy is resumed in the next interval $(t, t+s)$ is independent of t. Then, the optimal rule in the stabilization phase is time-invariant. To derive the optimal rule we use the same method employed in section 2. Our starting point is the continuous time Bellman equation (equation 2.5). Before applying the Ito's lemma to the value function C, we should note that its argument z_i evolves according to the following stochastic process:

$$dz_i = -\pi 1_{\{N_t \geq 1\}}.dt + \sigma_i dw$$

The above representation means that the stochastic process for z will change after the first arrival occurs. Let us represent by G the value function after the monetary authorities renege. Then, the differential of the value function before T

can be represented as:

$$dC(z_i) = \left[\frac{\sigma_i^2}{2}C''(z_i)dt + C'(z_i)\sigma_i dw_i\right] + dq[G(z_i) - C(z_i)]$$

where dq , the differential representation of the Poisson process, is one if the monetary authorities renege at this instant and zero otherwise. The first squared brackets expression is the usual formula for the differential of a function of a diffusion and the second one is the difference that will result if a change occurs in the stochastic process of z_i . Taking expectations conditioned on the information at time t, we get:

$$E_t[dC(z_i)] = \frac{\sigma_i^2}{2}C''(z_i)dt + \lambda dt[G(z_i) - C(z_i)] \tag{5.1}$$

Substituting back into the Bellman equation (equation 2.5), yields the following ordinary differential equation:

$$\frac{\sigma_i^2}{2}C''(x) - (\lambda + \rho)C(x) - x^2 + \lambda G(x) = 0 \tag{5.2}$$

The homogeneous solution is:

$$C_h(x) = Ce^{\gamma x} + De^{-\gamma x} \tag{5.3}$$

where

$$\gamma = \frac{\sqrt{2(\lambda + \rho)}}{\sigma_i}$$

We need a particular solution for 5.2 in order to find the expression for the general solution. Once the latter is found, the constants C and D are jointly determined with the policy parameters (L, c, U) by the Value Matching and Smooth Pasting Conditions (equations 2.7 and 2.8, respectively). In appendix C, we argue that the following is a particular solution for equation 5.2:

$$\begin{aligned} C_p(z) &= \frac{\lambda A e^{\alpha z}}{\lambda + \rho - \alpha^2 \frac{\sigma_i^2}{2}} + \frac{\lambda B e^{\beta z}}{\lambda + \rho - \beta^2 \frac{\sigma_i^2}{2}} + \frac{z^2}{\rho} \\ &\quad - \frac{2\lambda \pi z}{(\lambda + \rho)\rho^2} + \frac{\sigma_i^2}{\rho^2} + \frac{2\lambda \pi^2}{(\lambda + \rho)\,\rho^3} \end{aligned} \tag{5.4}$$

Finally, the value function is found by adding the particular solution to the solution of the homogenous differential equation:

$$C(z) = Ce^{\gamma x} + De^{-\gamma x} + \frac{\lambda A e^{\alpha z}}{\lambda + \rho - \alpha^2 \frac{\sigma_i^2}{2}} + \frac{\lambda B e^{\beta z}}{\lambda + \rho - \beta^2 \frac{\sigma_i^2}{2}}$$

$$+\frac{z^2}{\rho}-\frac{2\lambda\pi z}{(\lambda+\rho)\rho^2}+\frac{\sigma_i^2}{\rho^2}+\frac{2\lambda\pi^2}{(\lambda+\rho)\,\rho^3} \tag{5.5}$$

The constants A,B,α and β are known from the solution for the value function G. So, the only unknown parameters in this equation are the constants C and D. Those are determined jointly with the policy parameters (L, c, U) using the VMC and SPC conditions.

5.2. Disinflation results

We carried out simulations for imperfectly credible disinflations, assuming that the money supply growth before the policy change and idiosyncratic uncertainty were both 0.3. After stabilization is launched, money supply growth falls to zero, and idiosyncratic uncertainty remains the same. Hence, the only source of aggregate uncertainty at this stage is the timing of the policy abandonment. We also supposed that firms believe that whenever the monetary authorities renege, money supply growth will return to its pre-stabilization value. In Figure 8 we show how the optimal trigger and resetting points (L, c, U) respond to different credibility parameters λ[21]. The two horizontal lines for each policy parameter

[21] For easiness of interpretation observe that the probability that the old policy is not resumed before t is $e^{-\lambda t}$. So, if $\lambda = 0.3$, the probability that the stabilization policy is kept for at least one year is approximately 0.74.

show the values relative to the polar cases of perfect credibility and no credibility. The values for the policy parameters (L, c, U) increase continuously as λ gets higher, starting from the lower line representing the full credibility case, and growing towards the no credibility line. Those results have important implications for inflationary inertia.

Recall that the parameter values for the no credibility case also correspond to the pricing policy before stabilization. Then, we see that if λ is high and credibility is low, the pricing rule will change very little. As argued in section 4, it is the change in the optimal pricing rule induced by stabilization that potentially reduces inflationary inertia. We should consequently expect inflationary inertia to be inversely related to credibility of the policy makers, as measured by the parameter λ.

Figure 9 shows disinflation paths for various credibility parameters. In the simulations performed, the monetary authorities never renege, although agents attribute a positive probability that it would occur in any time interval. Therefore inflation must converge to zero in the long run. Our aim is to evaluate how fast is this convergence, for different levels of credibility. In order to focus on the effects of credibility, we fix the remaining parameters of the model ($\pi = 0.3$, $\sigma_i = 0.3$, $\rho = 0.025$, and $k = 0.01$). The simulation results are as expected: inflationary inertia increases as the level of credibility is reduced. When $\lambda = 10$, which means that the agents assign a probability of 8.2% that the stabilization will last at least one quarter, the inflation path closely resembles that of the no credibility case.

6. Introducing Aggregate Uncertainty

We know introduce uncertainty in the monetary policy by assuming that the money supply follows a Brownian motion, instead of being deterministic:

$$dm = \pi dt + \sigma_a dw_a$$

By 2.3, each individual frictionless optimal price evolves according to the following stochastic differential equation:

$$dp_i^* = \pi dt + \sigma dw$$

where $\sigma = (\sigma_a^2 + \sigma_i^2)^{0.5}$.

The results for the individual optimal pricing rules are not modified. The only difference is that the total uncertainty faced by the firm is σ instead of σ_i. The main qualitative difference is the behavior of the aggregate price level p. First, there is no inflationary steady state in the strict sense: even in the absence of adjustment costs, inflation would not be constant but would fluctuate stochastically around a constant level. A consequence of that for the adjustment cost model is that the distribution of price deviations will not be invariant but will fluctuate stochastically around the ergodic distribution. The latter is the long run probability distribution of an individual price deviation. Hence, in this context the ergodic distribution is not an invariant distribution of price deviations but the average distribution of price deviations. Thus, if we assume that the economy has been for a long time under a certain inflationary regime when stabilization is launched, we do not know what is the distribution of price deviations at this instant. In the simulations below we assume that the distribution of price deviations at this instant is the ergodic distribution: the average among all possible distributions taken according to their likelihood.

Figure 10 shows realizations for non-credible disinflation paths correspondent to different levels of aggregate uncertainty (see the Appendix D for simulation methodology). The case of no aggregate uncertainty was reported in section 3, and is reproduced here for the purpose of comparison. It is clear from the figure that the path for the inflation rate when there is aggregate uncertainty fluctuates around the path that would take place in its absence. Furthermore, the amplitude of the fluctuations increase with the level of aggregate uncertainty. Those qualitative features are repeated in the case of credible and imperfectly credible disinflations. Thus, aggregate uncertainty about the money supply does not matter for the average costs of disinflation, although it adds realism by generating a pattern for a typical disinflation path realization which is less smooth than the ones engendered by the model without aggregate uncertainty, and therefore, more similar to the ones observed in real world experiences.

7. Conclusion

We used a state-dependent model where pricing rules are optimal to examine the costs of a money based cold turkey disinflation under various assumptions about the credibility of the policy change. Although individual prices are sticky, disinflation can be attained almost without costs. The result depends crucially on the change of rules engendered by the policy change. If the disinflation is perfectly credible, the optimal pricing rule changes instantaneously after the new policy is announced. This effect virtually eliminates inflationary inertia, despite the microeconomic rigidities. However, if the degree of credibility of the monetary policy change is low, the model predicts that some inertia will occur. The mechanism by which inflationary inertia is generated in our model, for disinflations with low degree of credibility, justifies the worries of policy-makers with the alignment of prices when stabilization plans are launched: the large proportion of prices that are lagged with respect to their desired levels in an inflationary steady state are the ultimate cause for inflationary inertia in this context.

APPENDIX

A. The Ergodic Distribution

The density function of the ergodic distribution of price deviations has the following form (see Bertola and Caballero, 1990) :

$$f(z) = \begin{cases} Me^{\tau z} + N & L \leq z \leq c \\ Pe^{\tau z} + Q & c \leq z \leq U \\ 0 & otherwise \end{cases} \tag{A.1}$$

with $\tau = -2\pi/\sigma^2$.

Because the density should die continuously, it should be zero at the extremes, that is, $f(L) = 0 = f(U)$. These conditions yield the following equations :

$$\begin{aligned} Me^{\tau L} + N &= 0 \\ Pe^{\tau U} + Q &= 0 \end{aligned} \tag{A.2}$$

Continuity of the density function at c requires $\mathrm{f}(c)^+ = f(c)$, which results in

:

$$Me^{\tau c} + N = Pe^{\tau c} + Q \tag{A.3}$$

The fact that the integral of the density function over the appropriate range is one gives us a fourth equation :

$$\frac{M}{\tau}(e^{\tau c} - e^{\tau L}) + \frac{P}{\tau}(e^{\tau U} - e^{\tau c}) + N(c - L) + Q(U - c) = 1 \tag{A.4}$$

Equations A.2, A.3 and A.4 determine the constants M,N,P,Q in equation A.1.

B. Discretization and Dynamics

The discrete representation of equation 2.4 is (again, see Bertola and Caballero, 1990) :

$$p^*_{i,t+\Delta t} = \begin{cases} p^*_{i,t} + n & with\ probability\ p = \frac{1}{2}(1 + \frac{\pi\Delta t}{n}) \\ p^*_{i,t} - n & with\ probability\ p = \frac{1}{2}(1 - \frac{\pi\Delta t}{n}) \end{cases} \tag{B.1}$$

As long as $n = \sigma\sqrt{\Delta t}$as $\Delta t \to 0$, this process will converge to a Brownian motion with drift, as specified by equation 2.4. The price deviation is bounded in the interval $[L, U]$. The relevant state space for this deviation is :

$$Z = [L, L+n, ...c-n, c, c+n, ...U-n, U]$$

Let f_0 be the discretized distribution of price deviations associated with the inflationary steady state (the ergodic distribution). In the case of no credibility, this is the starting point for the simulations. The distribution if money growth is reduced to zero, for every $z \in (L, U)$, and different than c, is :

$$f_{0+\Delta t}(z) = \frac{1}{2} f_0(z-n) + \frac{1}{2} f_0(z+n) \tag{B.2}$$

Similarly, for $t > 0$, :

$$f_{t+\Delta t}(z) = \frac{1}{2} f_t(z-n) + \frac{1}{2} f_t(z+n) \tag{B.3}$$

For the barriers and return point, we have :

$$\begin{aligned} f_{t+\Delta t}(L) &= \frac{1}{2} f_t(L+n) \\ f_{t+\Delta t}(U) &= \frac{1}{2} f_t(U-n) \end{aligned} \tag{B.4}$$

$$f_{t+\Delta t}(c) = \frac{1}{2}f_t(c-n) + \frac{1}{2}f_t(c+n) + \frac{1}{2}f_t(L) + \frac{1}{2}f_t(U)$$

Then, the average price deviation at each point of time is :

$$z_t = \sum_{z\in[L,U]} f_t(z).z \tag{B.5}$$

Since the drift is zero, equation 2.9 implies :

$$p_{t+\Delta t} - p_t = z_{t+\Delta t} - z_t \tag{B.6}$$

This determines the inflation path after the policy change. In the cases of perfect and imperfect credibility, to be analyzed ahead, nothing changes. The only difference is that the distribution f_0 will reflect the instantaneous change in the pricing rule, as explained in the main text (section 4). We perform the same recursions as above, starting not from the ergodic distribution, but from the distribution that obtains after the instantaneous price changes are accounted for (such as figure 6).

C. Finding a Particular Solution for ODE 5.2

We appeal to intuition in guessing that the following function is a particular solution of 5.2, in the main text:

$$C_p(x_0) = \int_0^\infty \lambda e^{-\lambda T} \left\{ \int_0^T e^{-\rho s} E[x_s^2 \mid x_0, T] ds + e^{-\rho T} E[G(x_T) \mid x_0, T] \right\} dT \quad \text{(C.1)}$$

where x follows the stochastic process of z when there is no control, that is a driftless Brownian motion with diffusion parameter σ_i. The first term of the expression between curley brackets can be interpreted as the expected discounted flow cost of being away from the optimal from zero to T, while the second term is the discounted expected value when abandonment occurs. So, it is assumed that no control is exerted until T, when abandonment occurs, and that an optimal control policy is exerted from then on. Since the time of abandonment is stochastic, the expression between curley brackets is evaluated for each possible T and the result is weighted according to its density. Here, $\lambda e^{-\lambda T}$ is the probability density that the first jump occurs exactly at time T. The function G is the value function after abandonment, and its expression is given by equation 2.6 (with the constants and the policy parameters jointly determined by the VMC and SPC conditions for the rule after abandonment). Then, the conditional expectation of the value after abandonment, taken at time zero, is given by:

$$\begin{aligned}
E[G(x_T) \quad | \quad x_0, T] &= E[E[G(x_T) \mid x_0, x_T, T] \mid x_0, T] \\
&= E\left[Ae^{\alpha x_T} + Be^{\beta x_T} + \frac{x_T^2}{\rho} - \frac{2\pi x_T}{\rho^2} + \frac{\sigma_i^2}{\rho^2} + 2\frac{\pi^2}{\rho^3} \mid x_0, T\right] \qquad \text{(C.2)} \\
&= Ae^{\alpha x_0 + \alpha^2 \frac{\sigma_i^2}{2} T} + Be^{\beta x_0 + \beta^2 \frac{\sigma_i^2}{2} T} + \frac{x_0^2}{\rho} + \frac{\sigma_i^2 T}{\rho} - \frac{2\pi x_0}{\rho^2} + \frac{\sigma_i^2}{\rho^2} + 2\frac{\pi^2}{\rho^3}
\end{aligned}$$

where the first equality results from the law of iterated expectations, the second from the substitution of the value function when there is no uncertainty about the monetary policy, and the last one from taking expectations over x_T conditioned on x_0 and T.

By substituting the expression found in C.2 into C.1 and integrating the resulting expression we obtain the final expression for the particular solution of 5.2:

$$\begin{aligned}
C_p(z) \quad = \quad & \frac{\lambda A e^{\alpha z}}{\lambda + \rho - \alpha^2 \frac{\sigma_i^2}{2}} + \frac{\lambda B e^{\beta z}}{\lambda + \rho - \beta^2 \frac{\sigma_i^2}{2}} + \frac{z^2}{\rho} \\
& - \frac{2\lambda \pi z}{(\lambda + \rho)\rho^2} + \frac{\sigma_i^2}{\rho^2} + \frac{2\lambda \pi^2}{(\lambda + \rho)\, \rho^3} \qquad \text{(C.3)}
\end{aligned}$$

It is straightforward to verify that this particular solution satisfies 5.2. Observe also that the limits of this particular solution actually make sense:

$$\begin{aligned}\lim_{\lambda\to 0} C_p(z) &= \frac{z^2}{\rho} + \frac{\sigma_i^2}{\rho^2} \\ \lim_{\lambda\to\infty} C_p(z) &= G(z)\end{aligned}$$

When $\lambda = 0$, the zero inflation policy is totally credible because agents believe that it is going to last forever with probability one. Hence, our particular solution should entail the expected present value of the cost of being away from the optimal when there is no drift and no control. When $\lambda \to \infty$, the new policy is not credible, and agents believe that the old inflationary policy will be resumed immediately. Consequently, the proposed particular solution should be equal to the value function in the inflationary environment when optimal control is exerted.

D. Dynamics with Aggregate Uncertainty

As explained in the text, we assume that the distribution of price deviations at the moment of the policy change is the ergodic distribution. As the disinflation paths analyzed are non-credible, there are no changes in the barriers with the policy change. However, the presence of aggregate shocks alters the way this density changes with time. First of all, we need to establish if the economy is experiencing a positive or a negative aggregate shock. A simple randomization solves this problem. Since after stabilization the money supply has no drift, a positive or a negative aggregate shock is observer with probability 0.5.

For all z $\in (L, U)$, and different than c, we have :

$$f_{t+\Delta t}(z) = p^{-} f_t(z-n) + p^{+} f_t(z+n) \tag{D.1}$$

For the barriers and return point, we have :

$$\begin{aligned} f_{t+\Delta t}(L) &= p^{+} f_t(L+n) \\ f_{t+\Delta t}(U) &= p^{-} f_t(U-n) \\ f_{t+\Delta t}(c) &= p^{-} f_t(c-n) + p^{+} f_t(c+n) + p^{+} f_t(L) + p^{-} f_t(U) \end{aligned} \tag{D.2}$$

where

$$p^{+} = \begin{cases} \frac{1}{2}(1+\frac{\sigma_a}{\sigma}) \; \textit{if the aggregate shock is positive} \\ \frac{1}{2}(1-\frac{\sigma_a}{\sigma}) \; \textit{if the aggregate shock is negative} \end{cases}$$

and $p^{-} = 1 - p^{+}$. We refer to Bertola and Caballero (1990), for a more detailed exposition.

With this, equations B.5 and B.6 determine the inflationary path.

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Figure 1

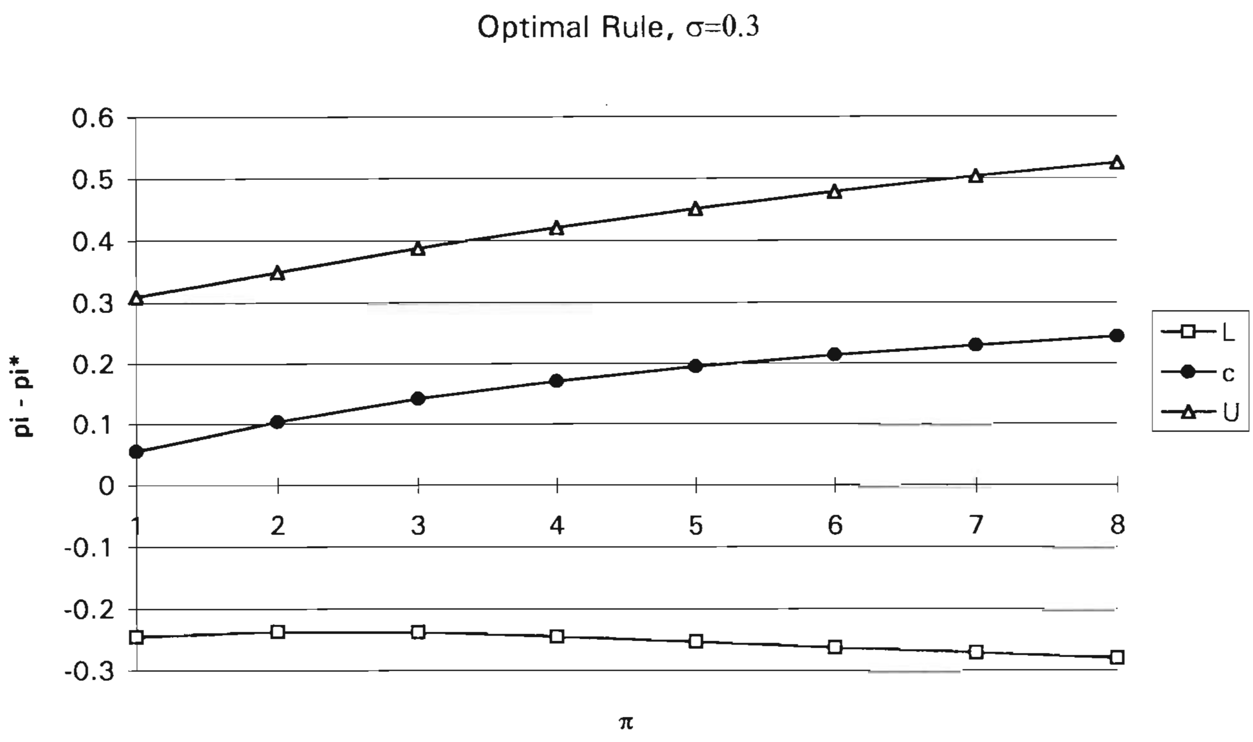
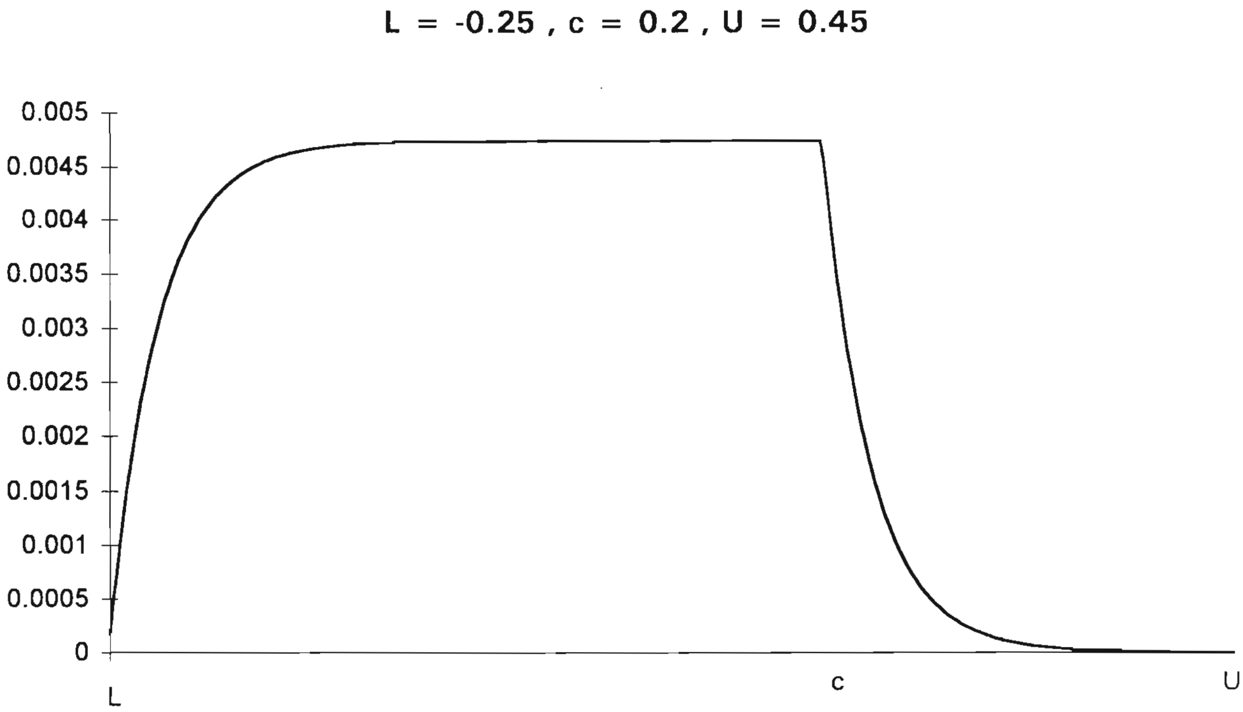

Optimal Rule, σ=0.3
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
pi - pi*
1
2
3
4
5
6
7
8
π
L
c
U

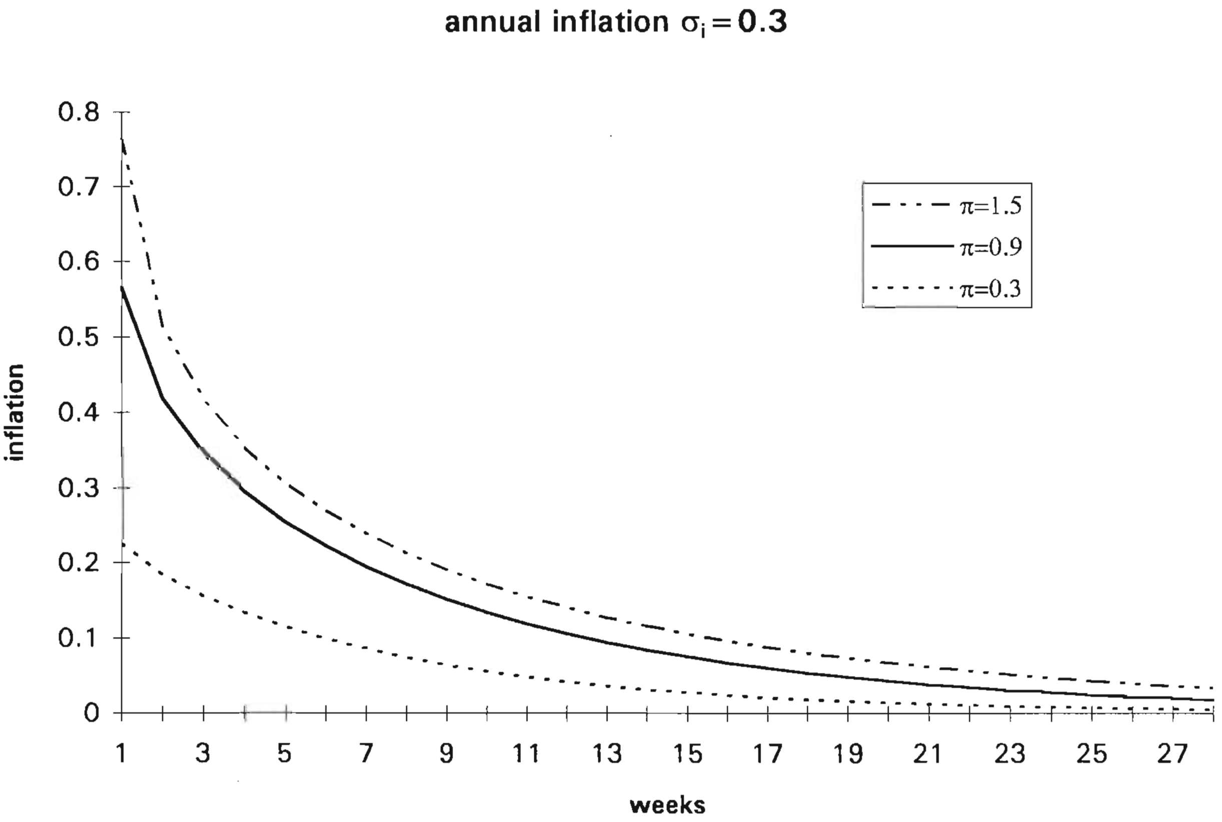
Figure 2

Figure 3



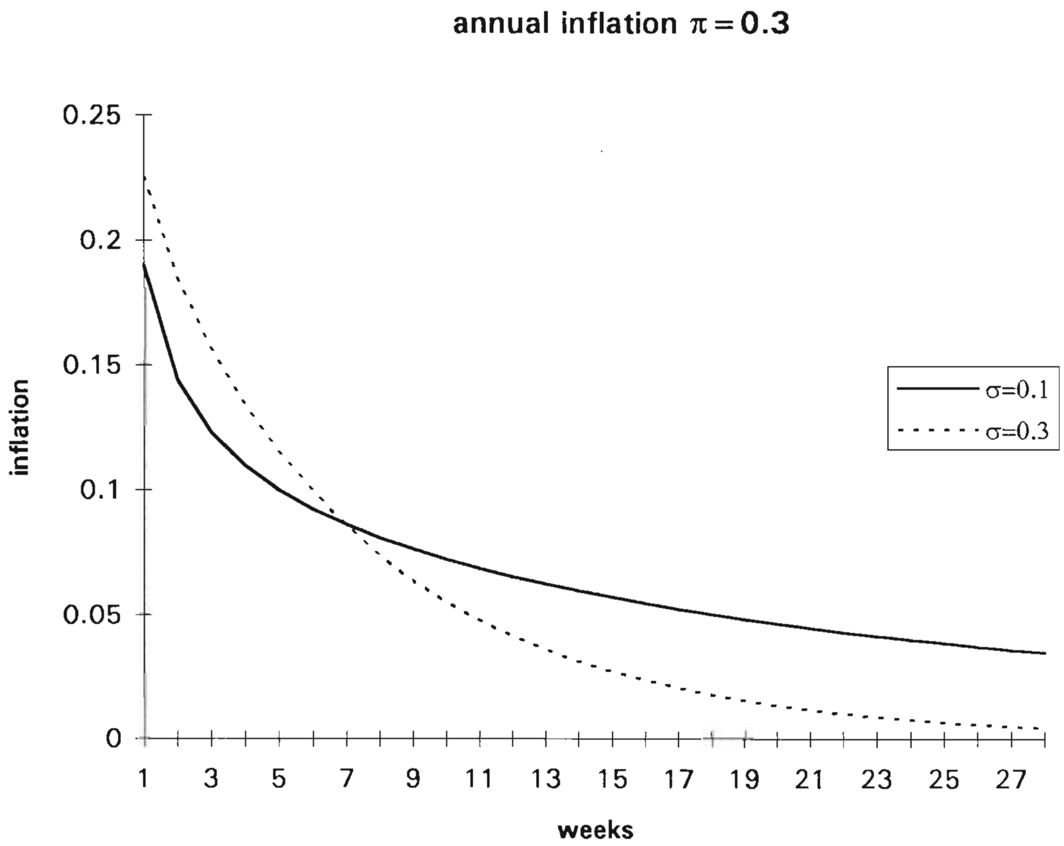
L = -0.25 , c = 0.2 , U = 0.45
0.005
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
L
c
U

Figure 4



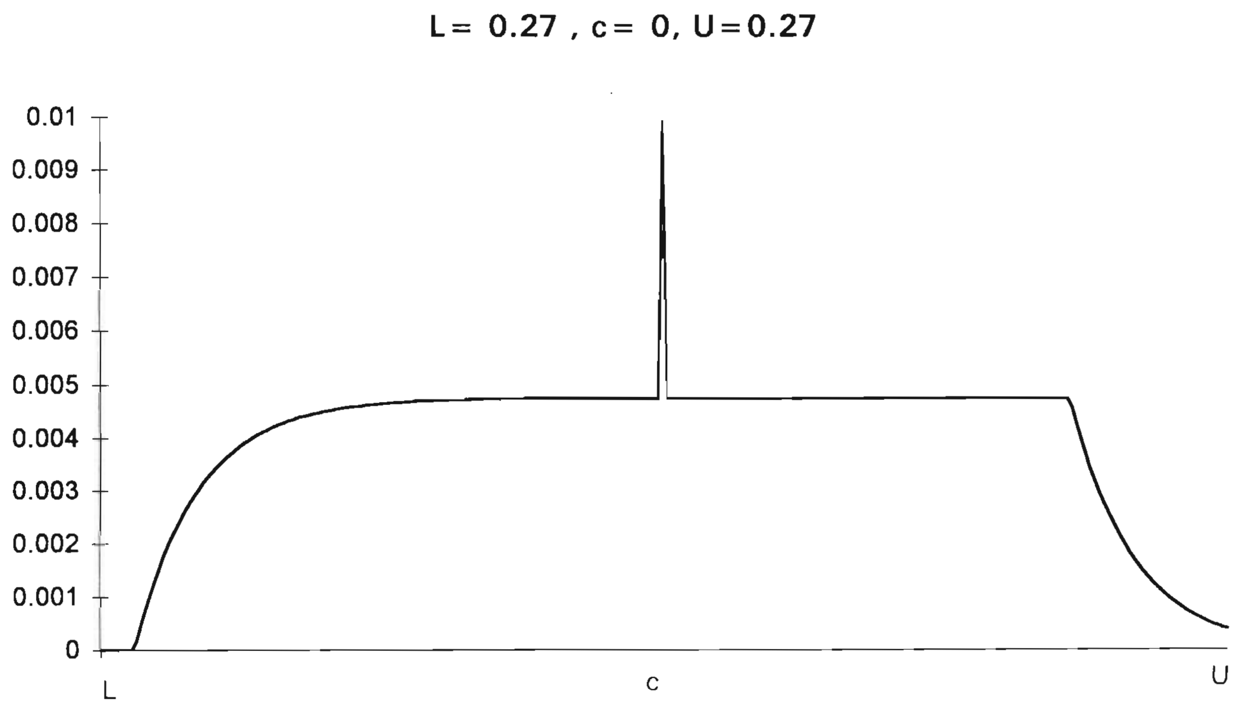
annual inflation $\sigma_i = 0.3$
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
inflation
π=1.5
π=0.9
π=0.3
1
3
5
7
9
11
13
15
17
19
21
23
25
27
weeks

Figure 5



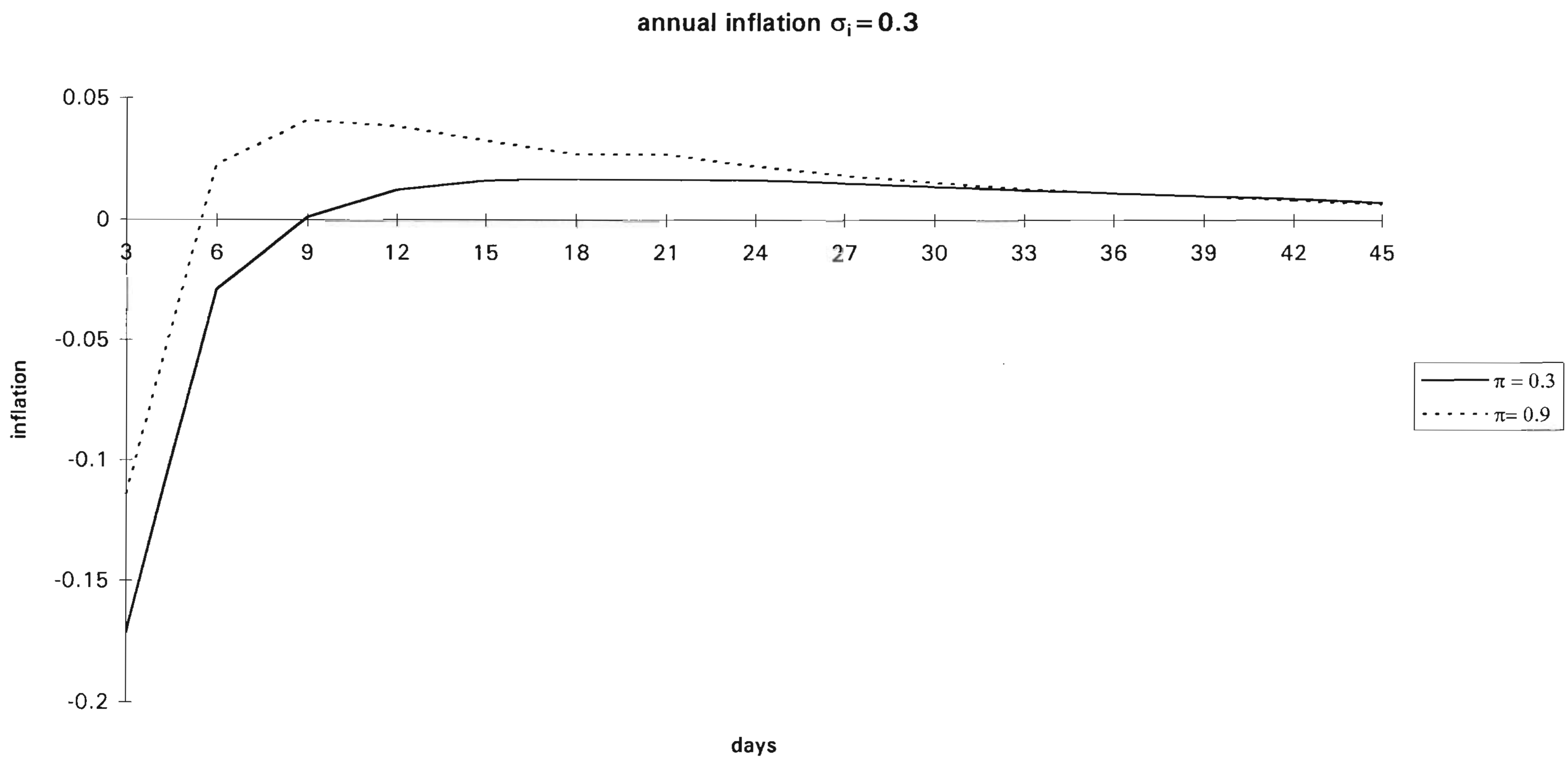
annual inflation $\pi = 0.3$
0.25
0.2
0.15
0.1
0.05
0
inflation
1
3
5
7
9
11
13
15
17
19
21
23
25
27
weeks
σ=0.1
σ=0.3

Figure 6



L= 0.27 , c= 0, U=0.27
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
L
c
U

Figure 7



annual inflation σi = 0.3
0.05
0
-0.05
-0.1
-0.15
-0.2
inflation
3
6
9
12
15
18
21
24
27
30
33
36
39
42
45
days
π = 0.3
π= 0.9

Figure 8

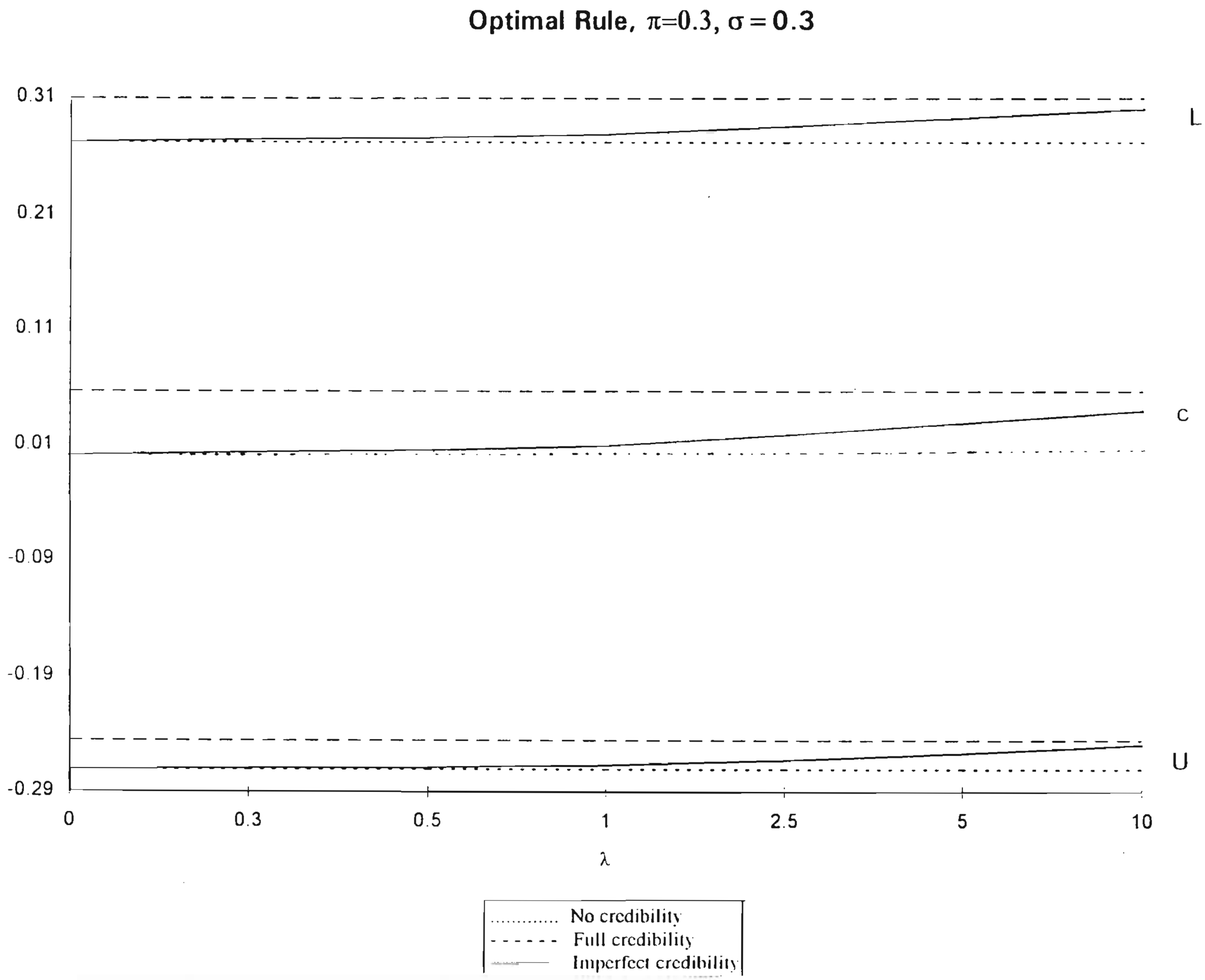

Optimal Rule, π=0.3, σ = 0.3
0.31
0.21
0.11
0.01
-0.09
-0.19
-0.29
0
0.3
0.5
1
2.5
5
10
λ
L
c
U
No credibility
Full credibility
Imperfect credibility

Figure 9

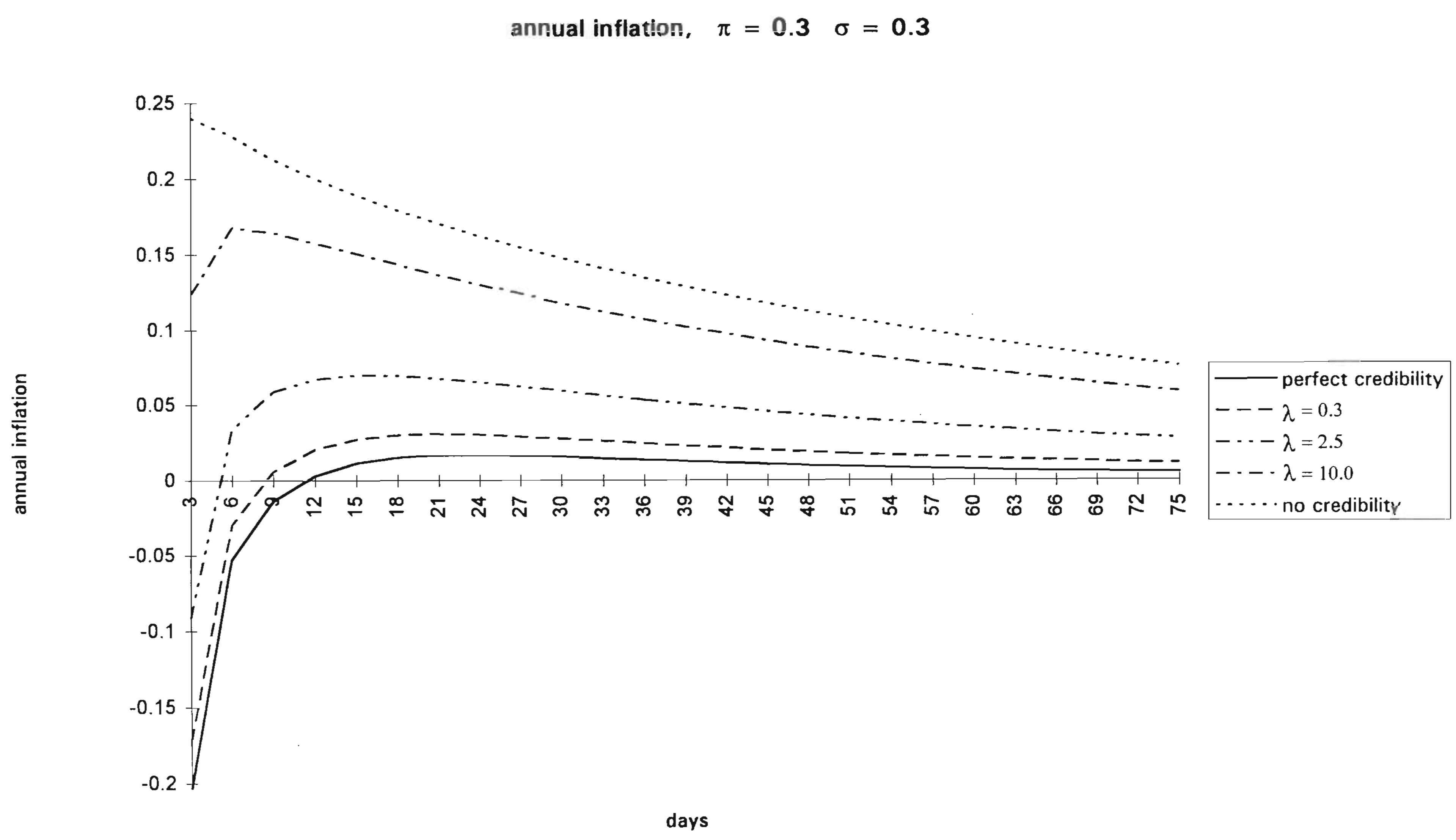
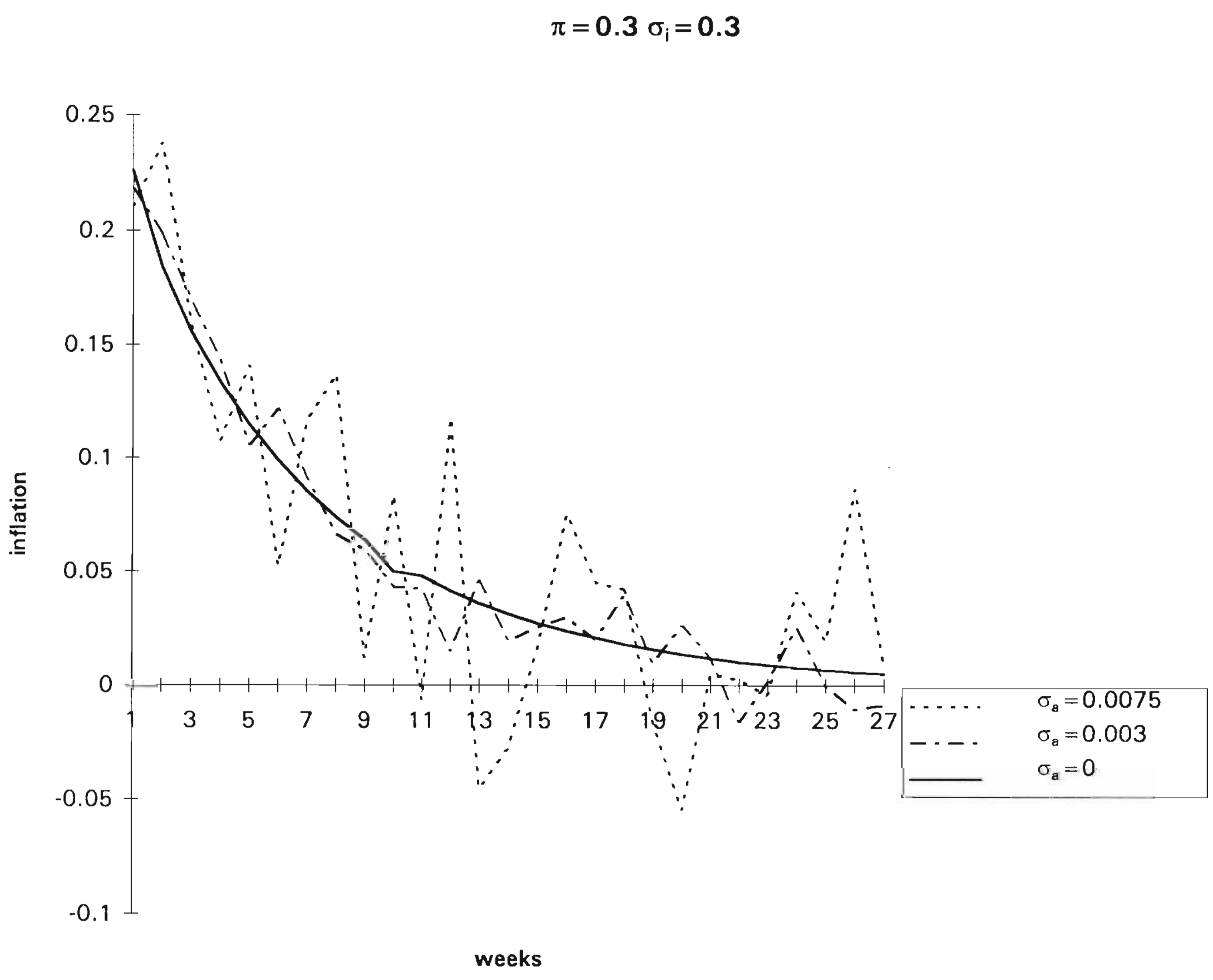

annual inflation, π = 0.3 σ = 0.3
annual inflation
days
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
3 6 9 12 15 18 21 24 27 30 33 36 39 42 45 48 51 54 57 60 63 66 69 72 75
perfect credibility
λ = 0.3
λ = 2.5
λ = 10.0
no credibility

Figure 10



$\pi = 0.3\ \sigma_i = 0.3$
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
inflation
1 3 5 7 9 11 13 15 17 19 21 23 25 27
weeks
$\sigma_a = 0.0075$
$\sigma_a = 0.003$
$\sigma_a = 0$

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