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Staggered prices and trend inflation: some nuisances

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Suomen Pankki
Bank of Finland
P.O.Box 160
FIN-00101 HELSINKI
Finland
☎ + 358 9 1831

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* Department of Economics and Quantitative Methods, University of Pavia, Via San Felice 5, 27100 Italy. Tel. +39-382-606211, Fax +39-382-304226, E-mail: gascari@eco.unipv.it.

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Staggered prices and trend inflation: some nuisances

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Abstract

Most of the papers in the sticky-price literature are based on a log-linearization around the zero inflation steady state, a simplifying but counterfactual assumption. This paper shows that when trend inflation is considered, both the long-run and the short-run properties of DGE models based on the Calvo staggered price model change dramatically. It follows that results obtained by models log-linearized around a zero inflation steady state are quite misleading. Furthermore, the same is not true for models based on the Taylor staggered price model, which is robust to changes in trend inflation. As a conclusion, the Taylor model is to be preferred, unless one is willing to index nominal variables.

Key words: inflation, staggered price/wages

JEL classification numbers: E24, E32

Hintajäykkyydet ja inflaatiotrendi: eräitä kiusoja

Suomen Pankin keskustelualoitteita 27/2003

Guido Ascari
Tutkimusosasto

Tiivistelmä

Useimmat hintajäykkyyksiä koskevat tutkimukset perustuvat malliin, joka on log-linearisoitu nollainflaation ympärillä. Oletus, että inflaation vaihtelut tapahtuvat nollan ympärillä, yksinkertaistaa analyysiä, mutta on epärealistinen. Tässä tutkimuksessa osoitetaan, että jos inflaatiotrendi otetaan huomioon, Calvo-sopimuksiin perustuvien dynaamisten yleisen tasapainon mallien ominaisuudet muuttuvat dramaattisesti. Siksi tulokset, jotka on johdettu nollan ympärillä linearisoiduista malleista, ovat varsin harhaanjohtavia. Lisäksi osoitetaan, että näitä ongelmia ei synny malleissa, jotka perustuvat limittäisiin Taylor-sopimuksiin, koska Taylor-malli on immuuni inflaatiotrendin muutoksille. Johtopäätöksenä on, että Taylor-mallia on pidettävä parempana kuin Calvo-mallia, paitsi indeksoitujen nimellismuuttujien tapauksessa.

Avainsanat: inflaatio, hintajäykkyydet, palkkajäykkyydet

JEL-luokittelu: E24, E32

Contents

1 Introduction

"Macroeconomics is moving toward a *New Neoclassical Synthesis*" (Goodfriend and King, p. 231). "Building on new classical macroeconomics and RBC analysis, it incorporates intertemporal optimization and rational expectations [...]. Building on New Keynesian economics, it incorporates imperfect competition and costly price adjustment [...]" (Goodfriend and King, p. 255). Judging from the amount of recent papers on dynamic general equilibrium models of sticky prices, mainly time dependent staggered prices, the moving seems to be completed.[1] Two main models of price adjustment are employed in the literature: one refers to Calvo (1983) and the other to Taylor (1980), the former being by far the most widely used in the literature for reasons of tractability. Given the aim to build quantitative models of economic fluctuations, models are simulated and then, following the RBC tradition, compared with actual data.

Many, if not most, of the works in the literature log-linearize their model around a particular steady state: the zero inflation steady state.[2] This is again due to reasons of simplicity, given that in actual data trend inflation in the developed world in the last thirty years have been quite different from zero. The average inflation rates from the seventies onwards in major European countries has ranged from approximately 3% in Germany to almost 10% in Spain, with the US around 5%.[3] It is obvious that a time-dependent sticky-price framework is ill-suited for describing economies with very high rates of inflation, because in such an environment the sticky price assumption is unreasonable.[4] On the contrary, post world war II data in developed economies show positive, but low levels of average inflation and thus the New Neoclassical Synthesis framework is applied to describe those data. The implicit assumption then must be that taking into account *low levels* of trend inflation would not matter anyway, because it would have a negligible effect both on the steady state (around which the model is log-linearized) and on the dynamic properties of the model.

This paper investigates this implicit assumption. First, it shows that it is actually invalid. It does so by analyzing a standard sticky-price dynamic general equilibrium model with the Calvo (1983) specification, which is the most commonly employed in the literature. The structure is otherwise taken from the well-known paper by Chari et al (2000). It also analyses the case in which capital is treated as fixed (another common assumption in this literature, following an argument put forward by McCallum and Nelson (1999)). It turns

[1] This new workhorse model has been extensively used to investigate various issues: persistence (eg, Jeanne (1998), Chari et al (2000), Ascari (2000)), monetary policy rule (eg, Rotemberg and Woodford (1997), Clarida et al (1999), Woodford (2003)), inflation dynamics (eg, Gali and Gertler (1999)) and open economy (eg, Chari et al (2002), Kollman (2001)).

[2] Some exceptions are King and Wolman (1996), Ireland (1997), Dotsey et al (1999), Ascari (2000) and Chari et al (2002).

[3] Using the Bureau of Labor Statistics data, in the Gali and Gertler (1999) sample (1960:01–1997:04), the average inflation rate in the US is 4,5%, .

[4] Therefore, it would be pointless to show that for high average inflation rates time-dependent sticky price models deliver counterfactual results.

out that when trend inflation is considered, both the long-run (ie, steady state) and the short-run (ie, dynamics) properties of the Calvo time-dependent staggered price models change dramatically. First, using standard calibration values from the literature, it is shown that the steady state output level is very much sensitive to the steady state rate of growth of money. Very mild levels of trend inflation imply large, and unrealistic, changes in the steady state output level. Second, consequently trend inflation matters for the dynamic properties of the log-linearized model. Indeed, the dynamics of the log-linearized model depend on the particular steady state around which it has been log-linearized. Since steady state differs a lot depending on the level of trend inflation, it comes as no surprise that trend inflation matters for the dynamics of the log-linearized model. Finally, early old-fashioned sticky-price models have been extensively used to address a very important topic: disinflation (see, eg, Blanchard and Fischer, ch. 10). Again, the level of trend inflation from which the disinflation policy starts is extremely important for the dynamic behavior of the model following a disinflation. In sum, this paper shows that disregarding trend inflation is quite far from being an innocuous assumption. As a consequence, the results obtained by models log-linearized around a zero inflation steady state are misleading.[5]

Second, the paper also investigates the properties of the Taylor staggering model.[6] It is shown that Taylor-type model does not suffer of any of the problems mentioned above. The steady state changes very little with trend inflation and so do the dynamics. Given that inflation targets are non-zero and have changed over time, it follows that one should use the Taylor model to fit the data rather than the Calvo model, since the latter is not robust to changes in trend inflation.

This paper can therefore also be interpreted as an investigation into the robustness of time-dependent (Calvo and Taylor) staggered price specifications with respect to positive trend inflation. As such the paper is quite related to two important recent contributions comparing the Taylor and Calvo specification. Kiley (2002) shows that, in contrast from common perception in the literature, the Taylor and Calvo models deliver very different dynamics. In the Calvo model, in fact, some price-setters do not adjust prices for many periods more that the average frequency of price adjustment, leading to an higher dispersion of prices and a more sluggish responses to a money shock.[7] Building on this result, Wolman (1999) modifies two implausible features of the Calvo model by assuming that: (i) the probability of price adjustment is increasing in time-since-last-adjustment; (ii) no firms keep price fixed for more than 8 quarters. Wolman (1999) then shows that the resulting dynamic behavior is fundamentally different from the original Calvo model, and concludes that the "Calvo model is an extreme special case, not just a

[5] The issue of trend inflation has not been really tackled so far in the literature. Only very few papers mention it, namely King and Wolman (1996) and Ascari (1998). Both papers, however, look mainly at the effects of trend inflation on the steady state. This paper will consider their results in what follows.

[6] I thank both referees for suggesting me to do this comparison.

[7] Note that actually, these price setters are producing relatively more output than other firms, since they have lower prices.

convenient simplification" (p. 43). This paper shows another problem with the Calvo model that does not seem to arise in the Taylor pricing framework, regarding robustness to trend inflation. Taking together the basic message of these papers is that while the Calvo model can be a very convenient model of price staggering for some specific questions, the Taylor one should be preferred in DGE models of the *New Neoclassical Synthesis.*[8]

2 The model

The model is meant to be the most standard sticky price dynamic general equilibrium model. Thus I will use the Calvo (1983) and Rotemberg (1982) sticky price specification, which is the most commonly employed in the literature, within the quite general model structure of the well-known paper by Chari et al (2000).[9] The model economy is therefore composed of a continuum of infinitely-lived consumers, producers of final and intermediate goods. The final goods market is competitive, while the intermediate goods producers enjoy market power. The model is so familiar by now that it does not need any detailed explanation (see Appendix 1 for the details). The functional forms are also standard:

Instantaneous utility function	$\left\{\left[bC^{\frac{\eta-1}{\eta}}+(1-b)\left(\frac{M}{P}\right)^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}}(1-L)^{e}\right\}^{1-\chi}/(1-\chi)$
Production function of intermediate goods producers	$Y_i = AK_i^{1-\sigma}L_i^{\sigma}$
Production function of final goods producers	$Y = \left[\int Y_i^{\frac{\theta-1}{\theta}}\right]^{\frac{\theta}{\theta-1}}$

where C = consumption, M = money, P = price of the final good, Y_i = output of the intermediate good producer i, K_i, L_i = capital and labor employed by the intermediate good producer i, Y = final good output. The utility function, same as Chari et al (2000), is chosen because of its generality, encompassing most of the utility functions employed in the literature on sticky price models.

Moreover: (i) intermediate goods producers behave as Dixit-Stiglitz monopolistic competitors because they are facing a downward sloping factor demand from final good producers, with elasticity equal to θ; (ii) they can change their price only in specific states of nature, and have to satisfy demand at the quoted price. The state of nature in which the firm can change its price will occur with probability $1-\alpha$, while with probability α the firm is stuck

[8] See also Dotsey (2002).

[9] Chari et al (2000) employs instead the Taylor type specification.

with the same price of the previous period. The problem of the intermediate goods producers can be defined as

$$\underset{\{P_{it}\}}{Max} \qquad E_t \left(\sum_{j=0}^{\infty} \alpha^j \Delta_{t,t+j} \digamma_{t+j} \right) \tag{2.1}$$
$$= E_t \left(\sum_{j=0}^{\infty} \alpha^j \Delta_{t,t+j} \left[\left(\frac{P_{i,t}}{P_{t+j}} \right) Y_{i,t+j} - TC_{i,t+j}(Y_{i,t+j}) \right] \right)$$

where $\Delta_{t,t+j}$ represents the real discount factor from t to $t+j$ applied by the firm to the stream of future real profits; $\digamma$ = real profits, P_i = price set by the firm, TC_i = real total costs. Given the demand function, $Y_{i,t+j} = \left(\frac{P_{i,t}}{P_{t+j}}\right)^{-\theta} Y_{t+j}$, the optimal price fixed by re-setting firms in period t is given by

$$P_{i,t}^{*} = \left(\frac{\theta}{\theta - 1} \right) \frac{E_t \sum_{j=0}^{\infty} \alpha^j \Delta_{t,t+j} MC_{i,t+j} P_{t+j}^{\theta} Y_{t+j}}{E_t \sum_{j=0}^{\infty} \alpha^j \Delta_{t,t+j} P_{t+j}^{\theta-1} Y_{t+j}} \tag{2.2}$$

where MC_i = real marginal cost of producer i. This equation represents the core of sticky price models, as thoroughly explained by King and Wolman (1996).

Finally, following an argument put forward by McCallum and Nelson (1999), the case where capital is a fixed factor in the production function of intermediate goods producers (eg, Rotemberg and Woodford) is also considered.

3 Trend inflation and steady state

In this section I perform an exercise similar to that of King and Wolman (1996); that is, I look at the effects of trend inflation on the steady state. While King and Wolman (1996) concentrated on the mark-up, I will focus on the effects on steady state output.

Assume that γ is the gross rate of growth of money in steady state: that is, $\gamma = \frac{M_t}{M_{t-1}}$, $\forall t$. The steady state is then characterized by the constancy of the real variables and by a rate of growth of the nominal variables equal to γ. There is broad agreement in the literature on the calibration values of most of the parameters. Calibrating a period as a quarter, α is thus set to 0.75, which implies that prices are on average fixed for one year. As in Chari et al (2000) θ is set to 10 (implying a mark-up of 1.1, in a zero-inflation steady state). The parameters for the money demand equation are taken from Chari et al (2000)[10], so $\eta = 0.39$ and b is set so that the ratio $(M/PC) = 1.2$. Then: $\beta = (0.965)^{1/4}, \sigma = 0.67$ and the depreciation rate $\delta = 1 - (0.92)^{1/4}$. The value of e, instead, varies across papers, ranging from a value of 1 to values more in line with the microeconomic estimates as 6. e is set equal to 1.5, again as

[10] Given that I employ the same utility function as Chari et al (2000), then I have the same money demand function.

in Chari et al (2000).[11] With these numbers, in a zero-inflation steady state (ZISS henceforth) the model presents an annualized capital-output ratio of 2.5 and an investment-output ratio of 0.2, while households enjoy two-thirds of their total endowment of time as leisure.

The steady state value of the optimal price set each period by the re-setting firms is

$$\frac{P_{i,t}}{P_t} = \left(\frac{\theta}{\theta - 1}\right)\left(\frac{1 - \alpha\beta\gamma^{\theta-1}}{1 - \alpha\beta\gamma^{\theta}}\right) MC \tag{3.1}$$

First, there is a maximum rate of growth of money supported by the steady state, because to get (3.1) the summations in (2.2) need to converge.[12] Hence it must be that $\alpha\beta\gamma^{\theta} < 1$; that is, trend inflation should be less than 12,6% annually. Unfortunately, this threshold number is not too far from the level of average inflation in the developed countries in the last thirty or forty years. Therefore, this first remark gives a first warning nuisance, since one wants to use these models to describe the behavior of inflation in post-war data.

Second, trend inflation has amazingly big effect on steady state output. Figure 1 plots the percentage deviation of steady state output from output in a ZISS, as a function of the rate of growth of money (annualized in the graph). Steady state output decreases strongly with inflation. A steady state annual rate of inflation of 10% leads to a steady state output level 26% lower than in a ZISS. 8% trend inflation lowers output by 10% (with respect to ZISS) and 5% ($\simeq$ average inflation in the US in the last forty years) by almost 3%. It is important to underline instead that the capital/output ratio, the investment/output ratio and the steady state fraction of time devoted to work do not change very much with trend inflation.[13] Hence, by calibrating the model one would not change the parameters' values.

Third, as mentioned above, following McCallum and Nelson (1999), capital is often treated as fixed (eg, Rotemberg and Woodford (1997)). In this case, the steady state properties of such a model are even more disturbing. First, the maximum sustainable level of steady state inflation is now only 8% (because the marginal costs are now increasing depending on σ, see Appendix A1A). Second, the steady state output level again seems to be very sensitive to steady state inflation, as shown by Figure 2. In particular, for example, 5% trend inflation lowers output by 11.5% with respect to the ZISS, while 7% trend inflation cause output to be 39% lower than in a ZISS. There is actually a sort of 'continuity' between the two Figures, in the sense that as the value of σ increases, Figure 2 'tends' to Figure 1, as shown in Figure 3. If $\sigma = 1$, the behavior of steady state output as a function of trend inflation is then similar to the case with capital. In other words, increasing σ stretches out Figure 2, by pulling the asymptote (ie, maximum level of sustainable trend inflation) to the right.

[11] In any case, surprisingly enough, given the attention devoted to the parameter governing the elasticity of labor supply in the literature, all the presented results are very little sensitive to changes in the value of e. Moreover, note that the values of the variables in steady state do not depend on the value of χ.

[12] This point has already been acknowledged by King and Wolman (1996): see footnote 12 at p. 96.

[13] Except when trend inflation gets very close to its limiting upper value.

Admittedly, the results are somewhat sensitive to the value of θ. Similarly to the increase in σ in the previous Figure, a lower value of θ implies a higher value of sustainable trend inflation; which in turn basically stretches out Figures 1 and 2, by shifting the vertical asymptote to the right (see Figure 4). For example, if $\theta = 4.3$, as in King and Wolman (1996), the maximum level of sustainable trend inflation is 32% and 19% in the model with capital and in the model with fixed capital respectively. In this case, 10% trend inflation would lower steady state output by 4% and 8% with respect to the ZISS, in the two different models respectively. In any case, most of the papers in the literature use values of θ between 10 and 6, because $\theta = 4.3$ seems to result in an implausibly high level of mark-up in a ZISS (ie, 30%; see Rotemberg and Woodford (1997)).[14]

These results actually are quite astonishing for their magnitude. The intuition behind them is however straightforward and somewhat already mentioned in the literature in the context of some versions of the Taylor specification (see, in particular Ireland (1995) and Ascari (1998)). In a ZISS of a time-dependent fixed price staggering model, there is only one price and all the firms charge that price. It follows that all of them are producing the same level of output. If there is some trend inflation, however, in each period firms have different prices in steady state and they produce different levels of output, according to their relative prices. Due to the usual non-linearities in the utility and production function, then, this causes an aggregate output loss. Hence, not surprisingly: (i) the higher θ, the higher the effect of relative prices on firms' output levels, and the higher the output loss; (ii) the lower σ, the higher the decreasing returns to scale and the higher the output loss.[15] In the Calvo model price dispersion is higher than in the Taylor model (see Kiley (2002)) so it is natural to expect a bigger output loss. What is surprising, it is the magnitude of this loss for standard model structure and calibration values.

To conclude, trend inflation has huge effects on the steady state properties of the model. The numbers above would imply enormous costs of inflation in terms of loss in output. Moreover, the steady state properties of a sticky price model are also different depending on whether capital is treated as fixed or not. In any case, these properties are particularly embarrassing for anyone willing to use these models to analyze important facts as disinflations (see 4.2).[16]

[14] Also the behavior of the mark-up, on which King and Wolman (1996) focuses the analysis, is similarly very sensitive to trend inflation when $\theta = 10$. The steady state formula for marginal and average mark up are the same as in King and Wolman (1996) (in particular, see equations (18) at p. 92 and (19) at p. 93 therein), because of the same Calvo pricing framework. King and Wolman (1996) overlooks the magnitude of the effect of trend inflation because of considering only values of $\theta \leq 4.3$.

[15] Not surprisingly the loss is also bigger in a model with strategic complementarity, which amplifies the non-linearities (see Bakhshi et al (2002)).

[16] This might be the reason why virtually no sticky price model has been devoted to such an issue, with the exception of some stylized models (ie, Dazinger (1988), Ireland (1995), Ascari and Rankin (2002)).

4 Trend inflation and dynamics

4.1 Log-linearization

Usually dynamic general equilibrium models are solved by log-linearizing the models around a steady state. However, we saw in the previous section that different levels of trend inflation lead to very different steady states. In general, then, the coefficients of the log-linearized equations would also depend on the steady state level of inflation. Thus, an immediate and uncomfortable implication of the previous section is that the steady state around which one log-linearizes should matter. Indeed it does.

To analyze how the dynamics of the model depend on trend inflation, the case with fixed capital and $\sigma = 1$ is examined. First, I set $\chi = 1$, as in Chari et al (2000) and because log-utility is widely used in the literature. In Figure 5, I plot the impulse responses of output to a 1% rate of money growth shock, at different levels of trend inflation.[17] When trend inflation is zero, the model has only real roots. Output jumps on impact and then returns gradually to steady state level. Turning the steady state rate of growth of money to positive values very soon results in complex roots. As shown in Figure 5, the oscillation in the impulse responses typically induced by complex roots become more and more pronounced as trend inflation increases. In particular, a recession starts to appear after some quarters and it becomes longer and deeper as trend inflation increases. As a result, the effect of the money shock persists for quite a long time.

Moving away from log-utility, ie, $\chi = 1$, the model becomes even more sensitive to changes in trend inflation. Figures 6a, b, and c show the same impulse responses as Figure 5 for $\chi = 5$.[18] The oscillations now becomes extremely pronounced even for very low values of trend inflation. The impulse responses for a ZISS, a 5% or a 7,5% trend inflation are very much different both qualitatively and quantitatively. Moreover, as the value of trend inflation gets closer to the upper limit some puzzling features occur: (i) the size of the short-run effect becomes substantially larger; (ii) the impact effect of a positive money shock becomes negative (see Figure 6c); (iii) the model does not satisfy the Blanchard-Kahn conditions anymore and starts to produce explosive behavior, by generating a number of explosive roots bigger than the number of non-predetermined variables.[19] Therefore, it seems that not only the steady state, but also the dynamic properties of the standard model are very sensitive to the value of trend inflation.[20]

[17] The process for the rate of growth of money supply used in these simulations is again taken from Chari et al (2000). Its autocorrelation term is 0.57.

[18] This is the value used in the NBER w.p. version of Chari et al (2000). The results of Figure 6, however, qualitatively hold even for lower value of χ, that is, as soon as we depart from log-utility.

[19] For $\chi = 5$ the explosive behavior starts for 11,25% annual trend inflation; for log-utility the stable roots increase monotonically with trend inflation, get very much close to one, but never cross the unit circle for admissible values of trend inflation.

[20] Both the cases with varying capital and with fixed capital and $\sigma = 0.67$ present similar qualitative features, and thus are not reported. In the case with $\sigma = 0.67$, the puzzling features begin to appear at very low levels of inflation, because the upper bound is only 8%.

Given the so strange behavior, it is not easy to provide an intuition. Again as in Kiley (2002), I think the problem lies in the particular kind of aggregation the Calvo model implies. The key equation is the one that relates employment with aggregate output (see (A.31) in Appendix A):

$$L_t = \left[\int_0^1 L_{i,t}di\right] = \left[\frac{Y_t}{A_t}\right]^{\frac{1}{\sigma}} \left[\frac{P_t}{\overline{P}_t}\right]^{\frac{\theta}{\sigma}} \tag{4.1}$$

where $\overline{P}_t = \left[\int_0^1 P_{i,t}^{-\frac{\theta}{\sigma}}di\right]^{-\frac{\sigma}{\theta}}$. P_t and $\overline{P}_t$ are two different aggregators. When they are equal, then there is a simple relationship between aggregate labor and aggregate output: $L_t = \left[\frac{Y_t}{A_t}\right]^{\frac{1}{\sigma}}$. Then L and Y move closely together. Even a slight difference between P_t and $\overline{P}_t$, however, has a big impact on the dynamics of L, given Y, since the elasticity is (θ/σ). Indeed, the higher the value of θ, and the lower the value of σ, the more a difference in the dynamics of P_t and $\overline{P}_t$ causes a wedge in the dynamics of L and Y. Now, in a ZISS, P_t and $\overline{P}_t$ coincide and, besides, they have the same dynamics in the log-linear model. Hence, log-linearizing around a ZISS P_t and $\overline{P}_t$ basically are the same variable. When there is trend inflation, however, they start to differ both in steady state values and in the log-linearized dynamics. *Ceteris paribus*, this simply implies that the higher trend inflation, the more the dynamics of L and of Y are different. Now, with log-utility the behavior of L does not enter the Euler equation, since consumption and leisure are separable. An exploration of the impulse responses for these variables in the exercise related to Figure 5 shows that actually L reacts much more than Y. When the utility function is not separable, however, the dynamics of L and Y are quite tightly linked also through the Euler equation. For positive values of trend inflation, a tension between equation (4.1) and the Euler equation arises: the former equation would imply a different behavior between L and Y, the latter not.[21] Not that the higher θ, and the lower σ, the worse the tension. The way to reconcile the two equations is by reducing the gap between p_t and $\overline{p}_t$, where lower-case letters stand for the log-deviation of variables from their steady state values. This can be done only by a very big jump in the resetted price, p_{it}, which indeed reacts much more for high rates of inflation. Note that in the extreme case, ie, Figure 6c, the jump in the newly resetted price p_{it} is so big that p_t overshoots immediately causing a slump on impact.

It is important to stress that the source of this bizarre behavior is thus the particular kind of aggregation involved in the assumptions of Calvo model. There are many different prices and, trend inflation increases price dispersion. Then, the model implies that some firms (with relative low prices fixed very far in the past) would face an high demand and produce a lot, while others (with relative high prices fixed recently) would face a low demand and produce a little. Given the non linearity of the Dixit-Stiglitz production (consumption)

[21] On the contrary, in a ZISS with $\chi = 5$, the dynamics of the log-linear model do not change much with respect to the same case in Figure 5, since in a ZISS P_t and $\overline{P}_t$ basically are the same variable. The only effect of a higher value of χ is a natural dampening of the response due to the increase in the concavity of the utility function.

basket, it would need a higher level of employment to produce (consume) one unit of that basket.

Analytical investigation sheds also some light on the high sensitivity of the pricing equation to trend inflation, and the implication for the so-called New Keynesian Phillips curve. Start with the well-known case where the log-linearization is taken around the steady state with zero inflation (ie, $\gamma = 1$). Define $\Pi_t = (P_t/P_{t-1})$ = gross inflation rate. The log-linearized version of (2.2) is

$$p_{it} - p_t = (1-\alpha\beta)E_t \sum_{j=0}^{\infty} (\alpha\beta)^j \left[\pi_{t,t+j} + mc_{t+j}\right] \tag{4.2}$$

where $\pi_{t,t+j} = (\pi_{t+1} + \pi_{t+2} + ... + \pi_{t+j})$ and $\pi_{t,t} = 0$. This equation is usually combined with the log-linearized version of the general price level equation (see equation (A.11) in Appendix A)

$$p_{it} - p_t = \frac{\alpha}{1-\alpha}\pi_t \tag{4.3}$$

in order to get the dynamics of inflation

$$\pi_t = \lambda mc_t + \beta E_t \pi_{t+1} \tag{4.4}$$

where $\lambda = \frac{(1-\alpha)(1-\alpha\beta)}{\alpha}$. As explained by Gali and Gertler (1999), among others, this is the so-called 'New Keynesian Phillips Curve'.[22] In other words, the inflation rate today depends just on the discounted sum of the future expected marginal costs, as can be easily found by iterating (4.4) forward

$$\pi_t = \lambda \sum_{j=0}^{\infty} \beta^j E_t mc_{t+j} \tag{4.5}$$

From a theoretical perspective, for a given expected future path of the marginal costs, the key parameter in the dynamics of inflation is therefore λ.

Again things are a bit different, however, when the log-linearization is taken around a steady state with trend inflation (ie, $\gamma > 1$), since (2.2) becomes

$$\begin{aligned} p_{it} - p_t \;=\; & E_t \sum_{j=0}^{\infty} (\alpha\beta\gamma^{\theta})^j (1-\alpha\beta\gamma^{\theta}) \left[\theta\pi_{t,t+j} + y_{t+j} + mc_{t+j}\right] \\ & - E_t \sum_{j=0}^{\infty} (\alpha\beta\gamma^{(\theta-1)})^j (1-\alpha\beta\gamma^{(\theta-1)}) \left[(\theta-1)\pi_{t,t+j} + y_{t+j}\right] \end{aligned} \tag{4.6}$$

Combining this last equation with the log-linearized formula for the general price level, that is,

$$p_{it} - p_t = \frac{\alpha\gamma^{\theta-1}}{1-\alpha\gamma^{\theta-1}}\pi_t \tag{4.7}$$

[22] In fact just assuming that the real marginal costs depend on output ($mc_t = \frac{1}{\phi}y_t$) and substituting, one gets

$$y_t = \frac{\alpha\phi}{(1-\alpha)(1-\alpha\beta)}\left[\pi_t - \beta E_t \pi_{t+1}\right]$$

yields the generalized version of (4.4), which can be written as

$$\begin{aligned}\pi_t &= \left(\frac{1-\alpha\gamma^{\theta-1}}{\alpha\gamma^{\theta-1}}\right)(1-\alpha\beta\gamma^{\theta})mc_t + \beta E_t\pi_{t+1} + \\ &+(1-\gamma)\beta(1-\alpha\gamma^{\theta-1})\left[y_t - \left(\theta + \frac{\alpha\gamma^{\theta-1}}{1-\alpha\gamma^{\theta-1}}\right)E_t\pi_{t+1} + \right. \\ &\left. -(1-\alpha\beta\gamma^{(\theta-1)})E_t\sum_{j=0}^{\infty}(\alpha\beta\gamma^{\theta-1})^j[(\theta-1)\pi_{t+1,t+1+j} + y_{t+1+j}]\right]\end{aligned} \tag{4.8}$$

Setting $\gamma = 1$ gives (4.4). Clearly (4.8) is quite different from (4.4), and it is evident that trend inflation influences the behavior of inflation. Nonetheless, (4.8) can be written in a compact way that remind of (4.4):

$$\pi_t = \overline{\lambda}(\gamma)mc_t + \beta E_t\pi_{t+1} + (1-\gamma)F(E_t\pi_{t+i}, E_t y_{t+i}) \tag{4.9}$$

where $\overline{\lambda}(\gamma) = \left(\frac{1-\alpha\gamma^{\theta-1}}{\alpha\gamma^{\theta-1}}\right)(1-\alpha\beta\gamma^{\theta})$. Following Gali and Gertler (1999), the literature stressed the fact that inflation behavior depends on marginal cost. (4.8), however, shows how this relationship is very much influenced by trend inflation.

$\lambda = 0.086$	$\gamma = (1.02)^{\frac{1}{4}}$	$\gamma = (1.05)^{\frac{1}{4}}$	$\gamma = (1.08)^{\frac{1}{4}}$	$\gamma = (1.1)^{\frac{1}{4}}$
$\overline{\lambda}(\gamma)$	0.06	0.031	0.012	0.0043
$(\lambda - \overline{\lambda}(\gamma))/\lambda$	30%	64%	86%	95%

Table 1. Values of λ as a function of trend inflation

Table 1 displays the sensitivity of the value of λ to the trend inflation rate. Even for a small level of trend inflation, ie, 2% annually, the value of λ is reduced by 30% with respect to a log-linearization around ZISS. This means that the dynamic response of inflation to marginal costs is overestimated if trend inflation is not taken into account. Moreover, the higher the level of inflation, the further apart are the values of λ and $\overline{\lambda}(\gamma)$. The model predicts that the dynamic response of inflation to marginal costs should be reduced by 64% if annualized trend inflation is 5%, up to 86% for 8% trend inflation and virtually zero for 10% trend inflation. Figure 7 visualizes this effect.[23]

From the analysis above some important points follow. First, the model therefore implies that the log-linear approximation (4.5) which expresses the dynamics of inflation as a function of the future expected path of marginal costs in a ZISS gets substantially worse as trend inflation increases. Hence, all the results in the literature obtained using the Calvo setup and a ZISS assumption should look very suspicious (the optimal monetary policy literature for example, eg, Clarida, Gali, and Gertler (1999) and Woodford (2003)). Second, it does not seem to be appropriate to compare simulation data obtained from a model with a ZISS with actual data (from VAR analysis, for

[23] If $\theta = 4.3$, λ is reduced of 30% if trend inflation is 5% and of 60% at 10% trend inflation, so the argument still holds.

example, eg, Ireland (1997) and Christiano, Eichenbaum, and Evans (2001)), where trend inflation is above zero. Finally, Gali and Gertler (1999) proposed an empirical formulation based on (4.4) to explain the dynamics of inflation.[24] Gali and Gertler (1999) argued that such a model could account for the behavior of US inflation in the sample 1960-1997, and estimated the structural parameters of the model (ie, α, β). From what has just been said above, a model based on (4.4) is questionable when values of trend inflation are not only in double digits, as in the pre-Volcker period, but just slightly above zero. More generally, if average inflation in a data sample is moving around (as it does in post world war II data in developed countries), then matching the data with such a model is not appropriate given that these movements in trend inflation would lead to a large variation in the dynamics. The ZISS assumption tends to simplify the analysis and to give neat results, which are however misleading since they disregard the effects of trend inflation .

4.2 Disinflation

Not surprisingly, the effect of a disinflationary policy would also depend on the rate of steady state inflation. A log-linearized model is not suited to solve for the path of output following a sizeable disinflation, because a disinflation involves a move from one steady state to another. Hence I use the package for non-linear simulations DYNARE.[25] Figure 8 shows the path of output following a 4% disinflation, again in the model with fixed capital and constant return to scale.[26] The disinflation experiment is an unanticipated permanent decrease in the money growth rate, that is, the initial values are from a steady state where the money growth rate is x% and then it is unexpectedly and permanently lowered to (x–4)%. After a disinflation from 4% to 0, output decreases by about 10%, and so disinflation causes a substantial slump on impact. Then output starts increasing monotonically, until it reaches its new, slightly higher steady state level (recall Figure 3).[27] The output path following a disinflation from 6% to 2% qualitatively is very similar, but the impact effect is smaller while the steady state effect is bigger. And these features swiftly intensify as the starting rate of growth of money increases. For a given size of the disinflationary policy (ie, 4%), the higher the starting rate of growth of money, the smaller the negative impact effect and the bigger the positive steady state effect. Disinflating from 10% to 6% does not cause any decrease in output level, which is always above the starting steady state level. The

[24] Gali and Gertler (1999) model is slightly different, since it also includes a fraction of backward-looking price setters.

[25] This package has been elaborated by Michel Juillard at CEPREMAP (see Juillard (1996)) based on the algorithm in Boucekkine (1995). King and Wolman (1996) also briefly discussed disinflations in Calvo model, but in a linear framework.

[26] χ is set to 1, but the results are very similar also for higher values of χ. Recall that the steady state does not depend on χ.

[27] In Figure 8 the final steady state level is normalized to 1. So one can easily read on the vertical axis scale on the left the difference between the starting and the final steady state.

long-run effect of the policy has taken over the short-run dynamics. The path in Figure 8b (from 12% to 8%) looks plainly unbelievable.

As a conclusion, trend inflation is found to matter a lot, not only for the steady state properties of the model but also, if not even more, for the effects on its dynamic properties.

5 A comparison with the Taylor model

In this section I carry out the same exercise for the Taylor (1980) staggering model. The model setup and the calibration are the same as before, but now the economy is divided into 4 sectors of equal size. Each firm in a sector fixes the price for 4 periods (calibrated to be a quarter) and sectors' pricing decisions are staggered. Facing the same problem, all the price resetting firms in the same sector fix the same price. Therefore, in each period, there are 4 different prices: one fixed today by a quarter of firms, the others fixed one, two and three periods ago respectively by the other three quarters of firms.

As we will see, this model does not show in any case the sensitivity to trend inflation that characterizes the Calvo model. The Taylor type staggering model is very robust to, even substantial, changes in trend inflation. The main reason lies in the different kind of aggregation in the Calvo and Taylor model. Taylor model has two appealing properties: (i) the price resetting firms in each period are the ones that resetted their prices further on in the past; (ii) price dispersion is much lower with respect to Calvo, since there are only four different prices in each period.

Figures 9–12 corresponds to Figures 1–4 for the Taylor model. First, the Taylor contract structure would not impose any upper bound on the steady state rate of money growth. In this case, in fact, the first order condition for price re-setting firms would present a ratio between finite summations, and so there would be no issue of convergence of infinite sums. Second, Figures 9–12 show that the effects of trend inflation and of the parameters σ and θ qualitatively are the same as Figure 1–4. The intuition is also the same. The numbers, however, are totally different: quantitatively changes in trend inflation affects the Taylor model only slightly. 10% trend inflation decreases output of 1,4% and 2,5% in the model with capital and in the fixed capital model respectively. Third, Figures 11 and 12 show that changes in σ or θ have no such dramatic effects as in the Calvo setup.

Figures 13 and 14, instead, are the parallel of Figures 5 and 6. In the case of log-utility (Figure 13), trend inflation has basically no effects on the response of output following a money shock. The impulse response of the Taylor model is less persistent with respect to the Calvo model, as we know from Kiley (2002). For higher values of χ, some effects appear. Again the direction (and intuition) is the same as in the previous section and again the numbers are totally different.

Finally, looking at disinflation, Figure 15 shows that while the long-run effect is not very sensitive to the initial level of trend inflation (recall Figure

11), the short-run effect, that is, the depth of the initial recession, is lower the higher the initial inflation rate.

To conclude, contrary to the Calvo model, the Taylor model seems to be quite robust to changes in the average inflation rate. While trend inflation affects both the steady state and the dynamics of the model, it does not seem to dramatically alter the model as in the case of the Calvo model.[28]

6 Indexation

It has been shown above that trend inflation has some disturbing effects both on the steady state and on the dynamics of a standard staggered price model with Calvo pricing. One way to free the model with all the problems mentioned above is indexation.

The literature proposes two indexation schemes, indexing the prices that cannot be reset either to the trend inflation rate (see, eg, Yun (1996) and Jeanne (1998)), or to the past inflation rate (see, Christiano, Eichenbaum, and Evans (2001)). Both of these schemes can be shown (see Appendix B) to cancel the effects of trend inflation: both the steady state and the dynamic equations of the optimal reset price are the same with positive or with zero money growth.[29] The intution is simple: in a non-stochastic steady state all the firms charge the same price, whatever the rate of growth of money, because the updating rule coincides with the steady state optimal pricing rule. In steady state there is no relative price issue, which concerns only the dynamics.

However, there are some difficulties in assuming this kind of automatic adjustment to trend or past inflation. The first one is obviously that in reality we do not observe such contracts, because most prices and wages are fixed within a year (see Taylor (1998)). Multiperiod *wage* contracts, rather than prices, can sometimes be indexed to past inflation. Moreover, we know from Gray (1976) that full indexation is not optimal. Whenever the indexation is only partial, then the nuisances described in this paper would still be present.

Finally, in terms of microfoundations, one of the rationales given for the directly postulated Calvo contract structure is that it is analytically equivalent to the Rotemberg (1982) model of quadratic cost of changing price. This would imply, however, that the microeconomic rationale for keeping the price fixed for a certain amount of time is a quadratic 'menu cost' of changing price, and it would be difficult then to justify a costless automatic 'menu' adjustment to trend or past inflation. Christiano, Eichenbaum, and Evans (2001) actually justified this scheme appealing to reoptimization costs rather than menu costs and, to rule-of-thumb behavior. This may be fine, but when we start to assume rule-of-thumbers is difficult to know where to stop. Indeed, the Christiano,

[28] It would be interesting to look in more details to the causes and implications of these effects in a Taylor model. In particular, different setups of the model (e.g., strategic complementarity, wage staggering, etc.) may make these effects larger (see Ascari (2000)). This will be the object of future research.

[29] Obviously here we are just referring to the equations regarding the behavior of inflation (pricing rule and price index). In general, other equations as well would depend on steady state inflation (eg, money demand, possibly leisure decisions etc.)

Eichenbaum, and Evans (2001) main justification for using this indexation scheme is empirical: to match the inflation inertia in the data.

Last, but not least, note that nothing then prevents firms from indexing to actual inflation, just allowing the prices to change exactly as the new resetted prices, which are observable. Well, it is easy to show that in this case, there are never relative price changes and the model becomes basically a flexible price model. There is no relative price issue neither in steady state nor in the dynamics.

In sum, I showed that trend inflation is very disturbing in a standard sticky-price Calvo model. No paper in the literature ever mentioned these problems. Indexation can get around them and possibly others. But theoretically, the validity of such schemes is still questionable.

As is well known, the only alternative is state-dependent models. A remarkable example is the model in Dotsey et al (1999). In fact, in a state-dependent model, the duration of contracts depends on the state of the economy and should respond to trend inflation. In other words, α should decrease with γ thus counteracting the effect of trend inflation, as it does in Dotsey et al (1999). Figure 16 shows the deviation of steady state output from ZISS as a function of trend inflation and of α.[30] It is evident then that the changes in α would mitigate the steady state effects of trend inflation and presumably also the effects on the dynamics, alleviating the nuisances. In other words, and as a bottom line, the Lucas critique seems to be really biting in these models.

7 Conclusion

To conclude, one of the most fruitful recent areas of research in macroeconomics is certainly the so-called *New Neoclassical Synthesis.* Most of the papers in this literature, however, use time-dependent Calvo-type staggered price model and assume zero trend inflation. It can hardly be justified to assume zero trend inflation to describe and model the data of post-war inflation.

This paper shows that, unfortunately, in these models trend inflation matters. If it is considered, then time dependent staggered price models demonstrate some limits: several nuisances appear both regarding their long-run (ie, steady state) and the short run (ie, dynamics) properties. Indeed, this paper shows that: (i) a very mild level of trend inflation implies huge, and unrealistic, changes in the steady state output level; (ii) trend inflation changes the dynamic properties of the log-linearized model; (iii) the level of trend inflation is also extremely important for the dynamic behavior of the model following a disinflation. In short, this paper shows that disregarding trend inflation is very far from being an innocuous assumption. The results obtained by models employing Calvo pricing and log-linearized around a zero inflation steady state are therefore quite misleading.

[30] In the white parts of Figure 16 the model is not defined, because the level of trend inflation is higher than its upper value.

Furthermore, the analysis suggests that Taylor-type pricing do not suffer of the problems above, being robust to changes in trend inflation. The steady state changes very little with trend inflation and so do the dynamics.

Inflation targets are non-zero, they have changed over time, and, trend inflation has moved around quite a bit in post world-war II data in developed countries. Unless one is willing to assume indexed nominal variables, or able to embed state-dependent pricing in a DGE model, this paper shows that we should use Taylor pricing to fit the data rather than Calvo pricing in our *New Neoclassical Synthesis* models.

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A Appendix

A.1 The model

(A1A) The Model with variable capital

1) Household
Given the utility function

$$U = \left\{ \left[bC^{\frac{\eta-1}{\eta}} + (1-b)\left(\frac{M}{P}\right)^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}} (1-L)^{e} \right\}^{1-\chi} / (1-\chi) \tag{A.1}$$

the first order condition for the representative households are the following:

$$\frac{W_t}{P_t} = \frac{eC_t \left[1 + \bar{b}\left(\frac{m_t}{C_t}\right)^{\frac{\eta-1}{\eta}} \right]}{1-L_t} \tag{A.2}$$

$$\frac{U_m(t)}{U_C(t)} = \bar{b}\left(\frac{C_t}{m_t}\right)^{\frac{1}{\eta}} = \frac{i_t}{1+_{i_t}} \tag{A.3}$$

$$E_t\left(\frac{U_C(t+1)}{U_C(t)}\beta(1+r_t)\right) \tag{A.4}$$

$$= E_t\left[\left(\frac{C_{t+1}}{C_t}\right)^{\frac{-1}{\eta}} \left(\frac{cm_{t+1}}{cm_t}\right)^{\frac{1}{\eta}-\chi} \left(\frac{1-L_{t+1}}{1-L_t}\right)^{e(1-\chi)} \beta(1+r_t) \right] = 1$$

where W_t = nominal wage; P_t = general price level; C_t = consumption; $m_t = \left(\frac{M_t}{P_t}\right)$ = real money balances; $\bar{b} = \frac{1-b}{b}$; $cm_t = \left[bC_t^{\frac{\eta-1}{\eta}} + (1-b)m_t^{\frac{\eta-1}{\eta}} \right]^{\frac{\eta}{\eta-1}}$; L_t = labor supply; $U_X(t)$ = marginal utility with respect to the argument X (for $X = C, m, L$); i_t = nominal interest rate; r_t = real interest rate.

2) Pricing equations
Final good producers use the following technology

$$Y_t = \left[\int_0^1 Y_{i,t}^{\frac{\theta-1}{\theta}} di \right]^{\frac{\theta}{\theta-1}} \tag{A.5}$$

Their demand for intermediate inputs is therefore equal to

$$Y_{i,t+j} = \left(\frac{P_{i,t}}{P_{t+j}}\right)^{-\theta} Y_{t+j} \tag{A.6}$$

The problem of the representative intermediate goods producer firms that reset the price is

$$\underset{\{P_{it}\}}{Max} \quad E_t\left(\sum_{j=0}^{\infty} \alpha^j \Delta_{t,t+j} \digamma_{t+j}\right) \tag{A.7}$$

$$= E_t\left(\sum_{j=0}^{\infty} \alpha^j \Delta_{t,t+j} \left[\left(\frac{P_{i,t}}{P_{t+j}}\right) Y_{i,t+j} - TC_{i,t+j}(Y_{i,t+j}) \right]\right)$$

$$s.t. \qquad Y_{i,t+j} = \left(\frac{P_{i,t}}{P_{t+j}}\right)^{-\theta} Y_{t+j}$$

where $\Delta_{t,t+j}$ represents the real discount factor from t to $t+j$ applied by the firm to the stream of future real profits[31]; F = real profits, P_i = price set by the firm, TC_i = real total costs. The optimal price fixed by re-setting firms in period t is

$$P_{i,t}^{*} = \left(\frac{\theta}{\theta-1}\right) \frac{E_t \sum_{j=0}^{\infty} \alpha^j \Delta_{t,t+j} MC_{i,t+j} P_{t+j}^{\theta} Y_{t+j}}{E_t \sum_{j=0}^{\infty} \alpha^j \Delta_{t,t+j} P_{t+j}^{\theta-1} Y_{t+j}} \tag{A.8}$$

where MC_i = real marginal cost of producer i. Note that (A.8) can be written as $P_{i,t}^{*} = \left(\frac{\theta}{\theta-1}\right)\frac{\Psi(t)}{\Phi(t)}$, where

$$\Psi(t) = MC_{i,t} P_t^{\theta} Y_t + \alpha\beta E_t \left[\Psi(t+1)\right] \tag{A.9}$$

$$\Phi(t) = P_t^{\theta-1} Y_t + \alpha\beta E_t \left[\Phi(t+1)\right] \tag{A.10}$$

The price of the final good is given by

$$P_t = \left[\int_0^1 P_{i,t}^{1-\theta} di\right]^{\frac{1}{1-\theta}} \tag{A.11}$$

3) Technology

Denoting by q_t the real user cost of capital, the cost minimization problem of a representative intermediate goods producer firm i is

$$\underset{\{K_{i,t-1}, L_t\}}{MIN} \qquad q_t K_{i,t-1} + \overbrace{w_t}^{W_t/P_t} L_{i,t}$$

$$s.t. \qquad Y_{i,t} = A_t (K_{i,t-1})^{1-\sigma} (L_{i,t})^{\sigma}$$

which gives the following usual first order conditions

$$q_t = A_t(1-\sigma)\left(\frac{L_{i.t}}{K_{i,t-1}}\right)^{\sigma} MC_{i,t} \tag{A.12}$$

$$w_t = A_t \sigma \left(\frac{K_{i,t-1}}{L_{i.t}}\right)^{1-\sigma} MC_{i,t} \tag{A.13}$$

Combining these two equations with the production function yields the equations for the demand of labor and capital and for the marginal cost

$$L_{i,t}^{d} = \frac{Y_{i,t}}{A_t}\left[\frac{\sigma}{1-\sigma}\frac{q_t}{w_t}\right]^{1-\sigma} \tag{A.14}$$

$$K_{i,t-1}^{d} = \frac{Y_{i,t}}{A_t}\left[\frac{1-\sigma}{\sigma}\frac{w_t}{q_t}\right]^{\sigma} \tag{A.15}$$

$$MC_{i,t} = \frac{1}{A_t}\left[\frac{w_t}{\sigma}\right]^{\sigma}\left[\frac{q_t}{1-\sigma}\right]^{1-\sigma} \tag{A.16}$$

[31] For simplicity, we will set that equal to β, the real discount factor in the utility function.

4) Market clearing

The aggregate resource constraint is

$$Y_t = C_t + X_t \tag{A.17}$$

where $X_t = \left[\int_0^1 X_{z,t} dz\right]$ and X_t = aggregate investment, while $X_{i,t}$ = investment of the intermediate goods producer i. $X_{i,t}$ is given by the following capital accumulation equation for the single intermediate goods producer i

$$K_{i,t} = (1-\delta)K_{i,t-1} + X_{i,t} \tag{A.18}$$

where δ = depreciation rate. This linear equation can be aggregated over all the intermediate goods producers and then substituted into the aggregate resource constraint to get

$$Y_t = C_t + K_t - (1-\delta)K_{t-1} \tag{A.19}$$

Market clearing on the capital and labor markets requires

$$K_{t-1} = \left[\int_0^1 K_{i,t-1}^d di\right] \tag{A.20}$$

$$L_t^d = \left[\int_0^1 L_{i,t}^d di\right] = L_t^s \tag{A.21}$$

Following Yun (1996) the equation to link intermediate goods output and final good output is given by

$$IO_t = \left[\int_0^1 Y_{i,t} di\right] = \left[\frac{P_t}{\widetilde{P}_t}\right]^{\theta} Y_t \tag{A.22}$$

where $\widetilde{P}_t = \left[\int_0^1 P_{i,t}^{-\theta} di\right]^{\frac{-1}{\theta}}$ and IO_t = 'aggregator' of intermediate goods output.

Finally, exploiting the property that, given the Cobb-Douglas production function for intermediate goods producer, the ratio $\left[\frac{K_{i,t-1}}{L_{i,t}}\right]$ is the same across all firms i, it is possible to aggregate to obtain:

$$IO_t = A_t K_{t-1}^{1-\sigma} L_t^{\sigma} \tag{A.23}$$

$$L_t^d = \frac{IO_t}{A_t}\left[\frac{\sigma}{1-\sigma}\frac{q_t}{w_t}\right]^{1-\sigma} \tag{A.24}$$

$$K_{t-1}^d = \frac{IO_t}{A_t}\left[\frac{1-\sigma}{\sigma}\frac{w_t}{q_t}\right]^{\sigma} \tag{A.25}$$

$$MC_t = \frac{1}{A_t}\left[\frac{w_t}{\sigma}\right]^{\sigma}\left[\frac{q_t}{1-\sigma}\right]^{1-\sigma} \tag{A.26}$$

The model is closed by the equation $r = q - \delta$.

(A1B) The model with fixed capital

Both the household problems and the pricing problem of the resetting firms do not change, and thus neither do the first order conditions. The difference is given by the technology of intermediate goods producers, now given by

$$Y_{i,t} = A_t L_{i,t}^{\sigma} \tag{A.27}$$

The labor demand and the real marginal cost of firm i is therefore

$$L_{i,t}^{d} = \left[\frac{Y_{i,t}}{A_t}\right]^{\frac{1}{\sigma}} \tag{A.28}$$

$$MC_{i,t} = \frac{1}{\sigma} A_t^{-\frac{1}{\sigma}} w_t Y_{i,t}^{\frac{1}{\sigma}-1} \tag{A.29}$$

The aggregate resource constraint is now simply given by

$$Y_t = C_t \tag{A.30}$$

and the link between aggregate labor demand and aggregate output is provided by

$$L_t^d = \left[\int_0^1 L_{i,t}^d di\right] = \left[\frac{Y_t}{A_t}\right]^{\frac{1}{\sigma}} \left[\frac{P_t}{\overline{P_t}}\right]^{\frac{\theta}{\sigma}} \tag{A.31}$$

where $\overline{P_t} = \left[\int_0^1 P_{i,t}^{-\frac{\theta}{\sigma}} di\right]^{-\frac{\sigma}{\theta}}$.

Note that now marginal costs depend upon the quantity produced by the single firm, given the decreasing returns to scale. In other words, different firms charging different prices would produce different levels of output and hence have different marginal costs. Consider the optimal reset price formula in a non-stochastic steady state. This is still described by

$$P_{i,t}^{*} = \left(\frac{\theta}{\theta-1}\right)\frac{\Psi(t)}{\Phi(t)} \tag{A.32}$$

$$\Phi(t) = P_t^{\theta-1} Y_t + \alpha\beta E_t\left[\Phi(t+1)\right]$$
$$\Psi(t) = MC_{i,t} P_t^{\theta} Y_t + \alpha\beta E_t\left[\Psi(t+1)\right]$$

The $MC_{i,t}$ in $\Psi(t)$ is now increasing over time, since

$$MC_{i,t+j} = \frac{1}{\sigma} A_{t+j}^{-\frac{1}{\sigma}} w_{t+j} \left(\frac{P_{i,t}^{*}}{P_{t+j}}\right)^{-\theta(\frac{1}{\sigma}-1)} Y_{t+j}^{(\frac{1}{\sigma}-1)}$$

and $P_{i,t}^{*}$ is fixed until the new resetting. The variable $\Psi(t)$ needs therefore to be deflated accordingly to make it stationary. In a non-stochastic environment,

$$\Phi(t) = \sum_{j=0}^{\infty} (\alpha\beta)^j P_{t+j}^{\theta-1} Y_{t+j} \tag{A.33}$$

$$\Psi(t) = \sum_{j=0}^{\infty} (\alpha\beta)^j MC_{i,t+j} P_{t+j}^{\theta} Y_{t+j} \tag{A.34}$$

$$= \sum_{j=0}^{\infty} (\alpha\beta)^j \frac{1}{\sigma} A_{t+j}^{-\frac{1}{\sigma}} w_{t+j} \left(\frac{P_{i,t}^*}{P_{t+j}}\right)^{-\theta(\frac{1}{\sigma}-1)} Y_{t+j}^{(\frac{1}{\sigma}-1)} P_{t+j}^{\theta} Y_{t+j}$$

Substituting (A.33) and (A.34) in (A.32) yields a dynamic equation that links $P_{i,t}^*$ to aggregate variables.

$$P_{i,t}^{*1+-\theta(\frac{1}{\sigma}-1)} = \left(\frac{\theta}{\theta-1}\right) \frac{\sum_{j=0}^{\infty} (\alpha\beta)^j \frac{1}{\sigma} A_{t+j}^{-\frac{1}{\sigma}} w_{t+j} Y_{t+j}^{\frac{1}{\sigma}} P_{t+j}^{\frac{\theta}{\sigma}}}{\sum_{j=0}^{\infty} (\alpha\beta)^j P_{t+j}^{\theta-1} Y_{t+j}} \tag{A.35}$$

In a non-stochastic steady state A_t, Y_t and w_t are constant over time, while $P_{t+1}/P_t = \gamma$, hence substituting it yields

$$\Phi(t) = P_t^{\theta-1} Y \sum_{j=0}^{\infty} (\alpha\beta\gamma^{\theta-1})^j \tag{A.36}$$

$$\Psi(t) = \frac{1}{\sigma} A^{-\frac{1}{\sigma}} w Y^{\frac{1}{\sigma}} P_t^{\theta/\sigma} P_{i,t}^{*-\theta(\frac{1}{\sigma}-1)} \sum_{j=0}^{\infty} (\alpha\beta\gamma^{\theta/\sigma})^j \tag{A.37}$$

Substituting the expression for $\Phi(t)$ and $\Psi(t)$ in (A.32) I can obtain a formula that links the reset price with the aggregate variables in the non-stochastic steady state and then solve for Y. It is clear, however, that the two summations in (A.36) and (A.37) need to converge. In particular, I need the following: $\alpha\beta\gamma^{\theta/\sigma} < 1$,ie, $\gamma < (\alpha\beta)^{-\sigma/\theta}$. Putting $\alpha = 0.75, \beta = 0.99, \sigma = 0.67, \theta = 10$, I get $\gamma < 1.02$, which means an annual rate of growth of money lower than 8%.

B Appendix

B.1 Indexation

(B2A) To trend inflation

Yun (1996) and Jeanne (1998) assume that the new price set in a generic period t is actually indexed to trend inflation. Hence, even if the firm is not allowed to revise its price, the latter grows at the same rate as trend inflation. Then the problem of the firm is

$$\underset{\{P_{it}\}}{Max} \quad E_t\left(\sum_{j=0}^{\infty}\alpha^j\Delta_{t,t+j}\digamma_{t+j}\right) \tag{B.1}$$
$$= E_t\left(\sum_{j=0}^{\infty}\alpha^j\Delta_{t,t+j}\left[\left(\frac{P_{i,t}\Pi^j}{P_{t+j}}\right)^{1-\theta}Y_{t+j} - TC_{i,t+j}(Y_{i,t+j})\right]\right)$$

where Π is trend inflation, which equals γ in steady state, and, $Y_{i,t+j} = \left(\frac{P_{i,t}\Pi^j}{P_{t+j}}\right)^{-\theta}Y_{t+j}$. The optimal price is

$$P_{it}^* = \left(\frac{\theta}{\theta-1}\right)\frac{E_t\sum_{j=0}^{\infty}\alpha^j\Delta_{t,t+j}MC_{i,t+j}\left(\frac{P_{t+j}}{\gamma^j}\right)^{\theta}Y_{t+j}}{E_t\sum_{j=0}^{\infty}\alpha^j\Delta_{t,t+j}\left(\frac{P_{t+j}}{\gamma^j}\right)^{\theta-1}Y_{t+j}} \tag{B.2}$$

The steady state value, with constant marginal cost, is

$$\frac{P_{i,t}}{P_t} = \left(\frac{\theta}{\theta-1}\right)MC \tag{B.3}$$

which coincides with the flexible price steady state. Moreover, note that there is no upper value for the steady state rate of growth of money.

The log-linearized optimal price setting rule equation coincides with the log-linearization of a typical Calvo framework around a zero money growth steady state

$$p_{it} - p_t = (1-\alpha\beta)E_t\sum_{j=0}^{\infty}(\alpha\beta)^j\left[\pi_{t,t+j} + mc_{i,t+j}\right] \tag{B.4}$$

which is also the case for the log-linearized general price level equation

$$p_{it} - p_t = \frac{\alpha}{1-\alpha}\pi_t \tag{B.5}$$

Putting them together one gets the usual New Keynesian Phillips Curve. Hence, indexing the Calvo model to trend inflation delivers exactly the kind of equations used in most models in the literature.

(B2B) To Past Inflation

Christiano, Eichenbaum, and Evans (2001) proposes the following price updating rule for the prices that cannot be optimally resetted in period t : $P_{i,t} = \Pi_{t-1} P_{i,t-1} = \frac{P_{t-1}}{P_{t-2}} P_{i,t-1}$. The problem of the firm is then

$$\underset{\{P_{it}\}}{Max} \qquad E_t \left(\sum_{j=0}^{\infty} \alpha^j \Delta_{t,t+j} \Gamma_{t+j} \right) \tag{B.6}$$
$$= E_t \left(\sum_{j=0}^{\infty} \alpha^j \Delta_{t,t+j} \left[\left(\frac{P_{i,t}\Pi_{t-1,t+j-1}}{P_{t+j}} \right)^{1-\theta} Y_{t+j} - TC_{i,t+j}(Y_{i,t+j}) \right] \right)$$

where $\Pi_{t-1,t+j-1} = \Pi_t \Pi_{t+1} ... \Pi_{t+j-1}$ and $\Pi_{t-1,t-1} = 0$. The first order condition for this problem yields

$$P_{it}^* = \left(\frac{\theta}{\theta - 1} \right) \frac{E_t \sum_{j=0}^{\infty} \alpha^j \Delta_{t,t+j} MC_{i,t+j} \left(\frac{P_{t+j}}{\Pi_{t-1,t+j-1}} \right)^{\theta} Y_{t+j}}{E_t \sum_{j=0}^{\infty} \alpha^j \Delta_{t,t+j} \left(\frac{P_{t+j}}{\Pi_{t-1,t+j-1}} \right)^{\theta-1} Y_{t+j}} \tag{B.7}$$

Now, recall that $\Pi_{t-1,t+j-1} = \Pi_t \Pi_{t+1} ... \Pi_{t+j-1} = \frac{P_{t+j-1}}{P_{t-1}}$, then (B.7) can be written as

$$\frac{P_{it}^*}{P_t} = \left(\frac{\theta}{\theta - 1} \right) \frac{E_t \sum_{j=0}^{\infty} \alpha^j \Delta_{t,t+j} MC_{i,t+j} \left(\frac{\Pi_{t+j}}{\Pi_t} \right)^{\theta} Y_{t+j}}{E_t \sum_{j=0}^{\infty} \alpha^j \Delta_{t,t+j} \left(\frac{\Pi_{t+j}}{\Pi_t} \right)^{\theta-1} Y_{t+j}} \tag{B.8}$$

It is thus immediate to see that the steady state value do not depend on the steady state rate of growth of money, since the terms in Π would cancel. Indeed, the non-stochastic steady state is the same as before, simply because in the steady state past inflation is equal to trend inflation. Log-linearizing around a steady state with a generic trend inflation rate gives

$$p_{it} - p_t = (1 - \alpha\beta) E_t \sum_{j=0}^{\infty} (\alpha\beta)^j \left[mc_{i,t+j} + \pi_{t+j} - \pi_t \right] \tag{B.9}$$

The log-linearization of the aggregate price level equation yields[32]

$$p_{it} - p_t = \frac{\alpha}{1 - \alpha} (\pi_t - \pi_{t-1}) \tag{B.10}$$

Putting the last two equations together, one gets equation (3.15) at p. 11 of Christiano, Eichenbaum, and Evans (2001), that is,

$$\pi_t = \frac{1}{1+\beta} \pi_{t-1} + \frac{(1-\alpha)(1-\alpha\beta)}{\alpha(1+\beta)} mc_{i,t} + \frac{\beta}{1+\beta} E_t \pi_{t+1} \tag{B.11}$$

The coefficients of the log-linearized equation, therefore, do not depend on the steady state rate of growth of money.

[32] $P_t = \left[\alpha (P_{t-1}\Pi_{t-1})^{1-\theta} + (1-\alpha) P_{i,t}^{1-\theta} \right]^{\frac{1}{1-\theta}}$.

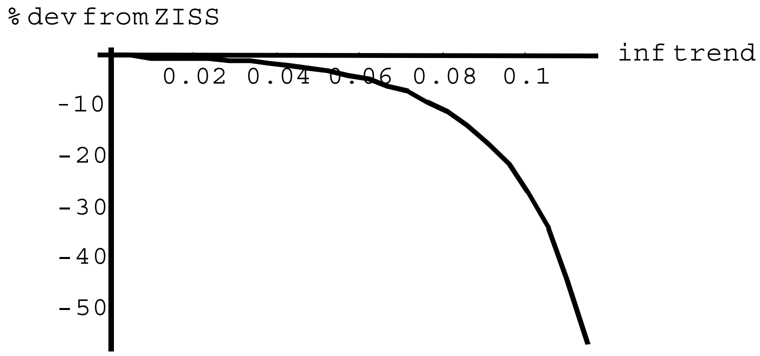

Figure 1. Percentage deviation from zero-inflation steady state output

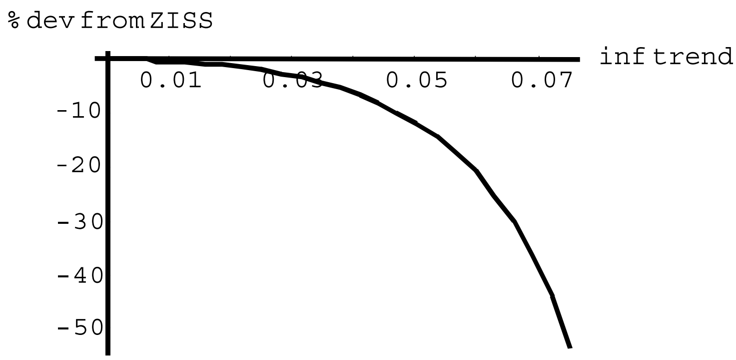

Figure 2. Percentage deviation from zero-inflation steady state output in the fixed capital model

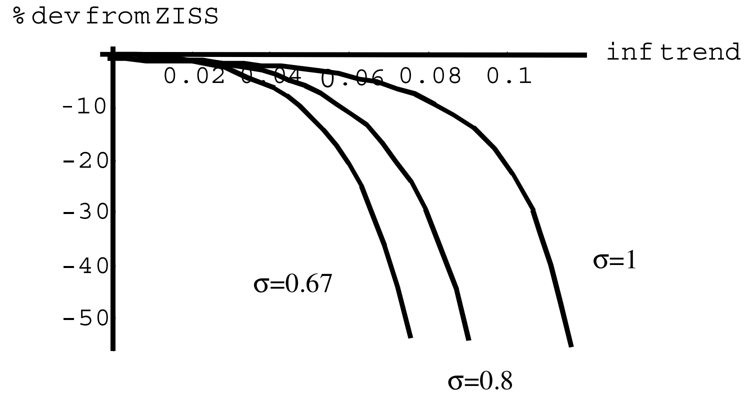

Figure 3. Percentage deviation from zero-inflation steady state output, as σ varies in the fixed capital model

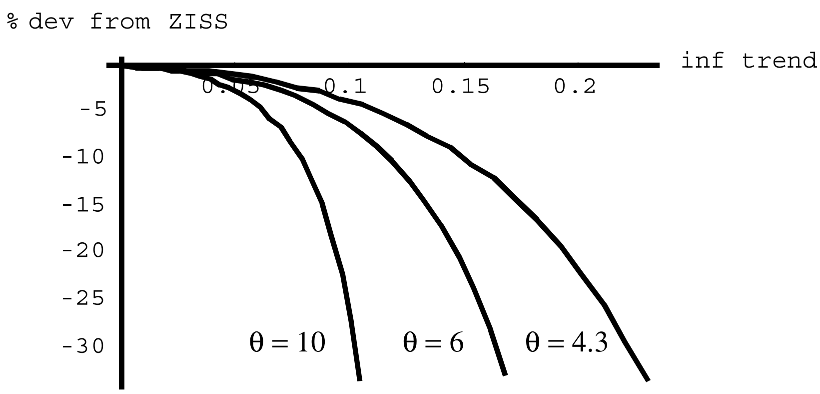

Figure 4. Percentage deviation from zero-inflation steady state output, as θ varies

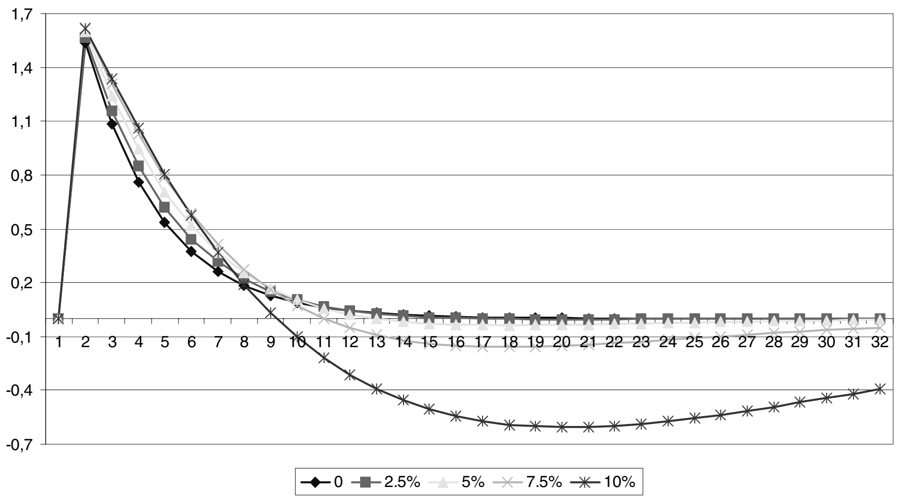

Figure 5. Impulse response of output to a 1% money growth shock.
Trend inflation: (i) 0; (ii) 2.5%; (iii) 5%; (iv) 7.5%; (v) 10%
(fixed capital model, $\sigma = 1$ and $\chi = 1$)

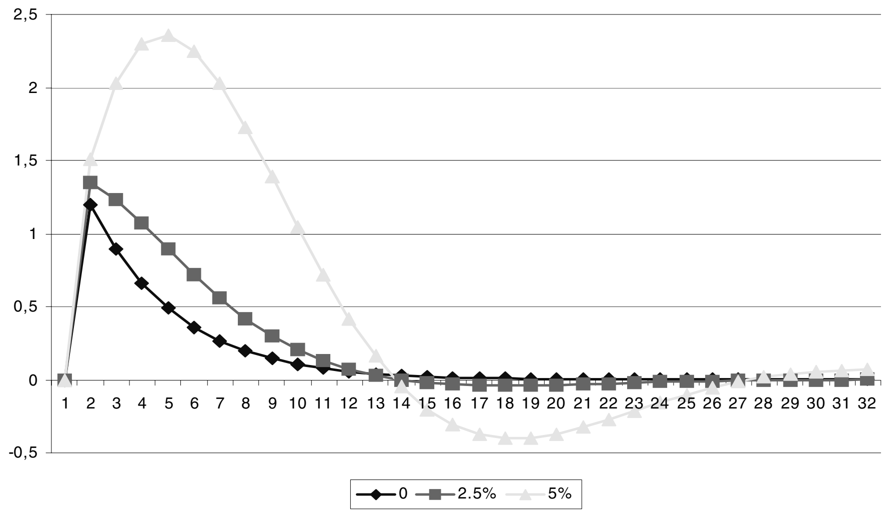

Figure 6a. Impulse response of output to a 1% money growth shock.
Trend inflation: (i) 0; (ii) 2.5%; (iii) 5%.
(fixed capital model, $\sigma = 1$ and $\chi = 5$)

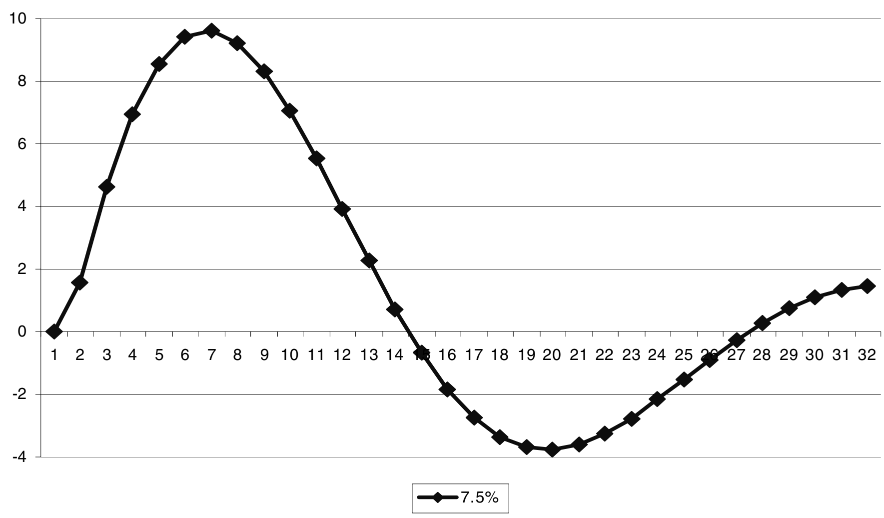

Figure 6b. Impulse response of output to a 1% money growth shock.
Trend inflation: 7.5%
(fixed capital model, $\sigma = 1$ and $\chi = 5$)

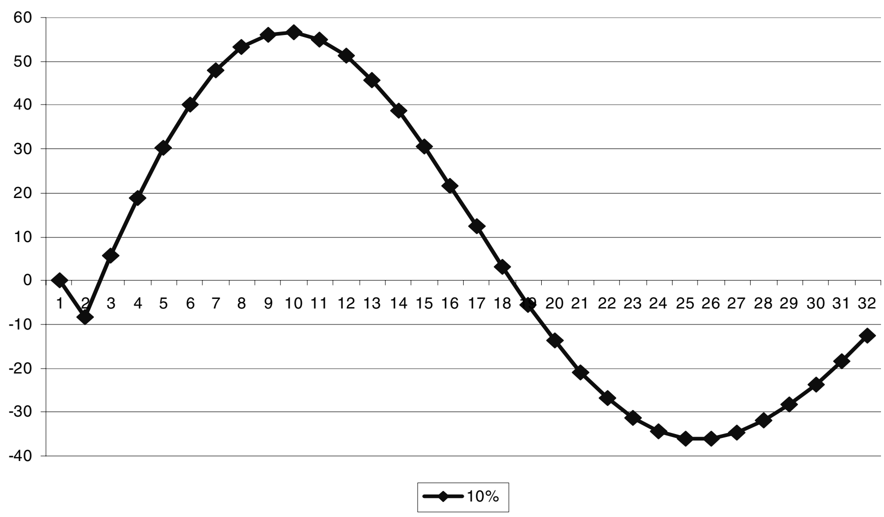

Figure 6c. Impulse response of output to a 1% money growth shock.
Trend inflation: 10%
(fixed capital model, $\sigma = 1$ and $\chi = 5$)

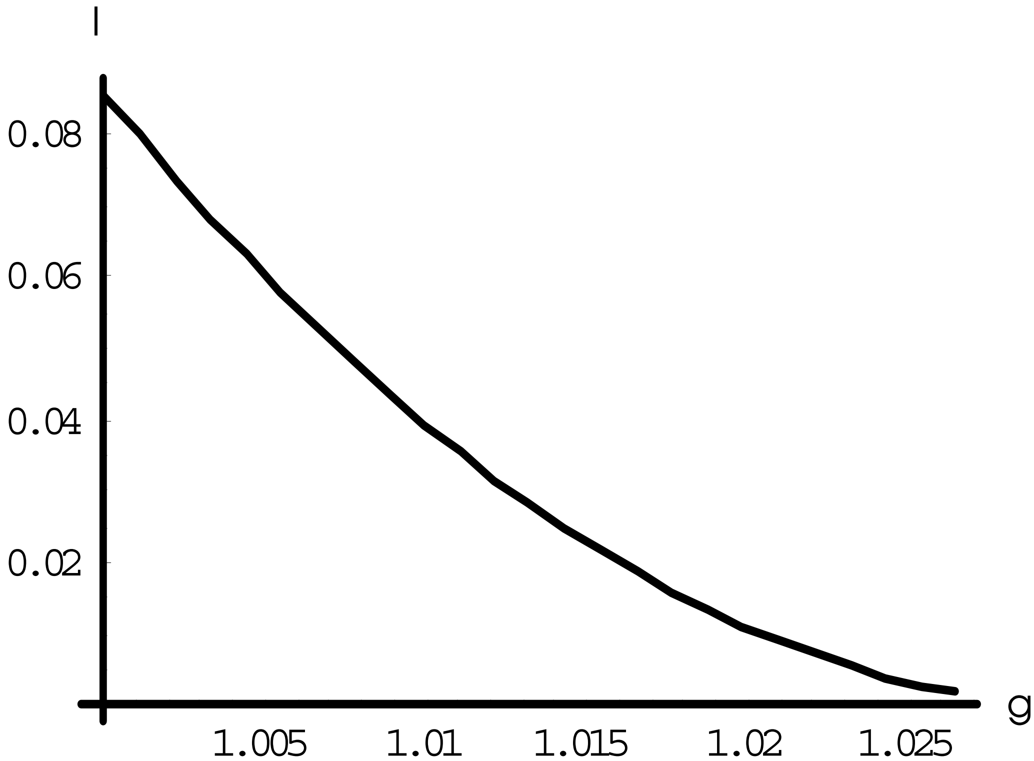

Figure 7. λ as a function of γ (quarterly rate)

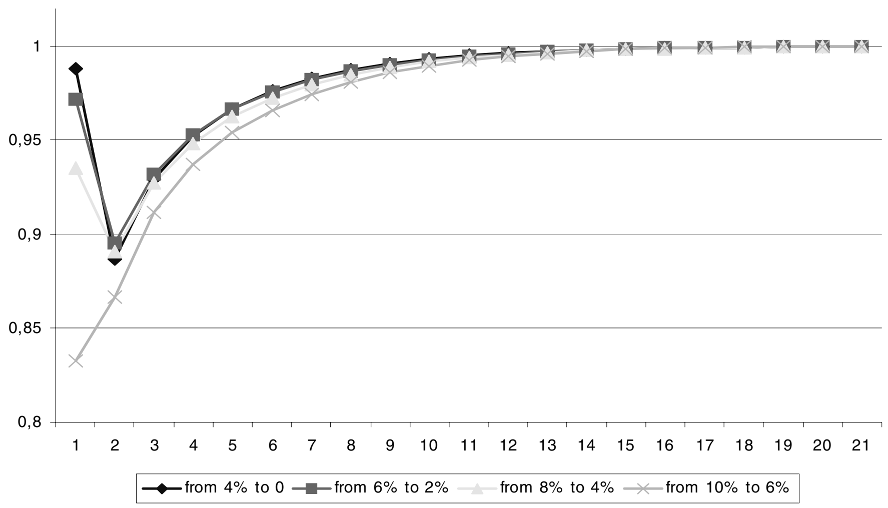

Figure 8a. Dynamics of output after a 4% disinflation, starting from: (i) 4%; (ii) 6%; (iii) 8%; (iv) 10%. (fixed capital model and $\sigma = 1$)

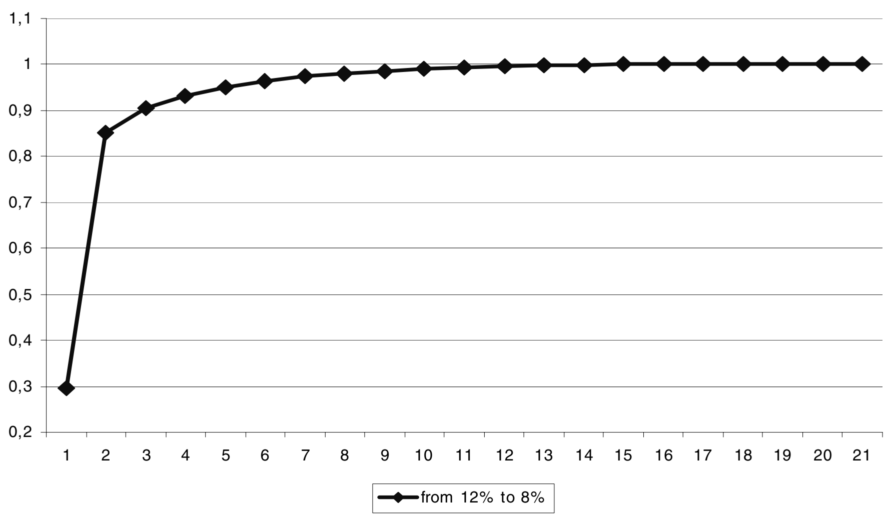

Figure 8b. Dynamics of output after a 4% disinflation, starting from 12% (fixed capital model and $\sigma = 1$)

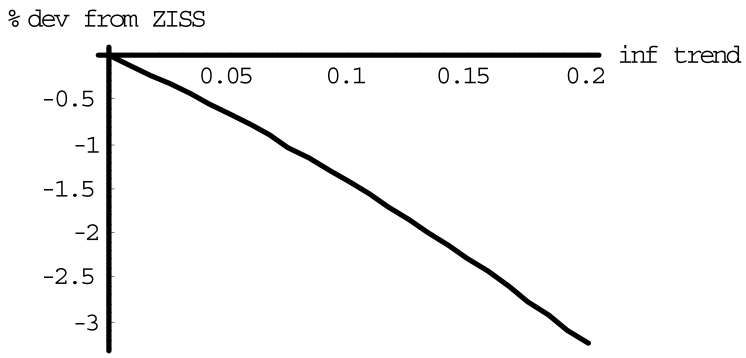

Figure 9. Taylor model: Percentage deviation from zero-inflation steady state output

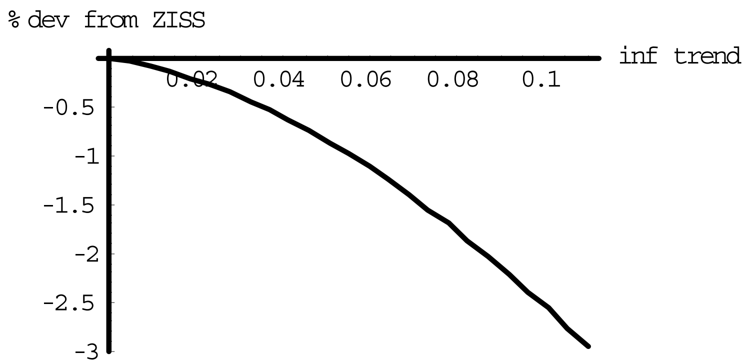

Figure 10. Taylor model: percentage deviation from zero-inflation steady state output in the fixed capital model

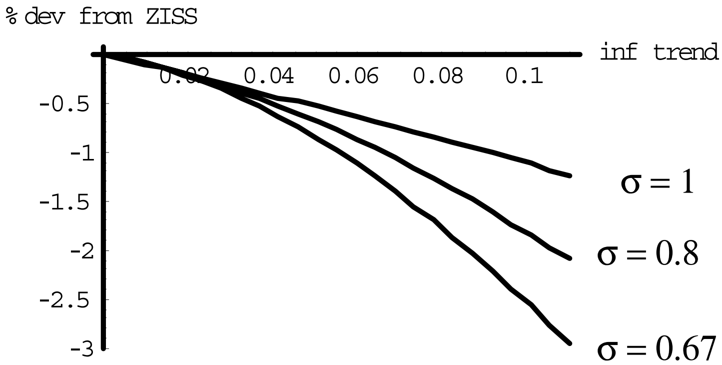

Figure 11. Taylor model: Percentage deviation from zero-inflation steady state output, as σ varies in the fixed capital model

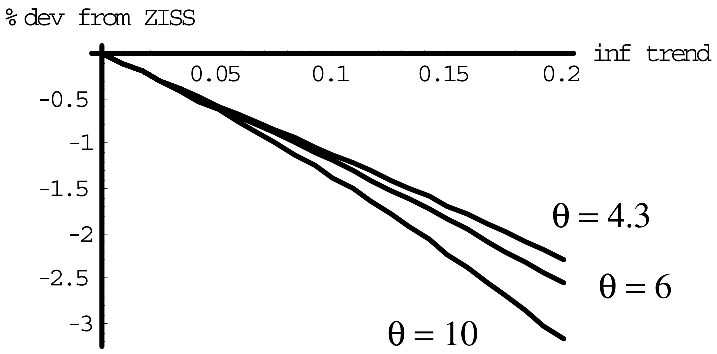

Figure 12. Taylor model: Percentage deviation from zero-inflation steady state output, as θ varies

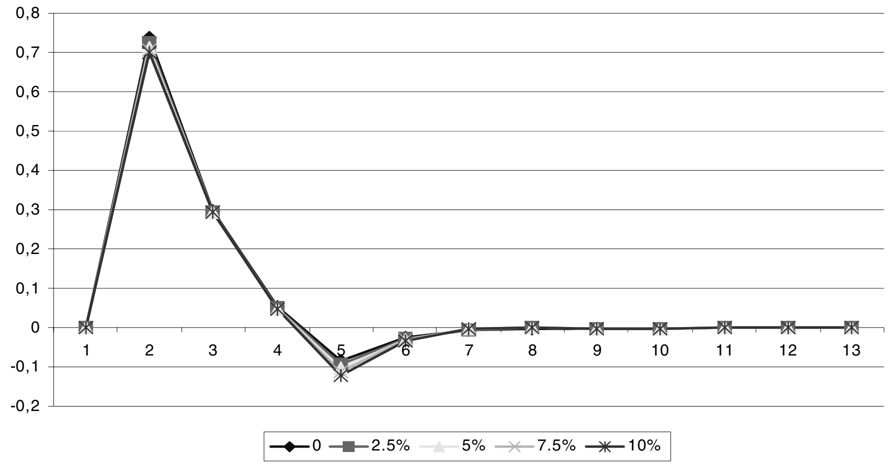

Figure 13. Taylor model: Impulse response of output to a 1% money growth shock.
Trend inflation: (i) 0; (ii) 2.5%; (iii) 5%; (iv) 7.5%; (v) 10%
(fixed capital model, $\sigma = 1$ and $\chi = 1$)

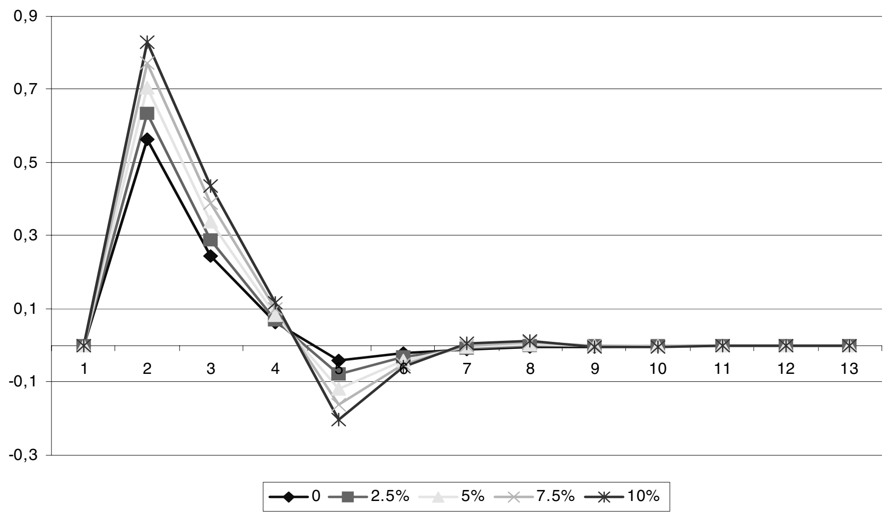

Figure 14. Taylor model: Impulse response of output to a 1% money growth shock.
Trend inflation: (i) 0; (ii) 2.5%; (iii) 5%; (iv) 7.5%; (v) 10%
(fixed capital model, $\sigma = 1$ and $\chi = 5$)

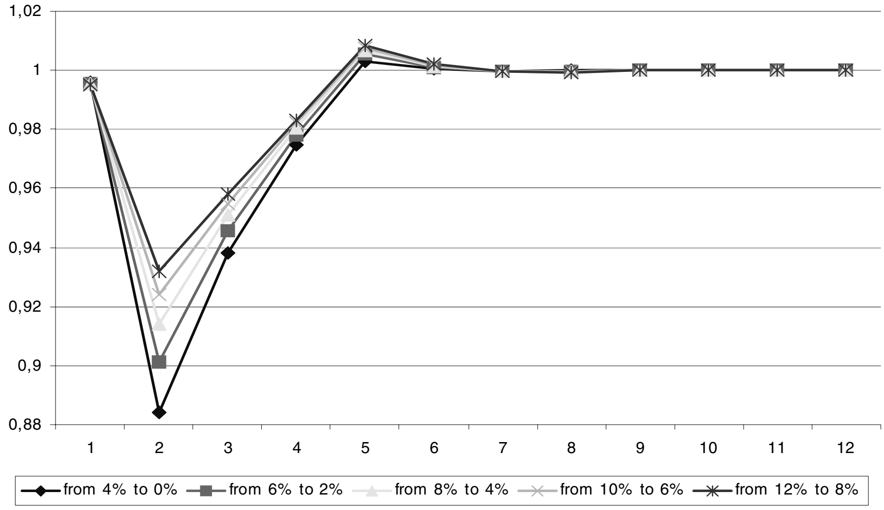

Figure 15. Taylor model: Dynamics of output after a 4% disinflation, starting from:
(i) 4%; (ii) 6%; (iii) 8%; (iv) 10%; (v) 12%.
(fixed capital model and $\sigma = 1$)

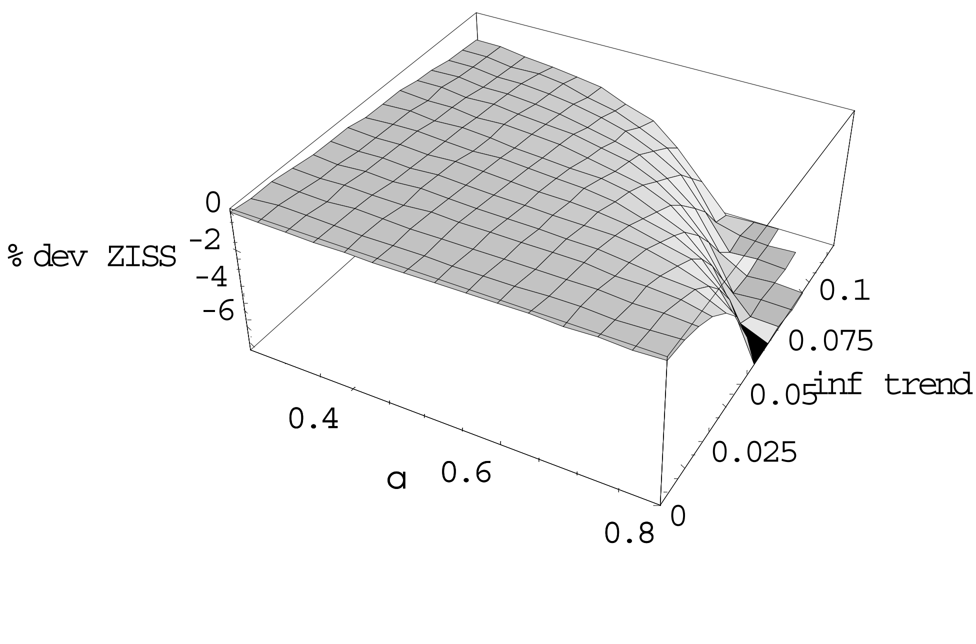

Figure 16. Percentage deviation from ZISS as a function of trend inflation and of α (Calvo model with capital)

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